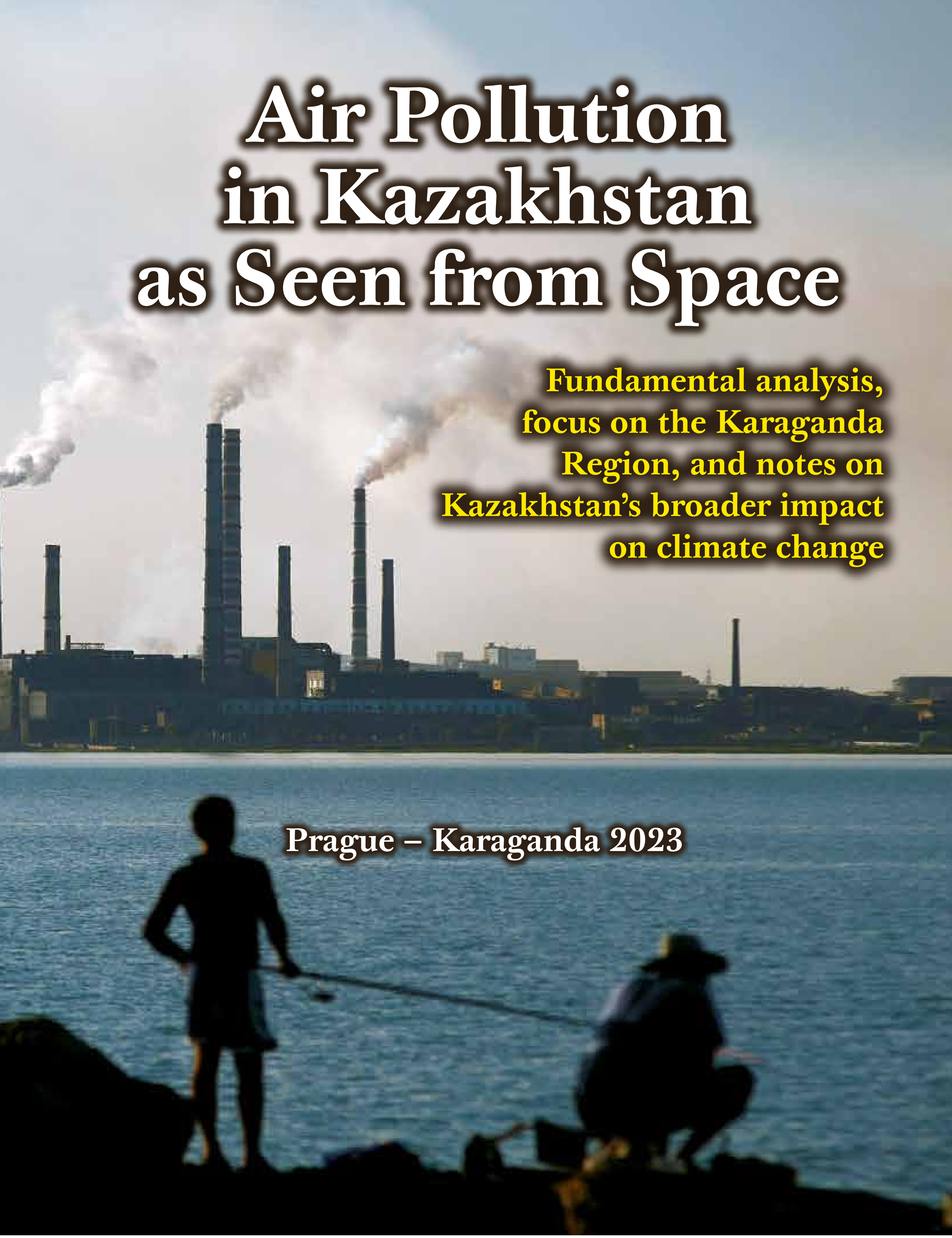

Air Pollution in Kazakhstan as Seen from Space

Fundamental analysis, focus on the Karaganda Region, and notes on Kazakhstan's broader impact on climate change

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Air Pollution in Kazakhstan as Seen from Space: Fundamental analysis, focus on the Karaganda Region, and notes on Kazakhstan's broader impact on climate change

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Contents

Abbreviations and acronyms

CAMS – Copernicus Atmosphere Monitoring Service
CH$_4$ – methane
CO – carbon monoxide
ECMWF – European Centre for Medium-Range Weather Forecasts
EEA – European Environment Agency
EIA – Environmental Impact Assessment
EPA – U.S. Environmental Protection Agency
EU – European Union
GIS – geographic information system
GFDRR – Global Facility for Disaster Reduction and Recovery
IEA – International Energy Agency
IFORCE – European Commission Forest Resources and Carbon Emissions
IPCC – Intergovernmental Panel on Climate Change
MAC – maximum allowable concentrations
NAQMN – National Air Quality Monitoring Network
NO$_2$ – nitrogen dioxide
OECD – Organisation for Economic Co-operation and Development
•OH – hydroxyl radical
PM10 – particulate matter under 10 μm
S5P – Sentinel-5P
SH – Sentinel Hub
SO$_2$ – sulphur dioxide
TROPOMI – TROPOspheric Monitoring Instrument
US – United States
WHO – World Health Organization

EXECUTIVE SUMMARY

Maintaining good air quality is essential for public health, societal prosperity, and the integrity of natural ecosystems. Reducing pollutant and greenhouse gas emissions is key to curbing the rapid progression of climate change. Kazakhstan, **ranked as the 21st top global greenhouse gas emitter** in 2019, faces the complex interplay of climate change and air pollution. Each year, **air pollution is linked to over 10,000 premature deaths**, with an economic toll of approximately $10.5 billion, as reported by the World Bank in 2023.

While the nation has joined major climate accords such as the Paris Agreement, **aiming for carbon neutrality by 2060**, comprehensive strategies such as the National Adaptation Plan are still in the initial stages. The 2021 Environmental Code update emphasises both adaptation and the "polluter pays" principle, highlighting the importance of **addressing both climate change and air pollution in tandem**. As the two crises amplify one another, monitoring air pollution becomes not just a matter of local health but also a pivotal aspect of the global climate change response.

Kazakhstan holds a prominent position as a **major global producer of coal, oil, gas, and copper**. Additionally, the country houses several **heavy industries, including metallurgy and refineries**. Compounded by its distinctly continental climate, characterised by prolonged inversions, Kazakhstan faces challenges in terms of air pollution and the need for comprehensive air pollution reduction measures. This issue not only affects the overall quality of life but also contributes to the accelerated pace of climate change.

This study seeks to understand the patterns, timing, and causes of air pollution and climate change, with a **particular spotlight on the heavily industrial Karaganda Region**. Here, rising pollution from industrial operations and household coal use highlights the deeply connected challenges of both issues.

Key findings

Nitrogen dioxide (NO_2) concentrations tend to be **higher in major cities and industrial sites** in Kazakhstan, with the highest concentrations found around **Pavlodar, Almaty, and Shymkent. Cities with extensive industry have higher pollution levels.** This is particularly evident in the industrial cities of Ekibastuz, known for its thermal power plant and coal mine ($0.59\ 10^{-4}$ mol/m^2), and Temirtau, recognised for its major steel industry ($0.44\ 10^{-4}$ mol/m^2), which exhibit NO_2 concentrations two to three times higher than those in cities of comparable size (~$0.20\ 10^{-4}$ mol/m^2). **Winter** months record **higher NO_2 air pollution** levels, while in **spring and summer**, pollution levels **decrease** in most areas, **except for the surroundings of Almaty, Shymkent, and Pavlodar**, where concentrations remain high. This is apparently due to high traffic and the proximity to coal-fired power plants and the metallurgical industry. During the COVID-19 pandemic a decrease in NO_2 emissions in several areas was observed as a result of the effects of lockdowns.

An **increased concentration of methane (CH_4)** was detected **in the vicinity of coal mines**. Overall, surface mine methane emissions tend to be lower and also diffuse more when compared to emissions from underground mines. The country experienced **annual increases in methane levels** from 2018 to 2022, consistent with the global trend of increasing atmospheric methane. The highest regional concentrations occur in the city of **Shymkent** and the surrounding region of Turkistan and in the regions of **Mangystau and Kyzylorda**.

High levels of **sulphur dioxide (SO_2)** pollution in Kazakhstan are predominantly observed around mining industries and coal-fired power plants. In regions such as **Pavlodar, Almaty, Oskemen, Astana, and Karaganda**, the SO_2 concentrations surpass both the daily maximum limits set by the World Health Organization (WHO) and Kazakhstan's own quality standards. **The Almaty Region** has the **highest concentrations overall**, while the **Pavlodar Region** has the **highest year-round concentrations** because of coal-fired power plants and the mining industry. The **seasonal pattern of SO_2** concentrations displays **a peak in the winter** season because of **low deposition and increased house heating emissions.**

The concentrations of **particulate matter between 2.5 and 10 µm (PM_{10})** are high in **the south and south-east of Kazakhstan** because of **natural sources** such as dust storms from bare soil and deserts. Increased concentrations of **PM_{10}** from anthropogenic sources are experienced **in urban areas in other** parts of Kazakhstan, including **Karaganda, Oskemen, Aktobe, Astana, and Kostanay.** Natural conditions influence **seasonal PM_{10}** air pollution changes with higher concentrations in the south and south-east because of dust storms, while anthropogenic activity causes **higher concentrations in all seasons in areas such as Karaganda and Oskemen.**

On the territory of the **Karaganda Region, there are several anthropogenic sources of pollution**, such as coal-fired power plants, coal mines, the steel industry, and others. **For all the pollutants studied here, increased levels were detected in the vicinity of the cities of Karaganda and Temirtau**, where these sources of pollution are concentrated.

Recommendations

A **comprehensive set of recommendations** has been put forth to enhance air quality and climate change mitigation activities in Kazakhstan. One crucial aspect is the strengthening of **air quality monitoring and data collection**. This can be achieved by expanding the monitoring infrastructure and strategically locating stations equipped with high-quality instruments. Additionally, **reducing coal usage and promoting the deployment of renewable energy** sources are pivotal strategies. To enforce air quality standards effectively, it is essential to **bolster regulatory frameworks and environmental liability**. This can be accomplished through the implementation of inspections, audits, and penalties for non-compliance. Promoting **energy efficiency measures** is another key aspect, including initiatives such as renovating buildings and implementing smart transportation solutions. **Public awareness and participation** are also vital components as Kazakhstan faces challenges because of low public awareness, high car usage, and reliance on polluting heating methods.

To improve air quality in the **Karaganda Region**, priority should be given to **coal power stations, coal mines, and the steel industry.** Coal power stations should be encouraged to adopt advanced pollution control technologies and enforce strict emission standards. This can be achieved by investing in flue gas desulphurisation systems, electrostatic precipitators, or fabric filters to capture and remove pollutants before they are released into the atmosphere. Similarly, measures to mitigate dust emissions from coal mining operations, such as improved dust suppression techniques and enclosed conveyor systems, should be implemented, along with rigorous monitoring and enforcement. Promoting the adoption of cleaner production technologies, such as electric arc furnaces, can significantly reduce emissions of harmful pollutants in the steel industry. Additionally, enhancing the air quality monitoring network by strategically locating monitoring stations equipped with high-quality instruments can provide accurate and real-time data on pollutant levels. The public should have better access to environmental data and be more actively involved in the decision-making process.

Althought Balkhash town is a centre of metallurgy, the lake of the same name is important source of fish and water for agriculture. (Photo: Ondrej Petrlik / Arnika)

INTRODUCTION

Kazakhstan has seen remarkable economic development over the past two decades, largely driven by its exports of fossil fuels and metals, which have played a significant role in boosting its GDP (World Bank, 2021). However, the growth has largely been built on the industrial groundwork laid during the Soviet era, characterised by a focus on swift expansion with scant regard for the environmental consequences. While recent economic growth has brought its own challenges, many of the environmental issues originated from unchecked industrialisation during the Soviet period. Decades of lasting improper management and exploitation of natural resources have led to severe ecological imbalances, including air, water, and soil pollution and negative impacts on biodiversity. These issues have remained largely unaddressed and have deepened over recent decades in the pursuit of further economic expansion. In 2021, this culmination of historical and contemporary factors led Kazakhstan to rank as the 23rd most polluted country globally by $PM_{2.5}$ pollution levels (IQAir, 2021).

Kazakhstan, straddling Central Asia and Eastern Europe, is the world's largest landlocked nation. Its diverse landscape (Fig. 1) includes grasslands, which make up a significant 70% of its terrain, especially in the northern and central regions (FAO, 2021). The country also houses vast deserts and bare lands, accounting for 22% of its land, predominantly in the south-central and western parts. These desert areas, often sandy or rocky, are scantily populated because of their harsh climate (European Commission, 2022). Meanwhile, forests are relatively sparse, covering just 3% of Kazakhstan. The country also boasts lakes, rivers, and marshes, which together cover about 2% of its land.

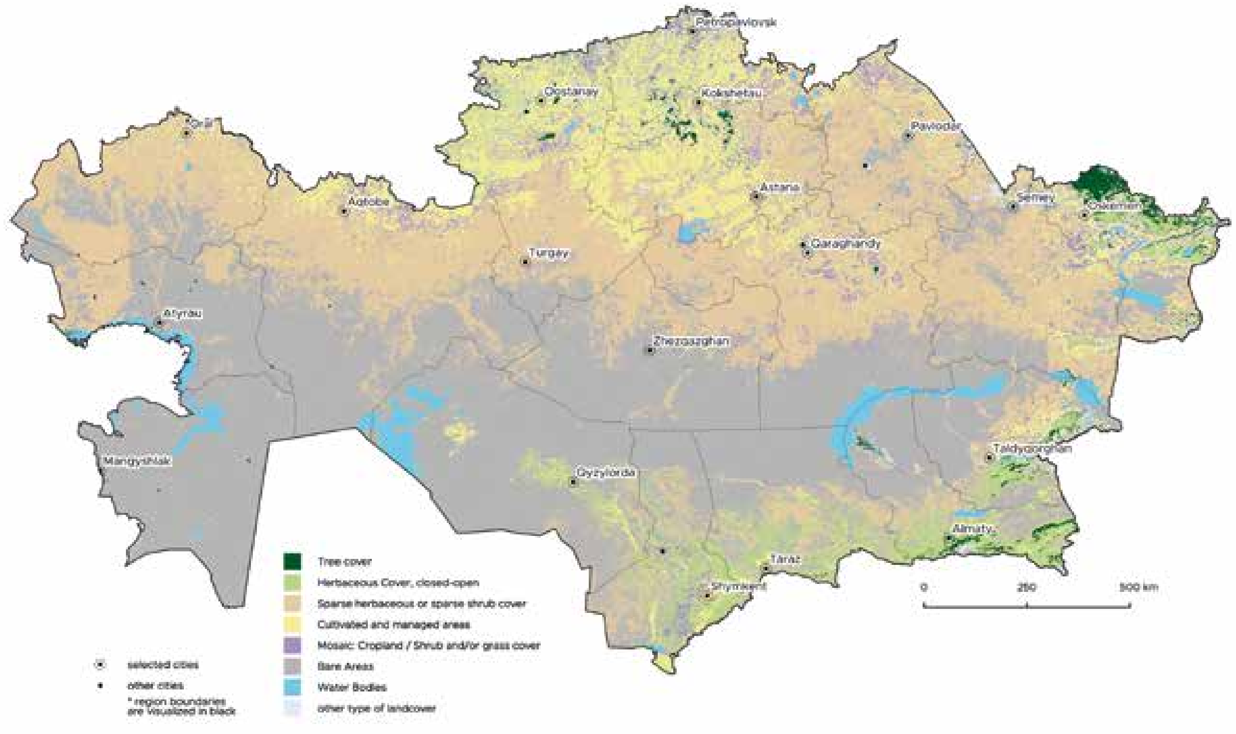

Fig. 1: Land cover of Kazakhstan. Source: Global Land Cover 2000 – European Commission, 2022.

Administrative division of Kazakhstan

The administrative division of Kazakhstan (Fig. 2), as utilised in this report, can be confusing at first. The country is divided into **17 regions** (originally called *oblasts*) and three major **cities**, which do not belong to the surrounding regions and form individual city-regions. These are Astana, Almaty and Shymkent. Since Almaty is also a name for the particular region around the city-region of Almaty, when referring to regions in the report, the three major city-regions are always denoted by "city". Each region is divided into **districts** (originally called *audandars*). To avoid further confusion (e.g. there is a district called Almaty in the city of Astana; there is a set of districts in the city of Almaty and another set of districts in the Almaty Region; there is a district called Pavlodar that includes the independent district-city of Pavlodar, both in the Pavlodar Region), when referring to districts, the respective region and all denominations are always indicated.

Fig. 2: Regions and districts of Kazakhstan. Source: HDX, 2022.

Interplay of climate change and air pollution

Kazakhstan's 2019 CO_2 emissions, predominantly from fossil fuels, positioned it as the 21st leading global polluter. The energy sector, being a significant emitter, underscores the nation's carbon-intensive nature, as pointed out by the 3rd Environmental Performance Review. Despite this, Kazakhstan possesses considerable potential to curtail its carbon footprint with the right measures in place.

Kazakhstan, as indicated by its national communications under the UN Framework Convention on Climate Change, faces heightened risks related to its agricultural, forestry, and water resource management, largely stemming from changing precipitation patterns and escalating drought occurrences. These vulnerabilities are not just ecological; they are societal. The changing climate has an adverse impact on public health through heightened heat stress in southern areas and the potential spread of disease.

A vivid example of the overlap between air pollution and climate change is the "black snow" event in Temirtau, a metallurgy and mining hub. With shifting wind patterns, pollutants are now more frequently confined within industrial and residential zones. Karaganda Oblast, a major industrial heartland, embodies this interplay. As home to numerous industrial sites responsible for substantial pollutant emissions, the region faces the dual challenge of escalating industrial smog and extreme pollution, primarily from coal combustion in homes.

While the 2016 updates to the 2007 Environmental Code improved the accessibility of environmental information, including climate data, more action is necessary. The state agency, Kazhydromet, handles climate data collection and forecasting, yet this invaluable information remains largely untapped for actionable purposes.

Kazakhstan's international climate pledges, such as the UN Framework Convention, the Kyoto Protocol, and the Paris Agreement, outline its commitment to addressing these issues. While the president's goal of carbon neutrality by 2060 is commendable, concrete legislative backing is vital. The newly implemented 2021 Environmental Code, which integrates considerations for climate adaptation, offers a glimpse of hope. However, the onus is on ensuring that revenues from emission charges funnel back into environmental protection initiatives.

Key pollutants

This study endeavours to serve as a foundational investigation into the key pollutants present in Kazakhstan. In the sections that follow, we will delve into a detailed examination of each specific pollutant, providing comprehensive insights into their sources, impacts, and prevalence within the country.

Nitrogen dioxide (NO_2)

Nitrogen dioxide (NO_2) is an important trace gas present in both the troposphere and the stratosphere; however, it is also a key atmospheric pollutant produced by anthropogenic activities. According to the WHO (WHO, 2000), 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. The interaction of NO_2 with water and other chemicals in the atmosphere leads to the formation of acid rain, causing changes in forests and aquatic ecosystems.

According to the European Environment Agency 2020 Air Quality report (EEA, 2022), **road transport** was the principal source of nitrogen oxides, being responsible for 37% of emissions. Other sources of NO_2 are **petrol and metal refining**, electricity generation from **coal-fired power plants**, manufacturing industries, and food processing. The natural sources of the gas are **microbiological processes in soils, wildfires, and lightning**.

Main human sources of NO_2
- motor vehicle exhaust
- coal-fired power plants
- petrol and metal refining

Methane (CH_4)

Methane is a colourless, odourless, and highly flammable gas that is the primary component of natural gas. It is also a potent greenhouse gas, with a global warming potential over 80 times greater than carbon dioxide (over a 20-year time frame) (IEA, 2021).

Methane is produced through natural processes such as the breakdown of organic matter in wetlands, where it is a byproduct of decomposing in the absence of oxygen. Another natural source of methane emissions is termites, which produce methane as part of their digestive process. During wildfires, methane can also be released as a byproduct of the combustion of organic matter. It can further be produced naturally in the earth's crust or found in coal seams, oil and gas fields, and geological formations, such as permafrost.

Human activities, such as agriculture, animal husbandry, fossil fuel production and use, and waste management, are significant sources of methane emissions. According to the latest estimates by the Intergovernmental Panel on Climate Change (IPCC), human activities contribute to around 60% of total methane emissions in the atmosphere.

The quantity of methane emissions from human activities varies, depending on factors such as the type of activity, the region, and the level of technology and management practices used. Agriculture, particularly livestock production and rice cultivation, is the largest source of anthropogenic emissions of methane, accounting for around 40% of total anthropogenic methane emissions.

Fossil fuel production and use, including coal mining, oil and gas extraction, and transportation, is another significant source, accounting for around 35% of total anthropogenic methane emissions. The remaining 25% comes from waste management, such as landfills and wastewater treatment (IPCC, 2021).

Sulphur dioxide (SO_2)

Sulphur dioxide (SO_2) enters the atmosphere from natural and anthropogenic sources and can be found 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 globally emitted SO_2 comes from natural sources such as **volcanoes**. Anthropogenic sources include **coal-fired power plants, industrial**

processes, or other **fossil fuel-burning activities** (such as domestic heating). Man-made contributions are of the greatest concern for environmental policy. According to the WHO (2021), "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 sulphuric acid, the main component of acid rain.

Natural sources of sulphur dioxide in Kazakhstan include **wildfires and dust storms.** Forest fires are common in Kazakhstan, especially in the summer months, when temperatures are high and vegetation is dry (NASA, 2005). These fires can release sulphur dioxide and other pollutants into the air. Kazakhstan is home to vast steppes and deserts, and dust storms can occur during periods of drought and strong winds. These storms can transport large amounts of dust and other particulate matter, including sulphur dioxide, over long distances. While natural sources of sulphur dioxide in Kazakhstan are generally less significant than human activities, they can still contribute to local and regional air pollution, especially during periods of wildfires (GFDRR, 2023).

Particulate matter (PM_{10})

Particulate matter, or atmospheric aerosols, is 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. The coarse fraction of PM_{10} contains larger particles ranging from 2.5 to 10 µm. Particles smaller than 2.5 µm ($PM_{2.5}$) are primarily produced by mechanical processes such as **construction activities**, **road dust** re-suspension, and wind, whereas PM_{10} 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, erosion, and seawater** (WHO, 2013). **Dust storms coming from bare land cover** can also contribute to the presence of PM_{10} in the atmosphere.

Main human sources

- construction activities
- transport
- domestic heating
- industrial processes
- power plants

There is a direct negative effect of high particulate matter concentrations on human health (WHO, 2005). The effect depends on the size, chemical composition, and shape, but generally concerns the respiratory and cardiovascular systems. PMs have toxic and genotoxic effects – they increase the carcinogenic risk (Karlsson et al., 2004), affect the structure and integrity of endoepithelial cells, increase the potential for vascular thrombosis (Gilmour et al., 2005), and increase blood coagulation and the risk of stroke, myocardial infarction, and atherosclerosis (Künzli et. al., 2005).

These particles can act as catalysts for chemical reactions on their surface. 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. Therefore, WHO experts have recommended values that determine the minimum risk to public health.

The WHO offers a **guideline of 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 particulate matter (**PM$_{10}$**) the value is **20 µg/m$_3$**. Short-term levels of pollution should not exceed 50 µg/m^3 (PM$_{10}$) on the 24-hour mean (WHO, 2023).

Air pollution from mining activities

Air pollution from mining activities in Kazakhstan is mainly concentrated in several regions where mining and metallurgical complexes are located. The regions where air pollution from mining is a major concern are Karaganda, East Kazakhstan, Pavlodar, and Atyrau. **The type of air pollutants in the surroundings of quarries depends on the minerals that are extracted and the extraction methods**.

One of the largest coal mining regions in the country is the Karaganda Coal Basin. It is one of the biggest sources of air pollution from mining activities in Kazakhstan. High concentrations of **nitrogen dioxide (NO$_2$)** can be also found in the Pavlodar Region, where several mining and metallurgical complexes are located, including the Aksu Ferroalloy Plant.

In terms of **sulphur dioxide (SO$_2$)** pollution, significant sources are located near Balkhash in the Karaganda Region and in the industrial city of Zhezkazgan and its surroundings (Askarov et al., 2023). These places are home to some of the largest copper mines, the extraction of which produces SO$_2$. Major mining companies include, for instance, the Zhezkazgan Copper Smelter and the Balkhash Copper Smelter.

In terms of **methane (CH$_4$)**, the Atyrau Region is home to several oil and gas fields and the related infrastructure, which may also contribute to air pollution as anthropogenic sources of methane include oil production and processing. The volume of methane released into the atmosphere depends on the type of extraction.

In other parts of the country, underground coal mining and open-pit mining have different methane emission profiles, with underground mining generally producing more methane emissions than open-pit mining. This is because underground mining involves extracting coal from underground seams where more methane is compressed per bedrock volume, while open-pit mining only removes the overlying rock to access coal seams with smaller methane concentrations (Irvin & Tailakov, 2000).

Coal-fired power plants were constructed in Kazakhstan to fulfil the energy demands of the country’s heavy industries. They were established in the northern, central, and eastern regions of Kazakhstan because of the active coal mines in these areas. The power generation and metallurgy sectors are responsible for 37% and 30% of the country’s gross industrial emissions, respectively. These two major industrial sectors contribute significantly to the country’s greenhouse gas emissions.

Air pollution limits in Kazakhstan

Kazakhstan's legislation has explicit guidelines for monitoring atmospheric air quality, as outlined in the Ecological Code and the Rules for the Unified State System for Monitoring the Environment and Natural Resources. The state supervises pollutant concentration levels using stationary and mobile posts operated by a state-affiliated entity, Kazhydromet. Legally, all the collected data must be stored in the "National Data Bank on the State of the Environment and Natural Resources of the Republic of Kazakhstan", ensuring public access to this information.

Beyond the state-operated Kazhydromet system, which falls under the Ministry of Ecology and Natural Resources, various independent monitoring systems exist. These have been set up by regional authorities and civic activists. Regrettably, data from these systems can only be accessed online and on an individual basis for each observation point. The state has yet to integrate or apply the data collected from these disparate monitoring systems in any cohesive manner. In this regard, satellite data can provide independent results and assessment of pollution.

Kazakhstan has established environmental limits for air pollution as part of its efforts to monitor and improve air quality. The country has adopted a national standard for maximum allowable concentrations (MAC) of pollutants in the air. It sets limits on several pollutants, including sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter (PM_{10} and $PM_{2.5}$). Kazakhstan has also established a national air quality monitoring network that measures the levels of various pollutants in the air in different regions of the country. The data from the network is used to assess compliance with the MAC standards and to identify areas where air pollution may be a significant problem (Assanov, 2021). **The permissible limit values of pollutants in Kazakhstan are higher than the WHO recommendations** (Tab. 1)**.**

Pollutant	One-Time MAC, µg m^{-3}		Average Daily MAC, µg m^{-3}		Average Annual MAC, µg m^{-3}	
	Kazakhstan	WHO	Kazakhstan	WHO	Kazakhstan	WHO
PM_{10}	300	-	60	50	-	20
$PM_{2.5}$	160	-	35	25	-	10
SO_2	500	-	50	20	-	-
NO_2	200	-	40	-	-	40

Tab. 1: Limit values of pollutants in the air according to the WHO and Kazakhstan's national standards. Source: Assanov, 2021.

Impact of COVID-19 on air pollution in Kazakhstan

Like most countries around the world, Kazakhstan has also been affected by the COVID-19 pandemic. The first case of COVID-19 in Kazakhstan was reported in early March 2020, and since then, the country has experienced several waves of the pandemic. The government took various measures to slow the spread of the virus, including lockdowns, curfews, and restrictions on public gatherings and transport. **The first lockdown came into force from March 16 to May 11, 2020**. On March 19, 2020, a strict quarantine was imposed on the cities of Astana and Almaty, where most of the cases occurred. On March 30, 2020, Atyrau and five cities in the Karaganda Region were put under lockdown. COVID-19 has had significant impacts on the healthcare system, economy, and daily life in Kazakhstan. The pandemic has had a significant negative impact on Kazakhstan's economy, with domestic consumption declining by 40% and the GDP growth rate declining by 2.8% in 2020 (Flanders Investment & Trade, 2022).

Influence of physical-geographical conditions on the distribution of air masses

The weather of Kazakhstan is influenced by its extremely continental position with a large temperature amplitude during the year. There is a significant increase in solar radiation from north to south and the country receives the largest amount of solar energy from June to August. The surface of Kazakhstan is diverse, with most of the territory consisting of flat low-mountain areas (FAO, 2021). Wind regimes vary throughout the year, with the predominance of south-westerly winds in winter, north-easterly winds in desert areas, and north-westerly, northerly, and north-easterly winds in summer. In mountainous areas and coastal zones, local winds are observed (Kazakhstan Meteorological Agency, 2023). The structure of the mountains in the south and south-east influences the air currents on a global scale, being a natural barrier to the passage of cold air masses to the south.

DATA AND METHODOLOGY

Sentinel-5P

Sentinel-5P (S5P) is a satellite devoted to atmosphere 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. S5P 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).

Sentinel-5P Level-2 (L2) products were used with "quality assurance value" pixels under the 0.5 threshold filtered out. NO_2 and CO products (from May 2018 to December 2022) are obtained via SH. L2 data products were used with "quality assurance value" pixels under 0.5 filtered out. The quality assurance 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.

Copernicus Atmosphere Monitoring Service (CAMS)

The monitoring of particulate matter (PM_{10}) and sulphur dioxide ($S0_2$) concentrations was obtained through the Copernicus Atmosphere Monitoring Service (CAMS). CAMS, a part of the Copernicus Programme implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF), provides global, quality-controlled information related to air pollution, solar energy, greenhouse gases, and climate forcing.

In Kazakhstan, CAMS global atmospheric composition forecasts (at a spatial resolution of 0.4 x 0.4°) were used to measure SO_2 and PM_{10}. The forecasts consist of more than 50 chemical substances (e.g. ozone, nitrogen dioxide, carbon dioxide) and seven different types of aerosols (desert dust, sea salt, organic matter, black carbon, sulphate, nitrate and ammonium aerosol). The analysis, which is the best estimate of the state of the atmosphere at the beginning of the forecast period, is derived from combining the latest satellite observations with a previous forecast, using a technique known as data assimilation. This method is used to establish the initial conditions for each forecast. Both the analysis and the forecast are available at hourly time steps at various pressure levels (CAMS, 2022).

Before interpreting the results of the SO_2 air pollution analysis, it is necessary to mention the modification by the dataset producer in the CAMS dataset that is used. Starting on July 7, 2019, the model data recalculation was modified to increase the vertical resolution from 60 to 137 levels. The ability to compare data remained only at the surface level. SO_2 concentrations in this report are analysed at the surface level but according to the results of the analysis, te data was also affected on the surface level in some cases. This is described in more detail in the Results chapter in the Sulphur dioxide (SO_2) section.

Outline of processing

All the data was automatically downloaded and preprocessed using our proprietary Python scripts and the SH service for **the study period, May 2018-December 2022.** The final processing steps were executed on a desktop GIS. **In maps and graphs, the pollutants were given in the following units:**

- NO_2 and CO in *10^{-4} mol/m²*
- PM_{10} and SO_2 in *µg/m³*
- CH_4 in *parts per billion* (ppb), which is more commonly used in the context of concentrations of this pollutant (the original values were divided by 0.0045 to get ppb)

The Sentinel-5 revisit time for Kazakhstan is more than once a day, with scanning overlaps at higher latitudes because of the near-polar, sun-synchronous orbit of the satellite. The processed data thus comprises all the available satellite measurements. Using all the available data meant combining data from several satellite orbits with varying grid sizes and orientations. To address this, all the S5P satellite observations were downscaled to obtain a regular grid with a resolution of 1×1 km. It is important to understand that the quality of the accessible pixels is highly dependent on weather conditions, sensor errors, and other parameters, such as cloud cover.

CAMS provides daily estimates of pollutant concentrations calculated using a combination of satellite data, ground-based observations, and numerical models. The global version of the model estimates pollutant concentrations for two timestamps each day: at 0:00 and at 12:00. The European version provides hourly estimates. Daily averages were calculated by taking the mean of all the daily pollutant concentration values.

The daily values were used to calculate various statistics to gain deeper insights into the data. These included all-time averages and medians from all values measured between 2018 and 2022, yearly averages and medians, seasonal averages and medians, and monthly averages and medians. The averages for each month were calculated by taking the mean of all the values measured during that month between 2018 and 2022. In the case of seasonality assessment, seasons were defined as three-month periods of winter (December-February), spring (March-May), summer (June-August), and autumn (September-November) to simplify the air quality caused by weather conditions.

Rasters representing per-pixel statistics were then used to calculate the average concentrations of pollutants within different zones of Kazakhstan. These zones included administrative units such as regions and districts, as well as oil and gas extraction sites, coal extraction sites, gas power plants, coal-fired power plants, and selected cities and towns (cities with a population of over 100,000 inhabitants in the case of the analysis focused on the whole country and towns over 5000 in the case of the analysis focused on the Karaganda Region). A 10-kilometre buffer zone was used around each extraction site/power plant/city as a basis for the calculation of the zonal statistics.

To visualise the results, maps and charts were created to represent pixel-based statistics and zonal statistics.

RESULTS

Effects of industry on air pollution

Kazakhstan ranks among the world's major producers of oil, gas, and coal. In Fig. 3, the distribution of major coal mining cities and oil and gas extraction sites can be seen. The map is supplemented by power plants, which are also significant air polluters. The impact of mining and power plants on increased concentrations of each selected pollutant is discussed in more depth in the following chapters.

Nitrogen dioxide (NO_2)

Basic analysis

The average NO_2 values for the whole observed period can be found in Fig. 4. It can be seen that the highest NO_2 concentrations are associated with residential areas and major industrial sites. The highest concentrations are found around the cities of Pavlodar, Almaty, Shymkent, and Karaganda. Supplementary larger-scale maps show the major study areas: the cities of Karaganda, where many mining sites are located, Pavlodar, one of the most important industrial cities of Kazakhstan, and Almaty, the most populous city in Kazakhstan. The increased NO_2 con-

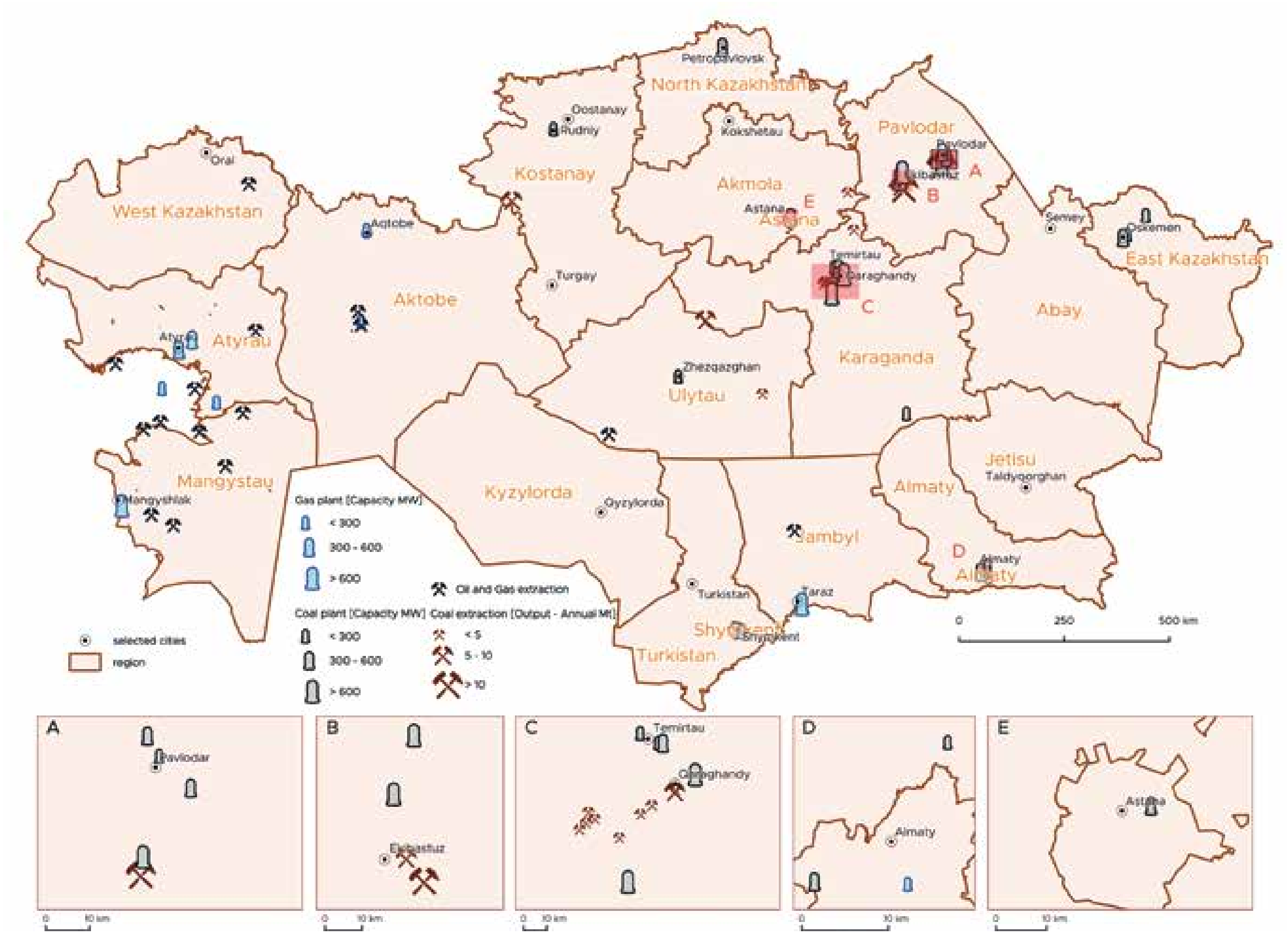

Fig. 3: Distribution of major coal mining and oil and gas extraction sites in Kazakhstan. Source: Global Energy Monitor, 2022.Источник: Global Energy Monitor, 2022.

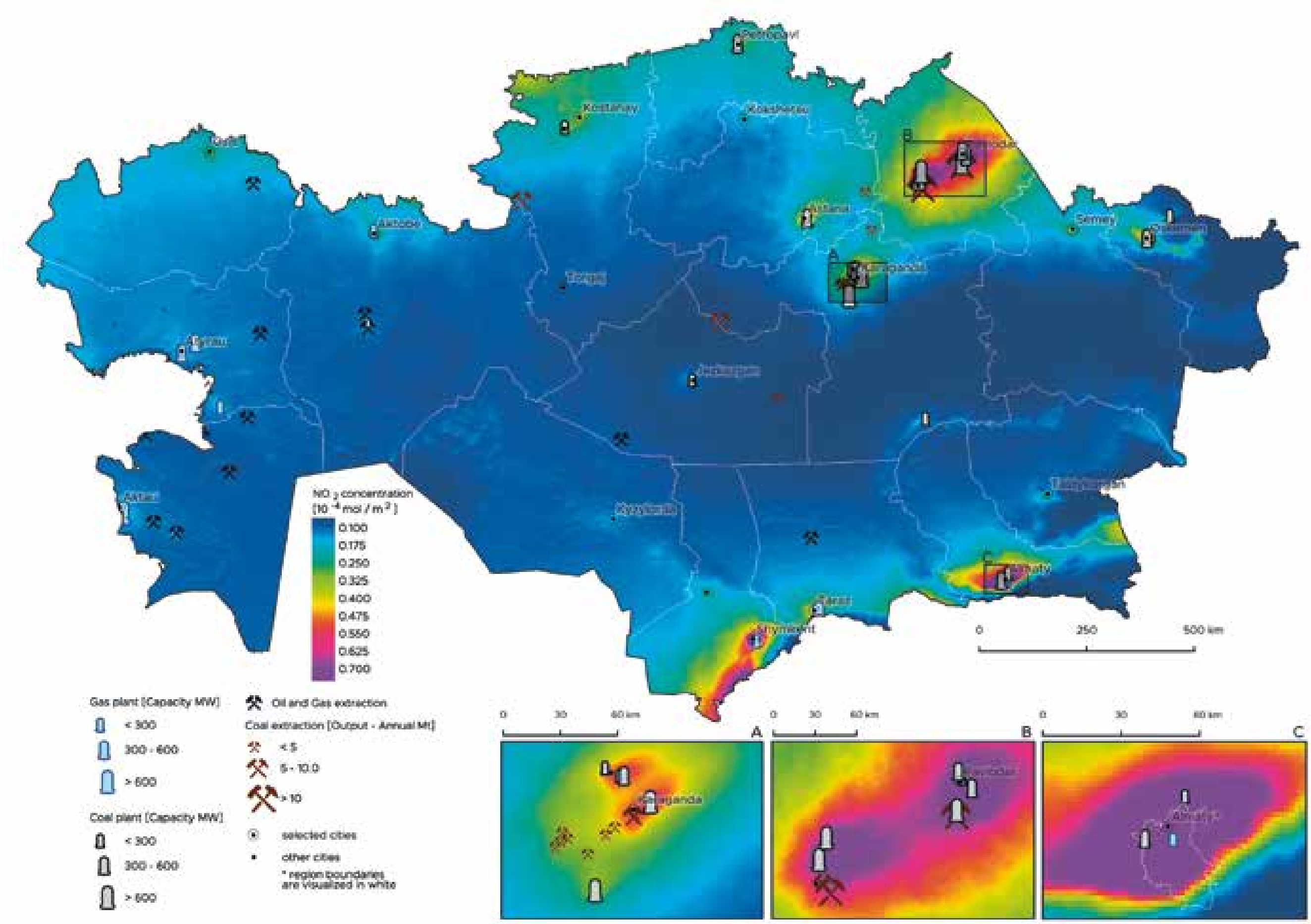

Fig. 4: Average NO_2 concentrations in Kazakhstan between May 2018 and December 2022, obtained from the Sentinel-5P satellite. The cities that are focused on are A) Karaganda, B) Pavlodar, C) Almaty. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022; Global Energy Monitor, 2022.

centrations in Almaty may also be influenced by the city's location in the foothills of the mountains, which results in higher concentrations of pollution, especially during winter months or smog situations.

No significant yearly changes are visible in most areas of Kazakhstan (Fig. 5). In general, a yearly increase in NO_2 concentrations is observed for the surroundings of Pavlodar, Astana, and Karaganda. A partial decrease in NO_2 concentrations occurs in the populated areas in 2020 with the first wave of the COVID-19 lockdown. The impact of the lockdown is better amplified when the lockdown period is compared with the same periods of the regular years (see the section COVID-19 pandemic in Kazakhstan).

The highest NO_2 concentrations per region are found in the three largest cities – Almaty (1.32 10^{-4} mol/m^2), Astana (0.38 10^{-4} mol/m^2), and Shymkent (0.79 10^{-4} mol/m^2). These are, however, small territories. The highest concentrations among non-city regions occur in the Pavlodar, Turkistan, and North Kazakhstan regions (Fig. 6). Pollution in the Pavlodar Region can be placed in a context with numerous coal mines and power plants. The Turkistan Region, which is calculated without the included city of Shymkent and features neither extensive industry nor energy generation sites, has high concentrations in

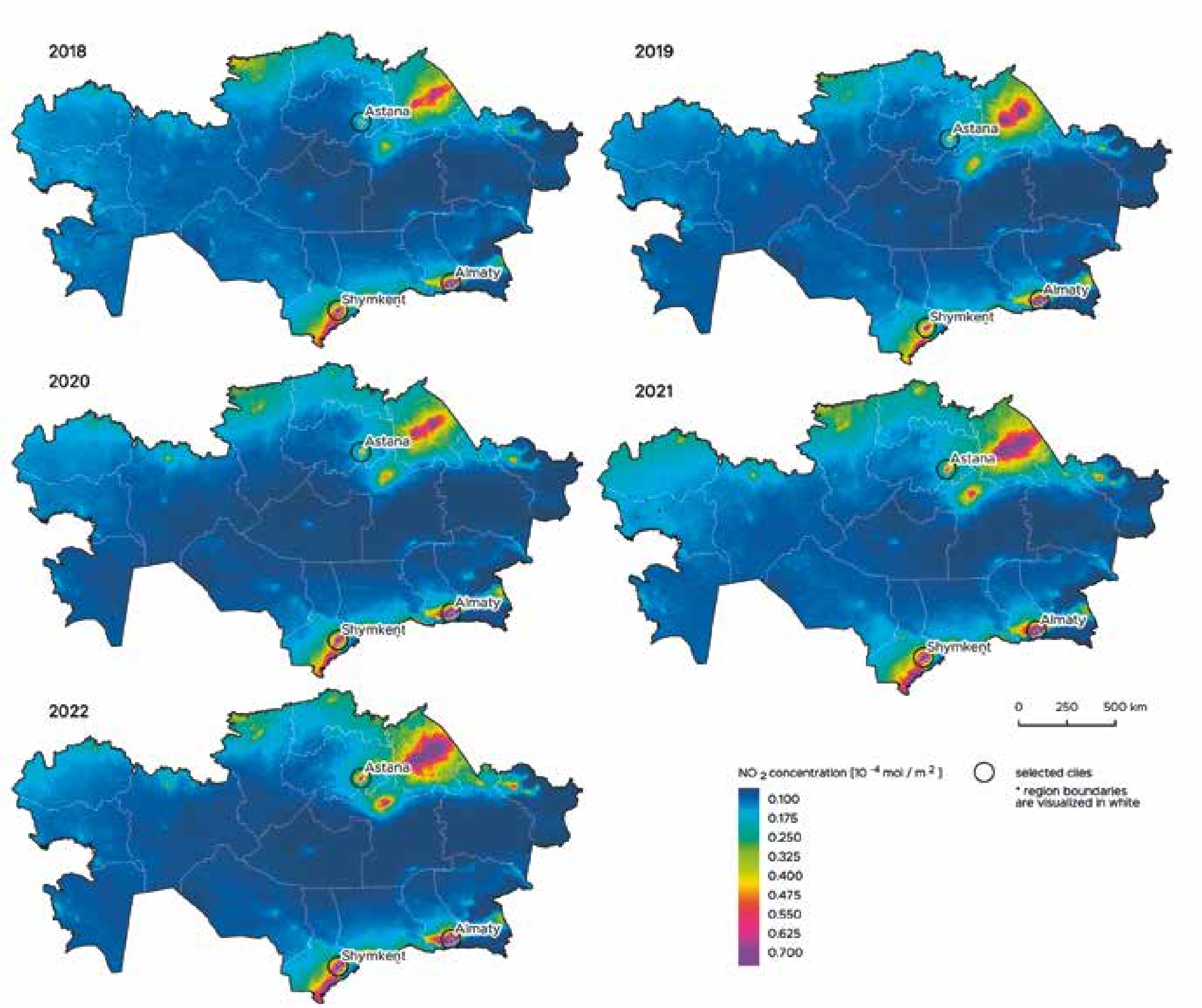

Fig. 5: Average yearly NO_2 concentrations in Kazakhstan between May 2018 and December 2022, obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022.

the southern part. This is most probably caused by the emission overflow from the Uzbekistan capital, Tashkent, a city of three million situated right at the border.

The NO_2 pollution distribution shows the highest concentrations in the Almaty Region (Fig. 7). Sources of NO_2 pollution here include transport, manufacturing industry, mining, and residential heating.

In urban areas, traffic is often the largest source of NO_2 emissions (WHO, 2000). The current transportation system in the city relies heavily on private cars, many of which are outdated and fail to meet the necessary technical requirements. This contributes to increased air pollution and congestion on the roads. Additionally, the public transport network lacks sufficient capacity to meet the demands of the passengers. The buses themselves are often old and in need of modernisation, while the metro network is not sufficiently developed and tram lines were cancelled. These factors hinder the efficiency and accessibility of public transport, further exacerbating the reliance on private vehicles.

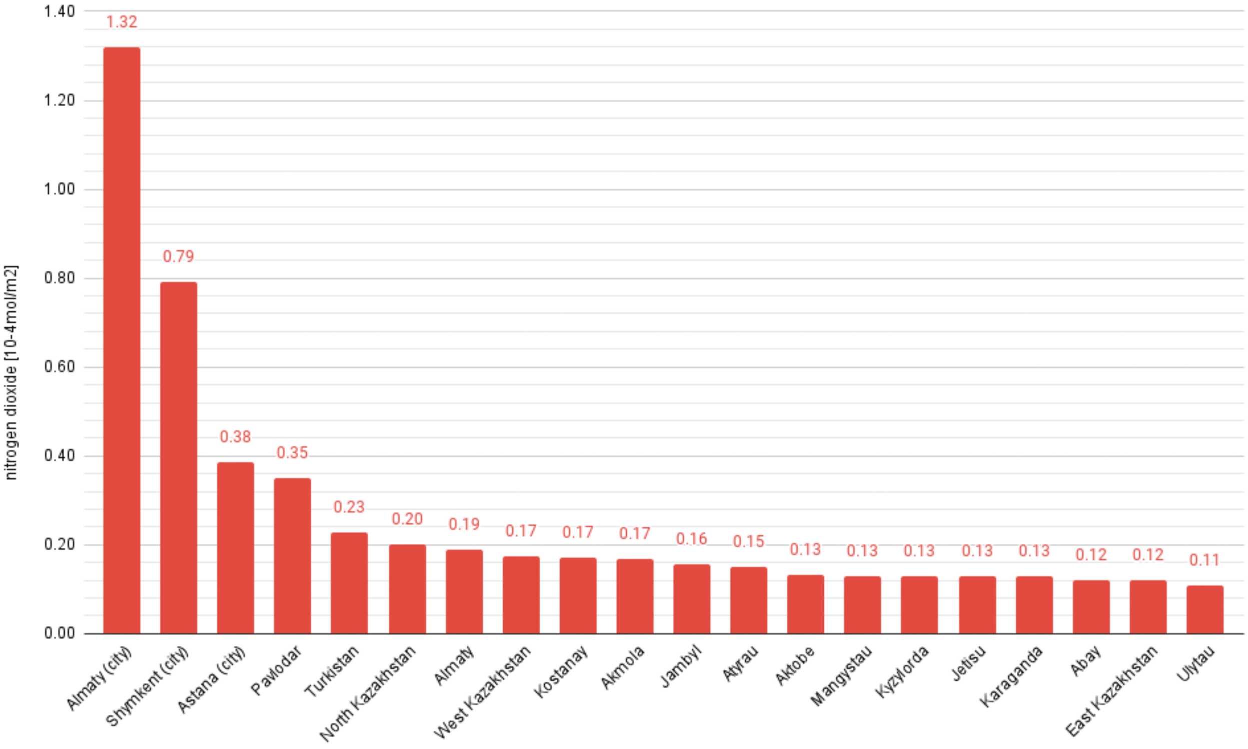

Fig. 6: Average NO_2 concentrations in the regions of Kazakhstan between May 2018 and December 2022, obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022.

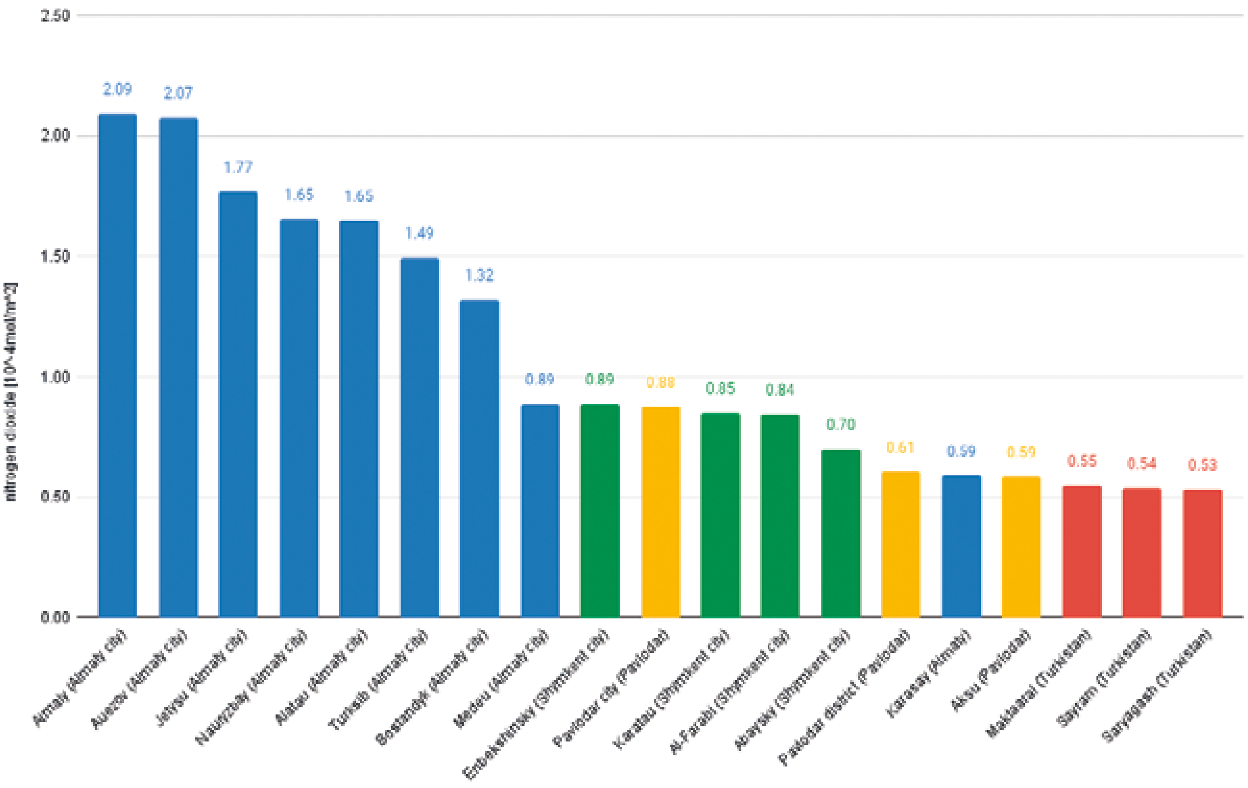

Fig. 7: 20 highest NO_2 concentrations in the districts of Kazakhstan (with indication of the region) between May 2018 and December 2022, obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022.

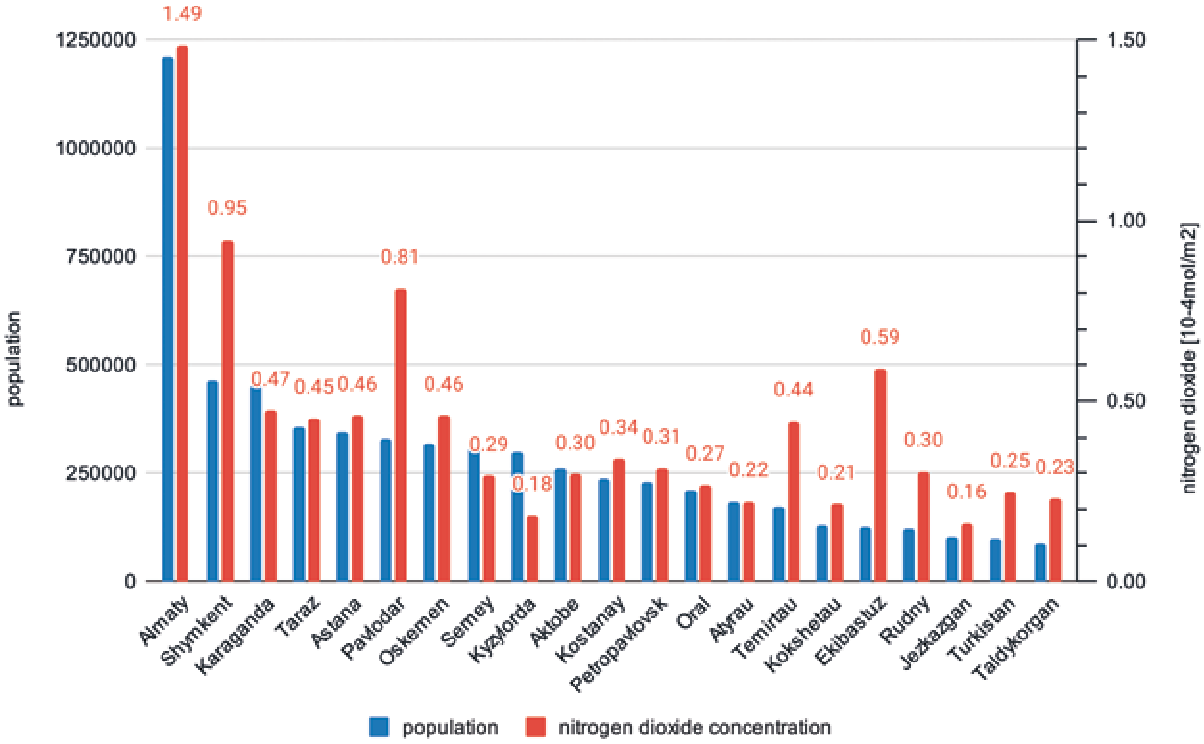

Fig. 8: Average NO_2 concentrations in selected cities and towns of Kazakhstan between May 2018 and December 2022, obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022; Natural Earth, 2022. Note: The population information comes from the current Natural Earth (2022) database, where the exact census dates are mostly unknown.

The average NO_2 concentrations in selected cities and towns (with a population above 100,000) can be observed in Fig. 8. In most cities, pollution decreases with a smaller population, with the exception of cities where the mining industry is concentrated or major metallurgical plants or coal-fired power plants are located. The highest discrepancy can be observed in the city of Ekibastuz (0.59 10^{-4} mol/m^2), where concentrations reach triple the levels in similarly-sized cities. Similarly, concentrations that are around double are observed in the cities of Pavlodar (0.81 10^{-4} mol/m^2), Temirtau (0.44 10^{-4} mol/m^2), and Shymkent (0.95 10^{-4} mol/m^2). Higher concentrations are also detected in the cities of Turkistan (0.25 10^{-4} mol/m^2) and Taldykorgan (0.23 10^{-4} mol/m^2). In Turkistan, it is difficult to determine the source of the pollution. An explanation may be offered by heavier traffic and intensified local emission production from facilities for the large numbers of pilgrims and tourists who visit Turkistan regularly because of its spiritual importance and targeted development of tourism (The Astana Times, 2021). In Taldykorgan, an extensive industrial zone south of the main railway station generates excessive NO_2 emissions. A mix of industries is present here, including a concrete plant, battery factory, and electric power component factory.

The average NO_2 concentrations around coal-fired power plants can be observed in Fig. 9. The graph is based on measurements within 10 km of the location of the power plant. It can be seen that the NO_2 concentrations may not only be related to the exhaust of the power plants. Some concentrations are

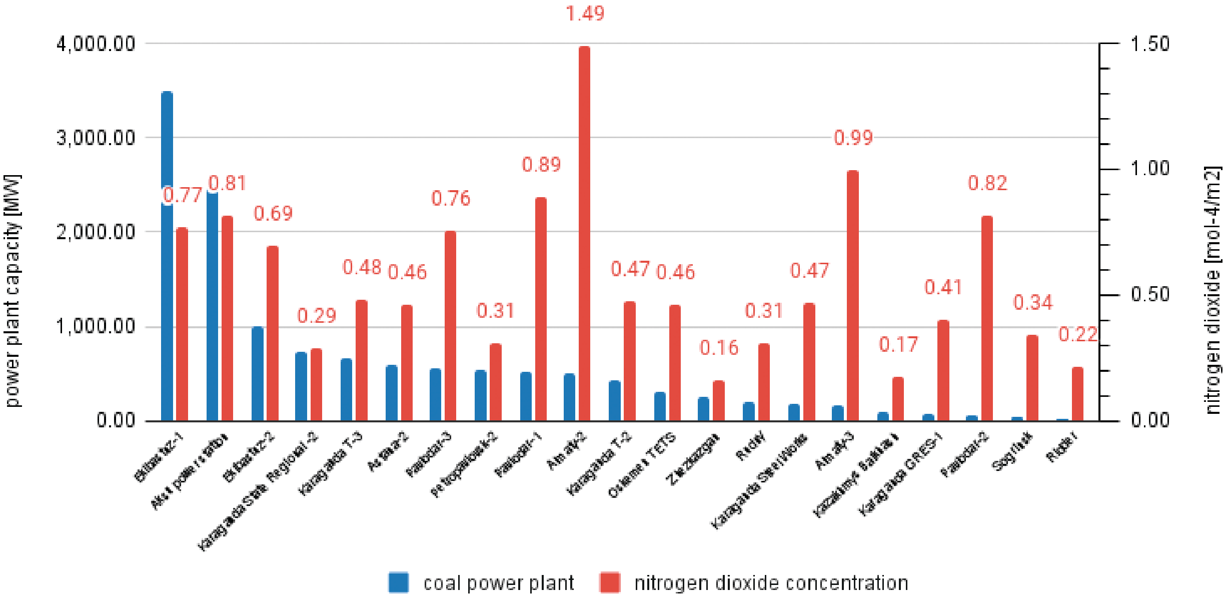

Fig. 9: Average NO_2 concentrations around selected coal-fired power plants in Kazakhstan between May 2018 and December 2022 as obtained from the Sentinel-5P satellite. Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022; Global Energy Monitor, 2022.

based on the combination of exhausts from multiple power plants in the same particular city and mainly other types of sources contribute to elevated NO_2 levels.

Seasonality of air pollution

The changes in NO_2 concentrations during the year can be observed in Fig. 10. In general, air pollution is more pronounced during the winter months in Kazakhstan, as is common in regions with cold winters. This is because low temperatures can cause air to become stagnant, which traps pollutants close to the ground. Simultaneously, the increased energy demand during the winter leads to more emissions from heating sources. The highest increase is observed in the northern parts of the country and around the cities of Almaty and Shymkent. The situation in the north is probably caused by cross-border emission overflows from Russia, especially from the heavily industrialised cities of Chelyabinsk, Magnitogorsk, and Kurgan and the Mikhailovsky GOK, one of the largest iron ore mines and processing facilities in Russia (Metalloinvest, 2020). The principle is probably similar with Omsk and its surroundings further east along the northern Russo-Kazakh border. In the spring and summer months, pollution generally decreases in most areas but concentrations are still high in the surroundings of Almaty, Shymkent, and Pavlodar.

In contrast, higher concentrations were observed in the summer months for most of the uninhabited territory of Kazakhstan (Fig. 11). There may be several explanations. Higher temperatures in summer can lead to more atmospheric mixing, which causes pollutants such as NO_2 to be dispersed over a wider area. NO_2 concentrations also increase with rising temperatures during summer months, in part as a result of enhanced atmospheric photochemistry and secondary NO_2 production (Otero et al., 2021). Precipitation can also play a role in reducing NO_2 concentrations by washing pollutants out of the atmosphere. Therefore, areas with less

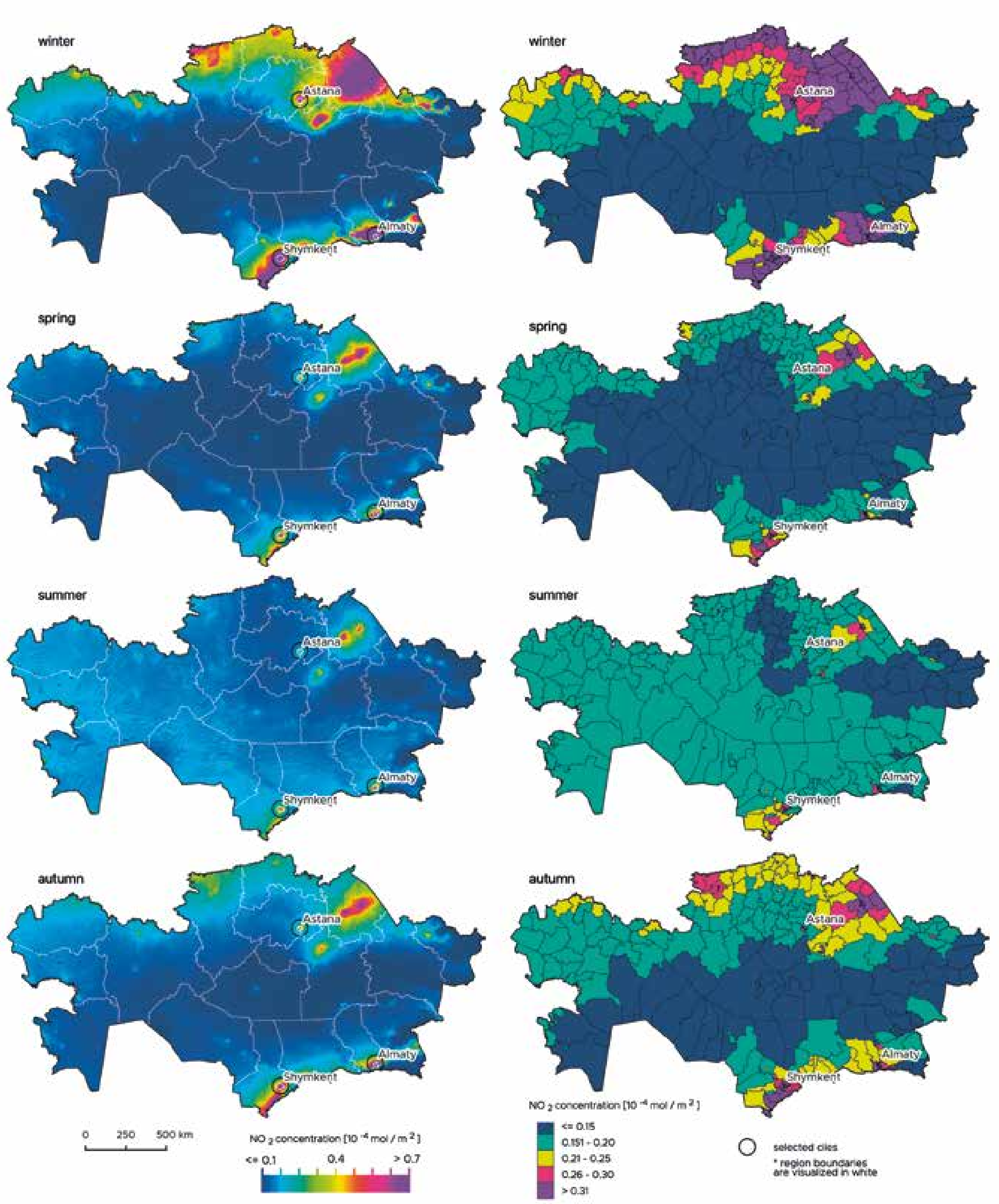

Fig. 10: Average NO_2 concentrations in districts of Kazakhstan calculated for seasons between May 2018 and December 2022, obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022.

precipitation may have higher NO_2 concentrations, particularly if there are significant sources of emissions nearby. However, other factors, such as wind patterns and topography, can also influence NO_2 concentrations and dispersion (Xu et al., 2020).

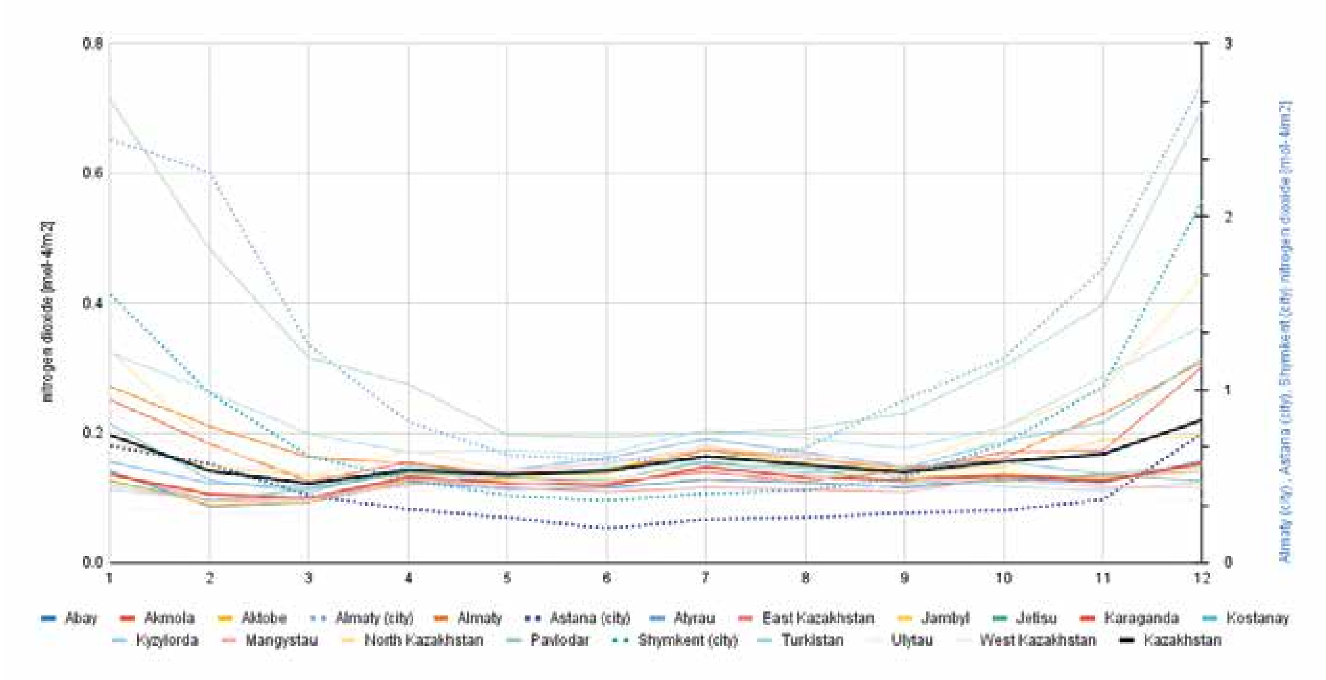

Fig. 11: Average monthly NO_2 concentrations in the regions of Kazakhstan between May 2018 and December 2022, obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022. Note: The right vertical axis refers to the cities of Astana, Almaty, and Shymkent only, while the left vertical axis refers to other regions.

COVID-19 pandemic in Kazakhstan

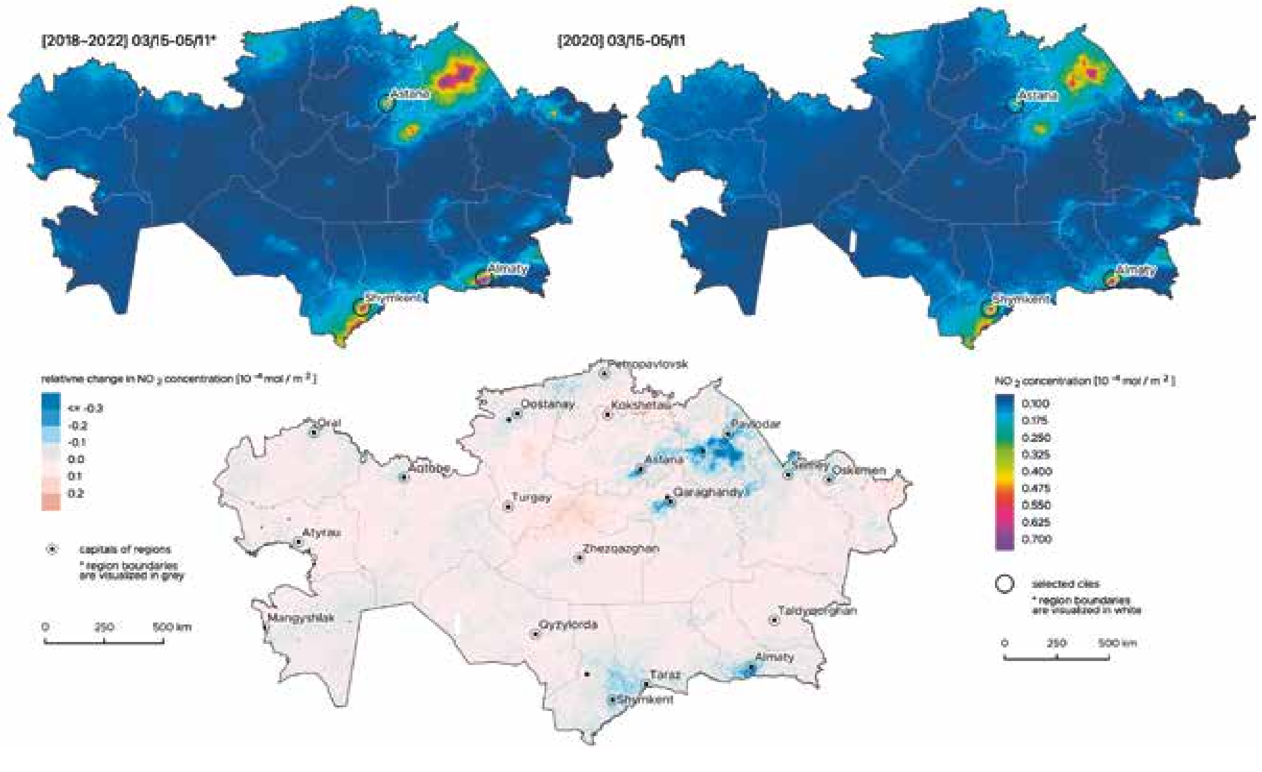

Fig. 12: NO_2 concentrations for the main COVID-19 period of March 15-May 11, averaged for 2020 (right) and for 2018-2019/2021-2022 (left). The difference in the averages is in the bottom map. Obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022.

NO_2 is primarily produced by combustion processes in transportation and industry. During the COVID-19 pandemic, lockdowns and reduced economic activity led to a decrease in these processes, which in turn resulted in a reduction in NO_2 emissions in many areas. Fig. 12 shows the difference between the lockdown period (March 15–May 11) in 2020 and the average values for the same period in the other years (2018-2019, 2021-2022). The highest decrease in NO_2 concentrations is tied to large cities and industrial regions.

Methane (CH_4)

Basic analysis

The S5P data has a limit in the valid detection of methane concentration over bodies of water and in mountainous areas. For this reason, a threshold of 80 valid observations (ca. 10% cut-off) has been selected as a minimum to sufficiently characterise the area's average concentration. The information is thus partly lost for areas of focus in the vicinity of bodies of water and some industrial zones.

Satellite and in situ observations play complementary roles in measuring atmospheric methane levels. In situ instruments provide high-precision measurements in the lower regions of the atmosphere; however, the measuring instruments are mainly located in accessible areas. The use of satellite data to measure methane concentrations over an area as large as Kazakhstan is appropriate. The causes of the spatial pattern of the average methane concentration for the study period (Fig. 14) are not entirely clear. One explanation could be the land cover and local climate; the arid southern part of the country has low potential for destroying CH_4 by the hydroxyl radical usually brought by moist air, which is why outlets of higher CH_4 concentrations from even more desertified parts of Turkmenistan and Uzbekistan occur.

According to the most recent official guidance on methane emitted from coal mines by UNECE in 2021, large-scale methane emissions from individual surface mines are rare (this fact is also confirmed by the measurements in Fig. 15), despite some surface mines having significant gas reserves. Overall, surface mine methane emissions tend to be lower and also diffuse more when compared to emissions from underground mines. On the contrary, it has been possible to expose some emissions with measurements from satellites with higher spatial resolution. According to GHGSat observations in 2021 (Ellis, 2022), methane concentrations exceeded 45,000 kg/hr in Bogatyr, one of the largest open-pit mines in Kazakhstan and in the world, located in Ekibastuz, near the city of Pavlodar. Because there is insufficient Sentinel-5 data around water bodies and in mountainous areas, there is a loss of information in the vicinity of mining areas around Pavlodar. However, a detailed view of the Bogatyr and Vostochny mines without data filtering confirms the GHGSat measurements, as the elevated concentrations are exceptions in the overall methane distribution in Kazakhstan.

While coal mining is the main source of CH_4 in Kazakhstan, oil and gas extraction and refining are also known to be significant sources of methane emissions. However, their emission impact is not observable by a clear spatial pattern in this study, probably because of the capabilities and qualities of S5P data over such areas. The long-term av-

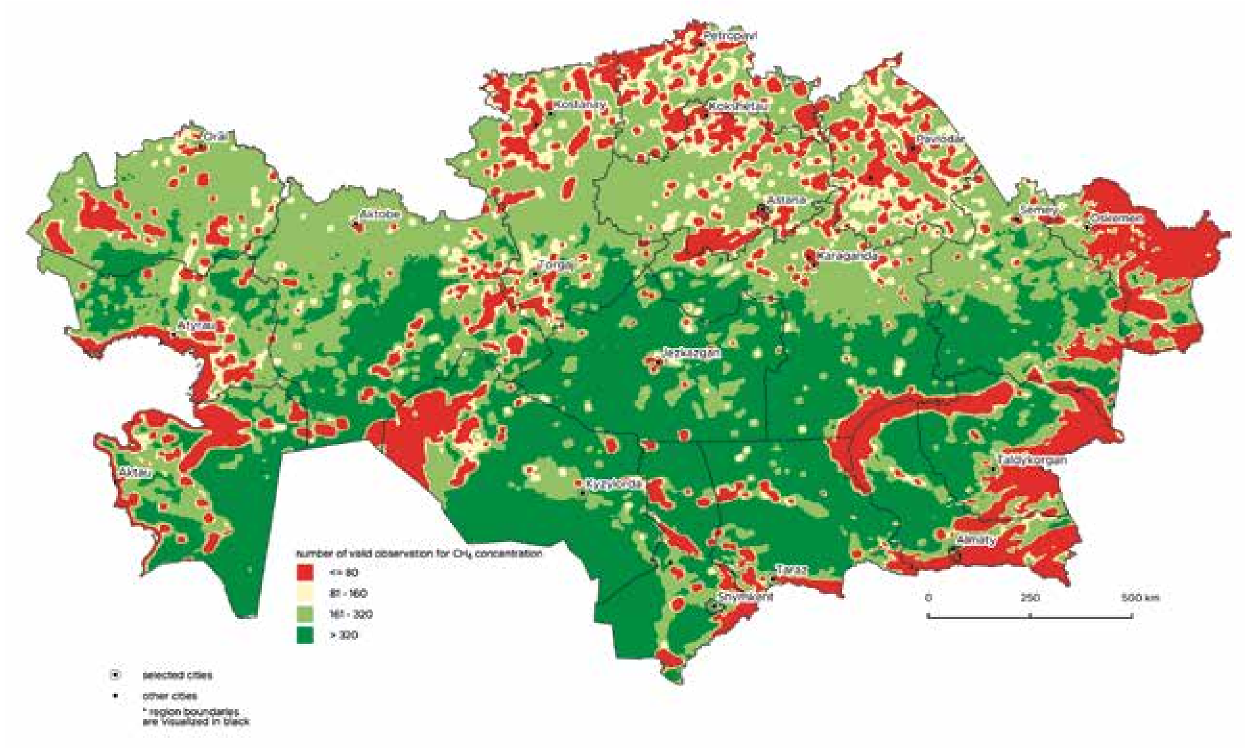

Fig. 13: Valid observations (per pixel) of CH4 concentrations in Kazakhstan between May 2018 and December 2022, obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022.

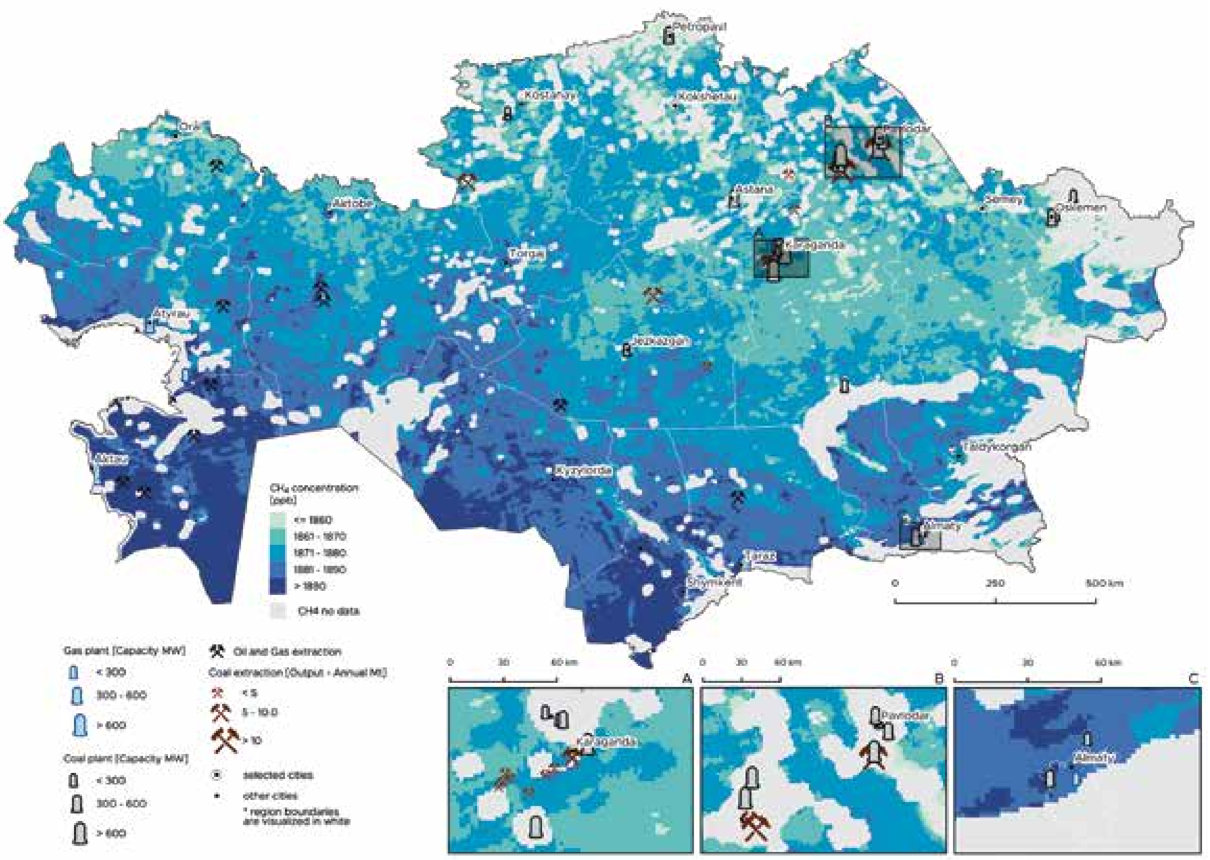

Fig. 14: Average CH4 concentrations in Kazakhstan between May 2018 and December 2022, obtained from the Sentinel-5P satellite. The cities that are focused on are A) Karaganda, B) Pavlodar, C) Almaty. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022; Global Energy Monitor, 2022.

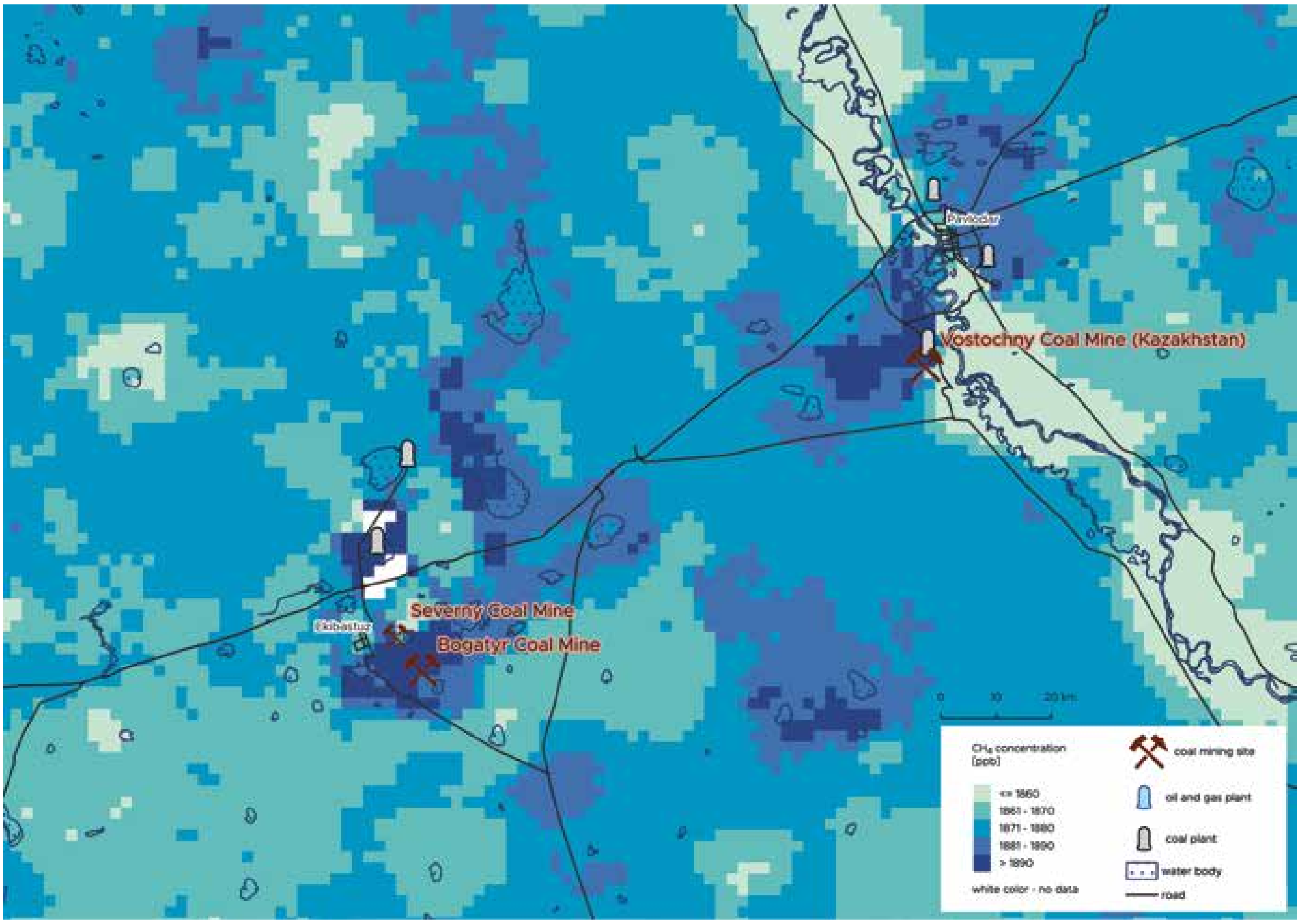

Fig. 15: Average CH_4 concentrations with a focus on mining sites in Ekibastuz and Pavlodar between May 2018 and December 2022, obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022; Global Energy Monitor, 2022.

erage emissions over the largest onshore gas and oil (or combined) fields, such as Karachaganak, near the city of Aksay in the north-west (West Kazakhstan Oblast), or the fields in the Pre-Caspian Basin in the west (e.g. Tengiz or Uzen), are overshadowed by the influence of land cover, which is seemingly the biggest driver for when CH_4 data is filtered by observation count and averaged from S5P. Besides the continual CH_4 release during extraction, a significant portion of methane leakages occurs in short-lived plumes during maintenance operations or accidents in the extraction fields or refineries (Lauvaux et al., 2022). These events are significantly attenuated by the principles of this study's methodology. It has, however, been recognised that Kazakhstan's coal, oil, and gas industries have continuously failed to capture much of the methane emitted when compared with the US or Ukraine (Roshchanka et al., 2017; Carbon Limits, 2016). Other analytical methods should be utilised to reveal the emission potential of oil and gas fields in the country.

The average concentrations for individual years within the study period can be found in Fig. 16. From 2018 to 2022, an annual increase in values can be observed throughout Kazakhstan. This corresponds to the global trend of

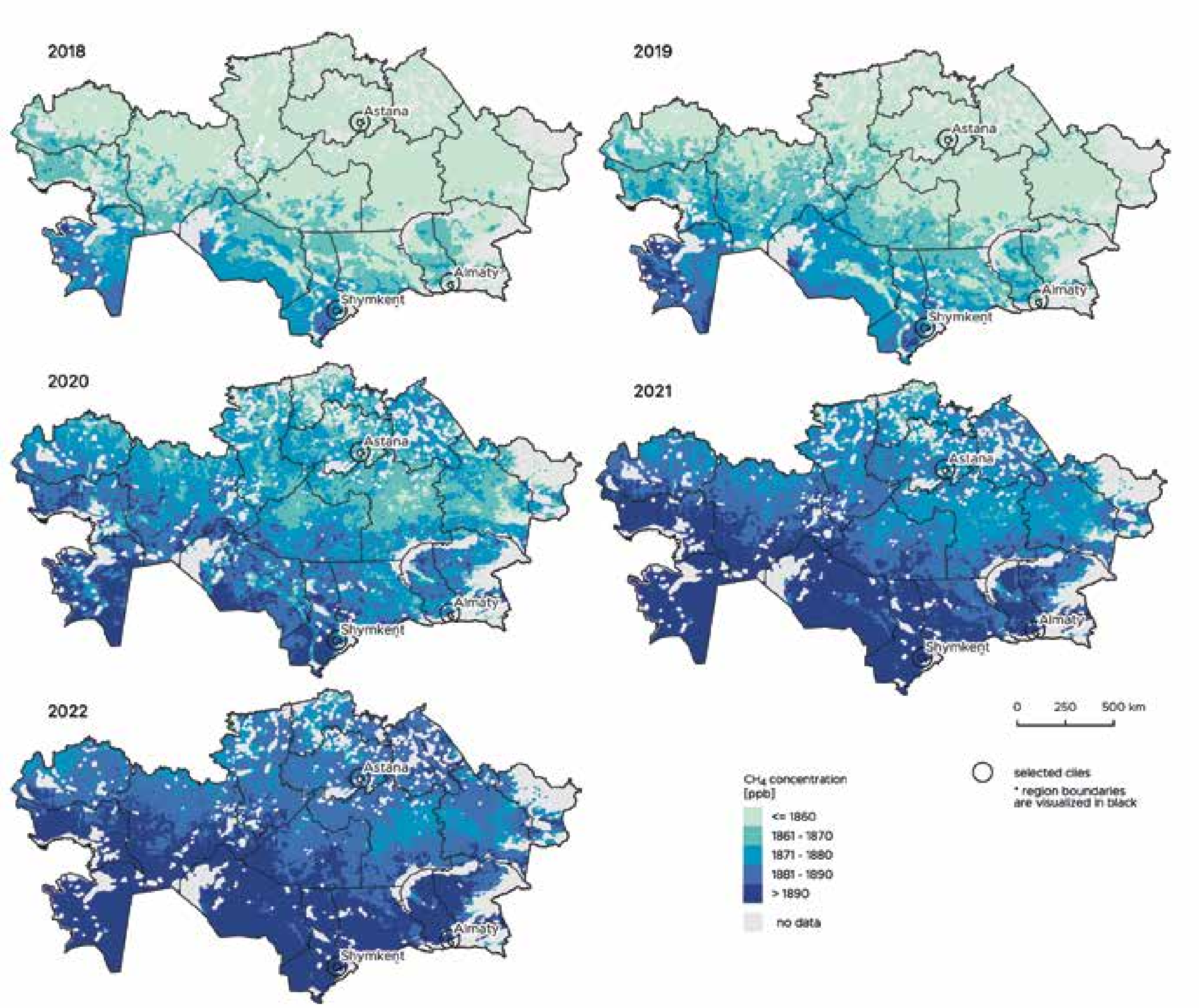

Fig. 16: Average yearly CH4 concentrations in Kazakhstan between May 2018 and December 2022, obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022.

rising amounts of methane in the atmosphere each year (NOAA-lan, 2023). The average annual growth in Kazakhstan for the study period has been calculated at 9.2 ppb in this analysis, which is very close to the global average rate (9 ppb/year since 2006) (Copernicus, 2021).

The highest concentrations per region occur in the city of Shymkent and the surrounding region of Turkistan, and in the regions of Mangystau, Turkistan, and Kyzylorda (Fig. 17). The pattern of these concentrations does not pinpoint specific anthropogenic sources and can possibly be explained by a lower oxidising potential of CH_4 in Kazakhstan's arid south.

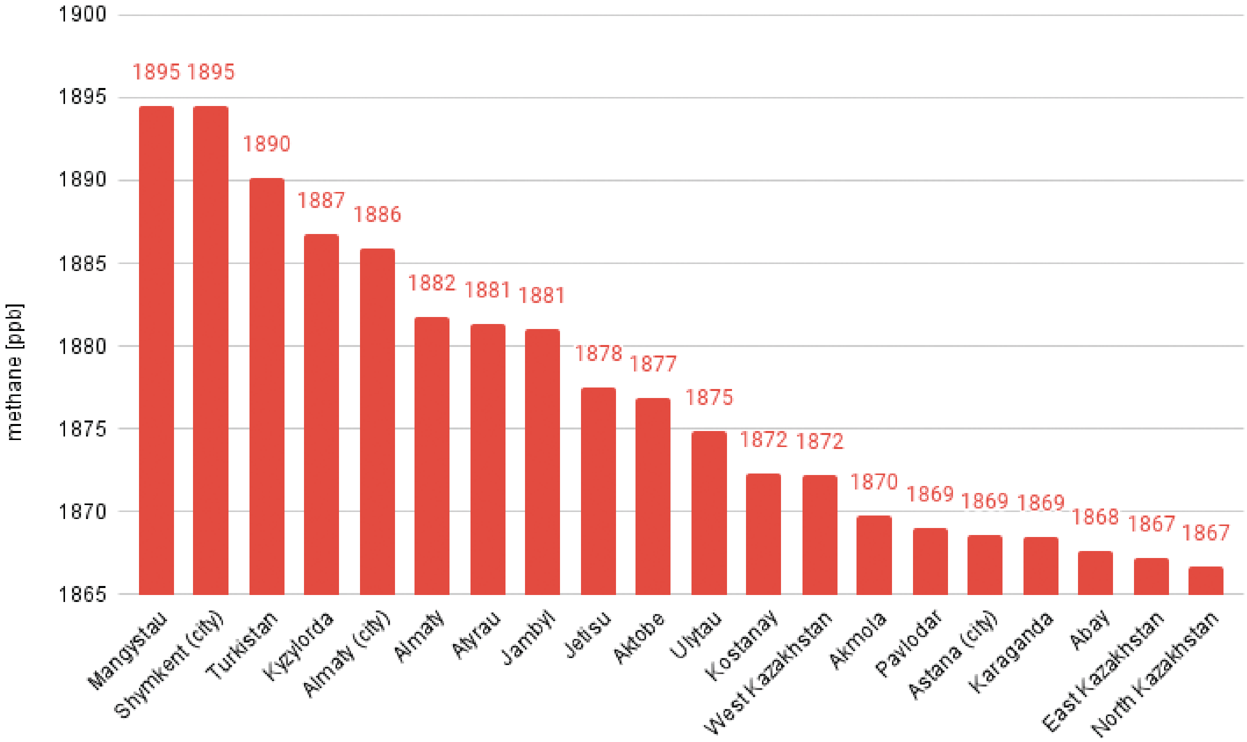

Fig. 17: Average CH4 concentrations in the regions of Kazakhstan between May 2018 and December 2022, obtained from the Sentinel-5P satellite. Source: Copernicus Sentinel data (ESA, 2018–2022; modified).

Seasonality of air pollution

Fig. 18 shows the seasonal variation of CH_4 concentrations in Kazakhstan. Natural conditions play an important role in influencing pollutant levels through several parameters. Here, the oxidation by •OH can be best observed. Areas with little rainfall and humidity and sparse vegetation (such as bare lands or deserts) have the highest concentrations of methane, regardless of the season. Methane has been shown to have monthly fluctuations, with the highest concentrations in September and October and the lowest in March and April (Javadinejad et al., 2019). This is confirmed in the analysis; the lowest concentrations in Kazakhstan happen in the spring months and the highest in autumn (Fig. 19).

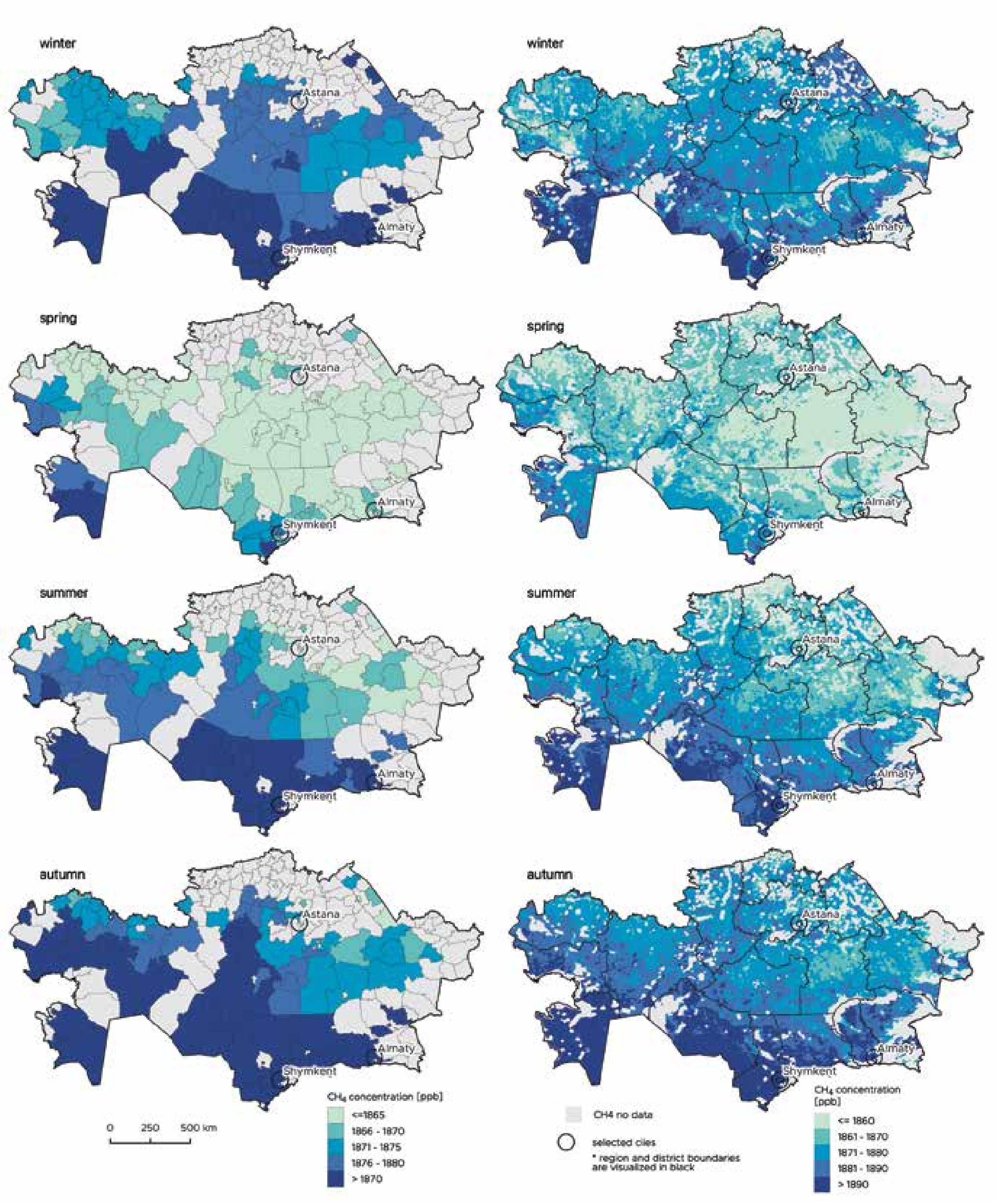

Fig. 18: Average seasonal CH4 concentrations in Kazakhstan for districts (left) and in general (right) between May 2018 and December 2022, obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022.

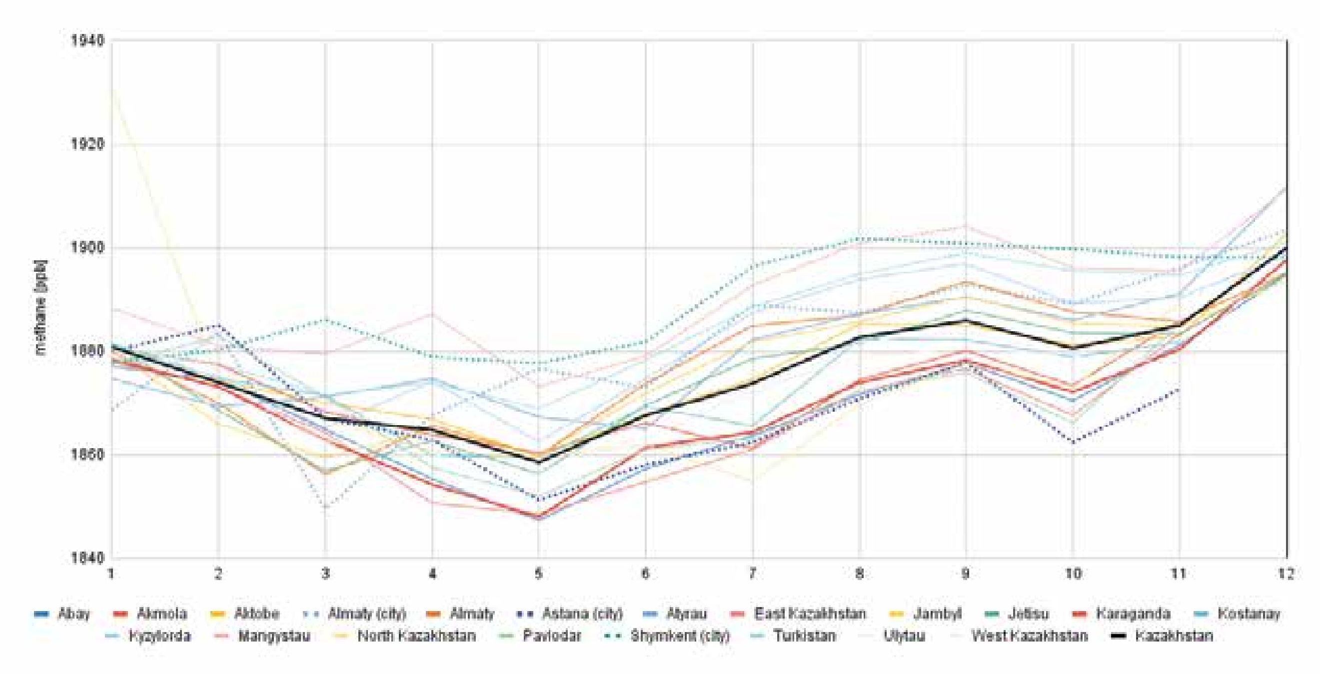

Fig. 19: Average monthly CH_4 concentrations in the regions of Kazakhstan between May 2018 and December 2022, obtained from the Sentinel-5P satellite. Source: Copernicus Sentinel data (ESA, 2018–2022; modified). Note: Values in December for Astana (city) and the regions of Kostanay, North Kazakhstan, Pavlodar, and West Kazakhstan are unavailable because of a lack of valid observations.

Sulphur dioxide (SO_2)

For SO_2, the change in the model calculation in 2019 needs to be taken into account for the analysis of SO_2 air pollution from CAMS. For this reason, two separate maps visualise the average pollution values in Kazakhstan.

Basic analysis

The comparison of the observation periods 2018-2022 and 2020-2022 in Fig. 20 shows that the model data until 2019 tends to underestimate or overestimate some areas. The impact of the change is seen in particular in the surroundings of the city of Zhezqazghan and the area to the north-west of Astana.

The copper mines south of Zhezqazgan are significant producers of SO_2. In copper smelter processing, elemental copper is separated from copper concentrates through several sulphidic oxidation steps. This is reflected by the elevated SO_2 values in this part of Kazakhstan.

In other locations, the pollution that is detected corresponds in both maps. The areas with the highest average concentrations are those with mining industries and the presence of coal-fired power plants. This regards particularly the regions of Pavlodar and Almaty. High concentrations have also been measured around Oskemen, Astana, and Karaganda. At several locations, the average values exceed the daily maximum limits (MAC) for SO_2 concentrations according to the WHO (20 µg/m^3) or even according to the quality standards of Kazakhstan (50 µg/m^3).

The differences caused by the change in the calculation of the SO_2 model can be seen clearly in Fig. 21. The map shows significantly elevated values

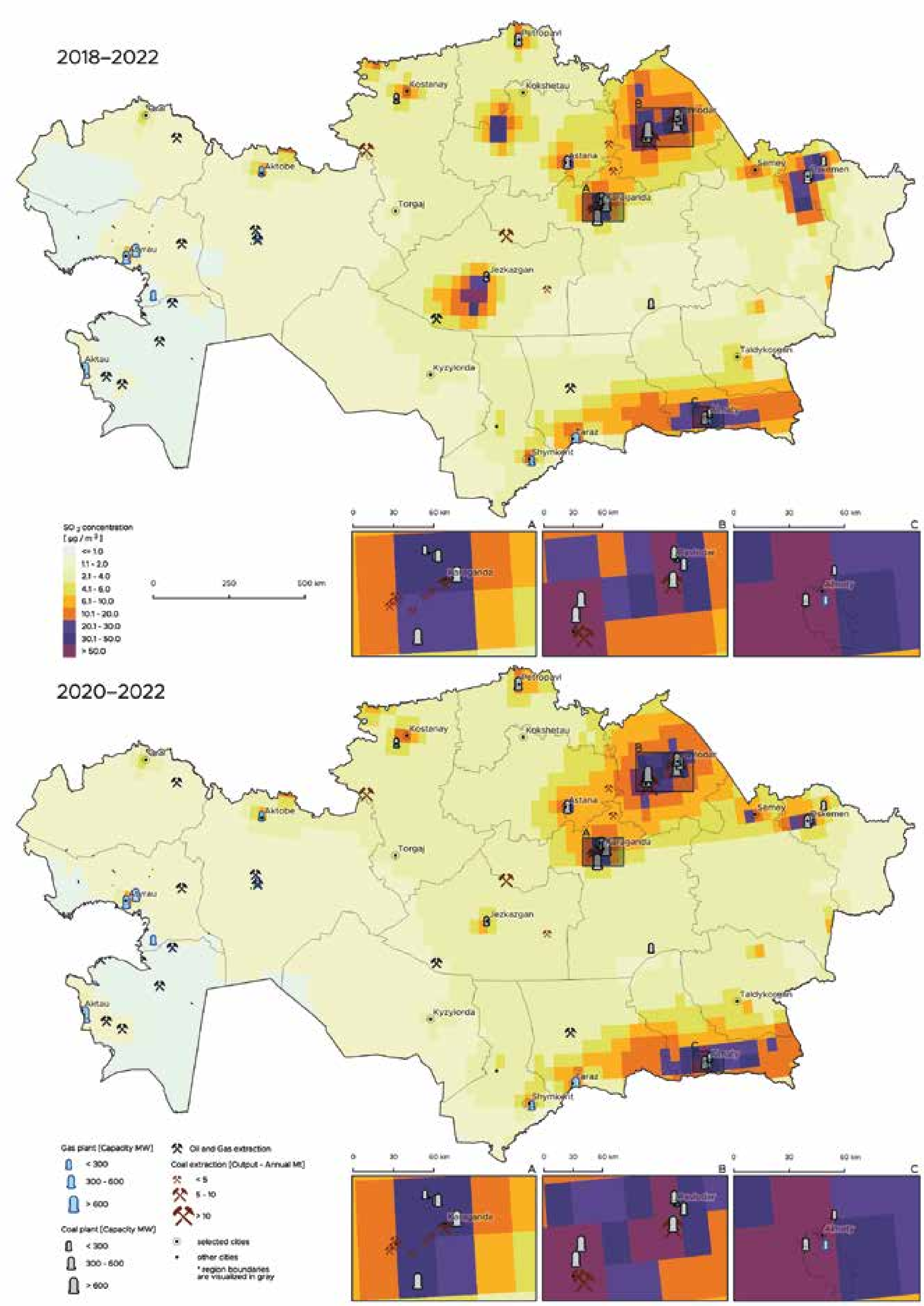

Fig. 20: Average SO_2 concentrations in Kazakhstan between May 2018 and December 2022 (top) and January 2020 and December 2022 (bottom), obtained from the Copernicus Atmosphere Monitoring Service. Source: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022; Global Energy Monitor, 2022.

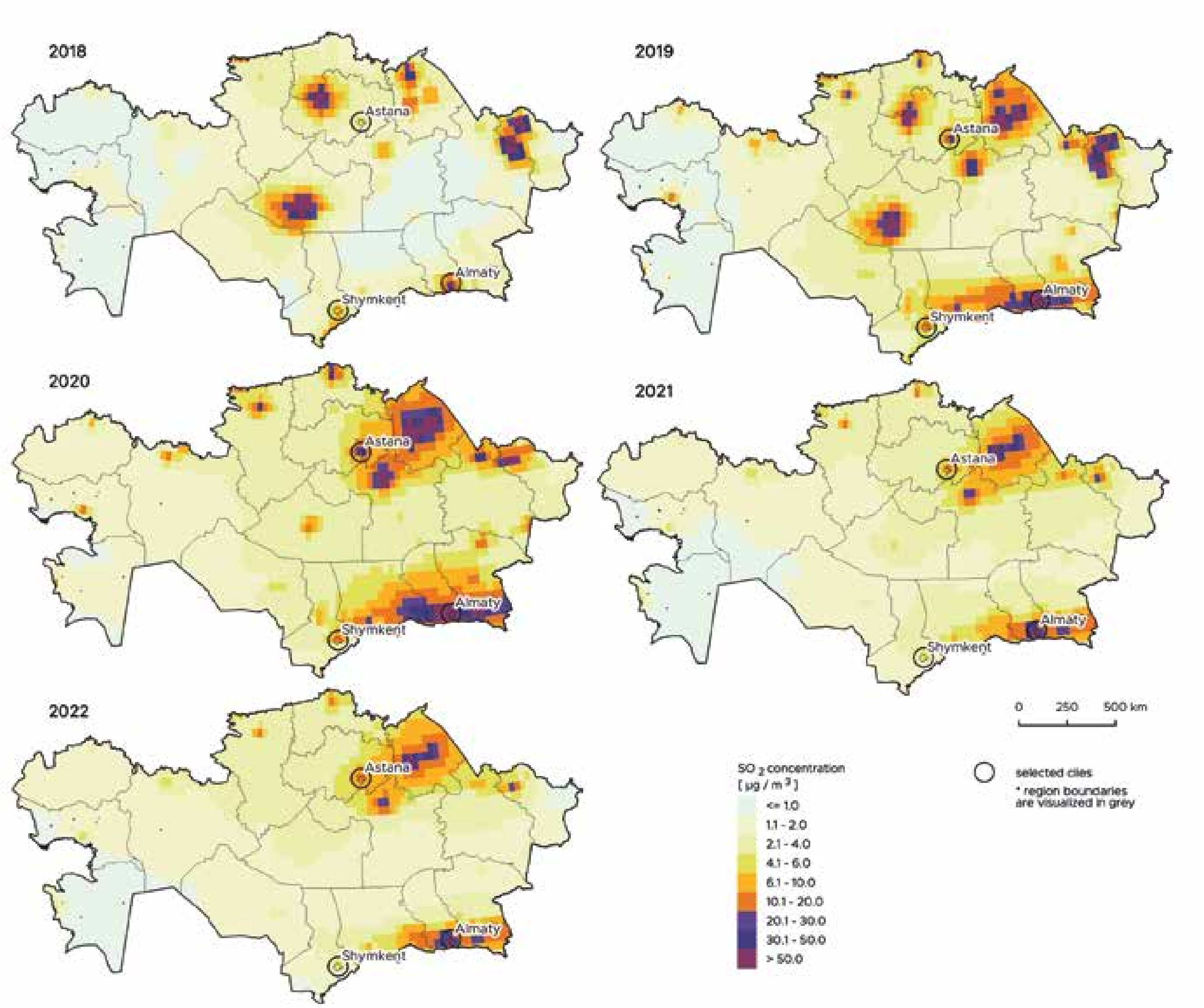

Fig. 21: Average yearly SO_2 concentrations in Kazakhstan between May 2018 and December 2022, obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022.

in 2018 and 2019 for the two locations mentioned above (the surroundings of the city of Zhezqazghan and the area to the north-west of Astana). Elevated values for multiple locations were detected in 2020 when compared to the 2021 and 2022 averages, which are similar. Using the data from the National Air Quality Monitoring Network, Baimatova et al. (2022) reported varying SO_2 concentration responses for the lockdown period, which did not affect the operation of heavy industries. Some cities supposedly reported an increase in concentrations (Petropavl, Shymkent), others a decrease (Almaty, Karaganda, Oskemen). This study can safely compare the major lockdown year of 2020 with the 2021 and 2022 averages, which suggests a prevailing SO_2 reduction in most cities.

The highest average SO_2 concentrations across districts are found in the Almaty Region, as can be seen in Fig. 22. This is also shown in the graph of average SO_2 values across all districts, with the Almaty (city) district having the highest average value, of 178 µg/m^3.

The average SO_2 concentrations in cities with a population above 100,000

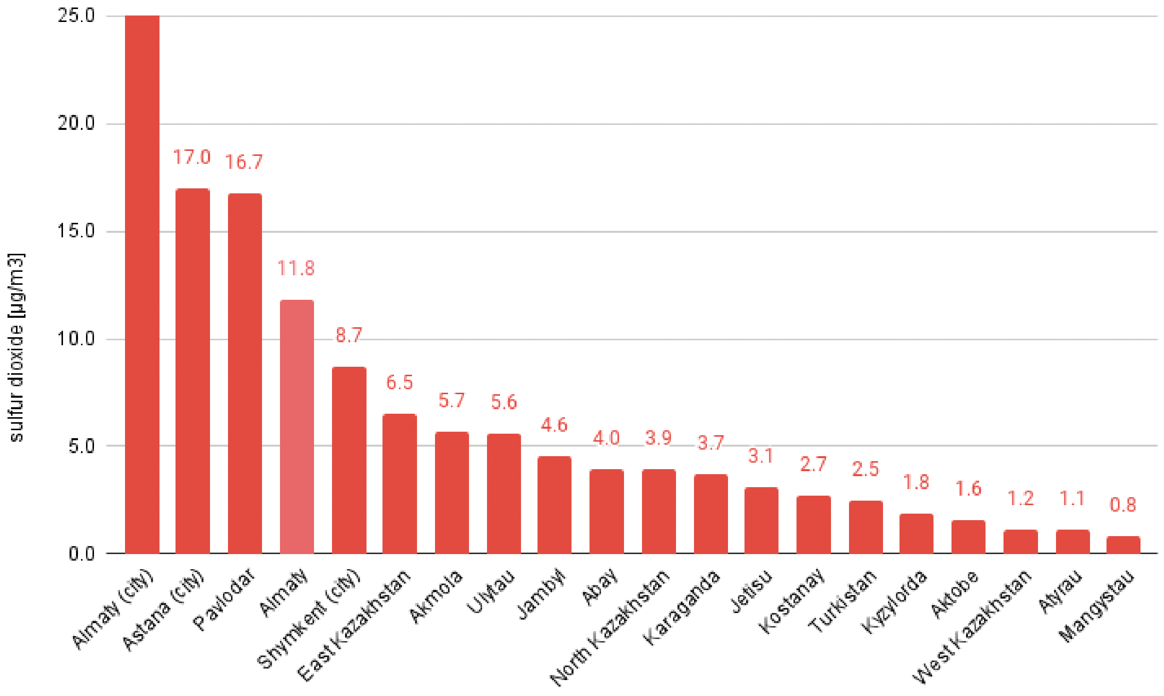

Fig. 22: Average SO_2 concentrations in the regions of Kazakhstan between May 2018 and December 2022, obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022.

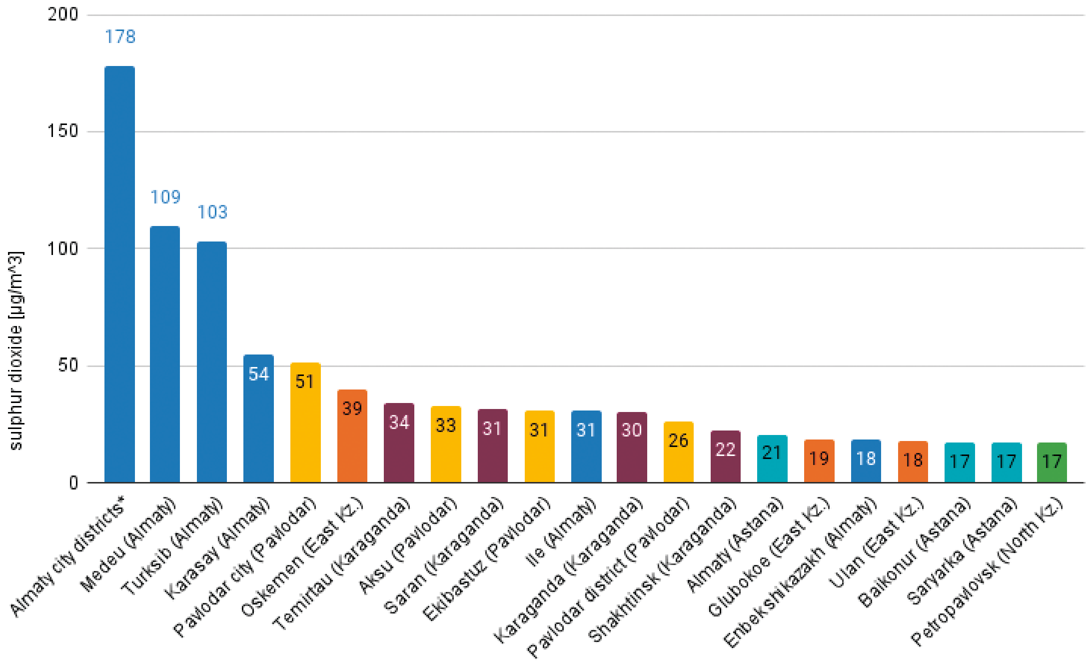

Fig. 23: The 20 highest SO_2 concentrations in the districts of Kazakhstan (with an indication of regions) between May 2018 and December 2022; Copernicus Atmosphere Monitoring Service data. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022. Note (*): "Almaty city districts" include six districts in the city of Almaty – Alatau, Almaty, Auezov, Bostandyk, Jetysu, Nauryzbay. Please refer to Administrative divisions of Kazakhstan.

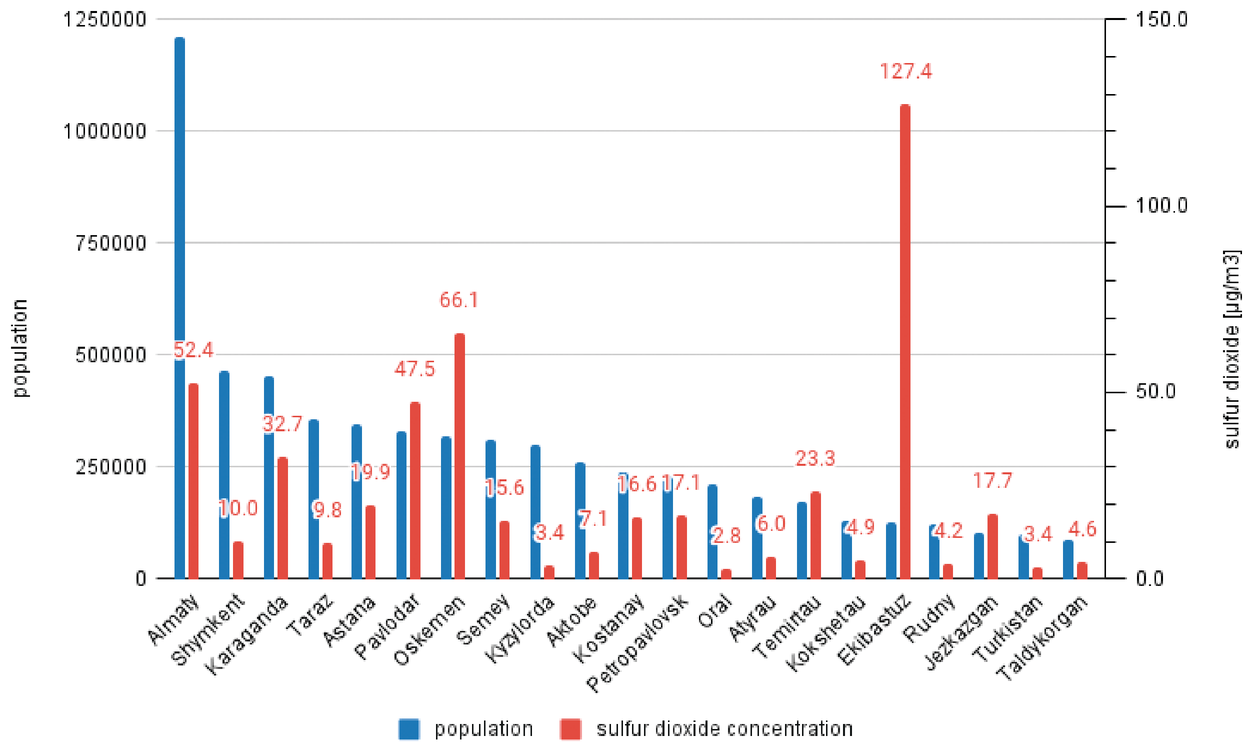

Fig. 24: Average SO_2 concentrations in selected cities of Kazakhstan between May 2018 and December 2022, obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022; Natural Earth, 2022. Note: The exact population numbers may not be current as they are based on Natural Earth data (2022) with no accurate dating.

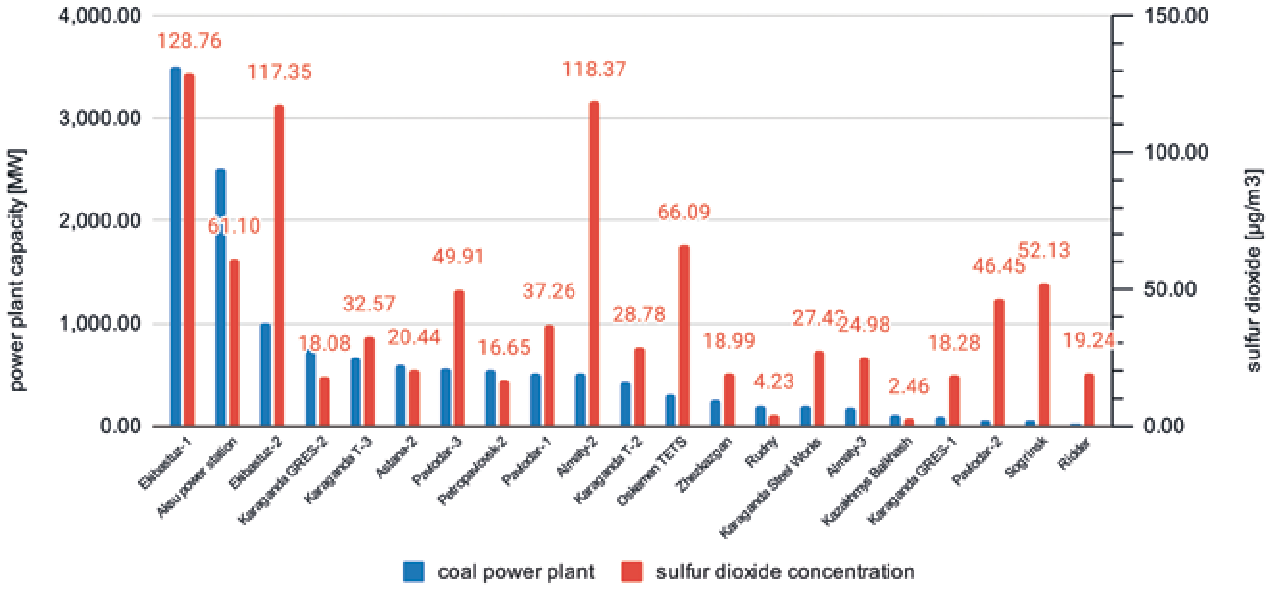

Fig. 25: Average SO_2 concentrations around selected coal-fired power plants in Kazakhstan between May 2018 and December 2022, obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022; Global Energy Monitor, 2022.

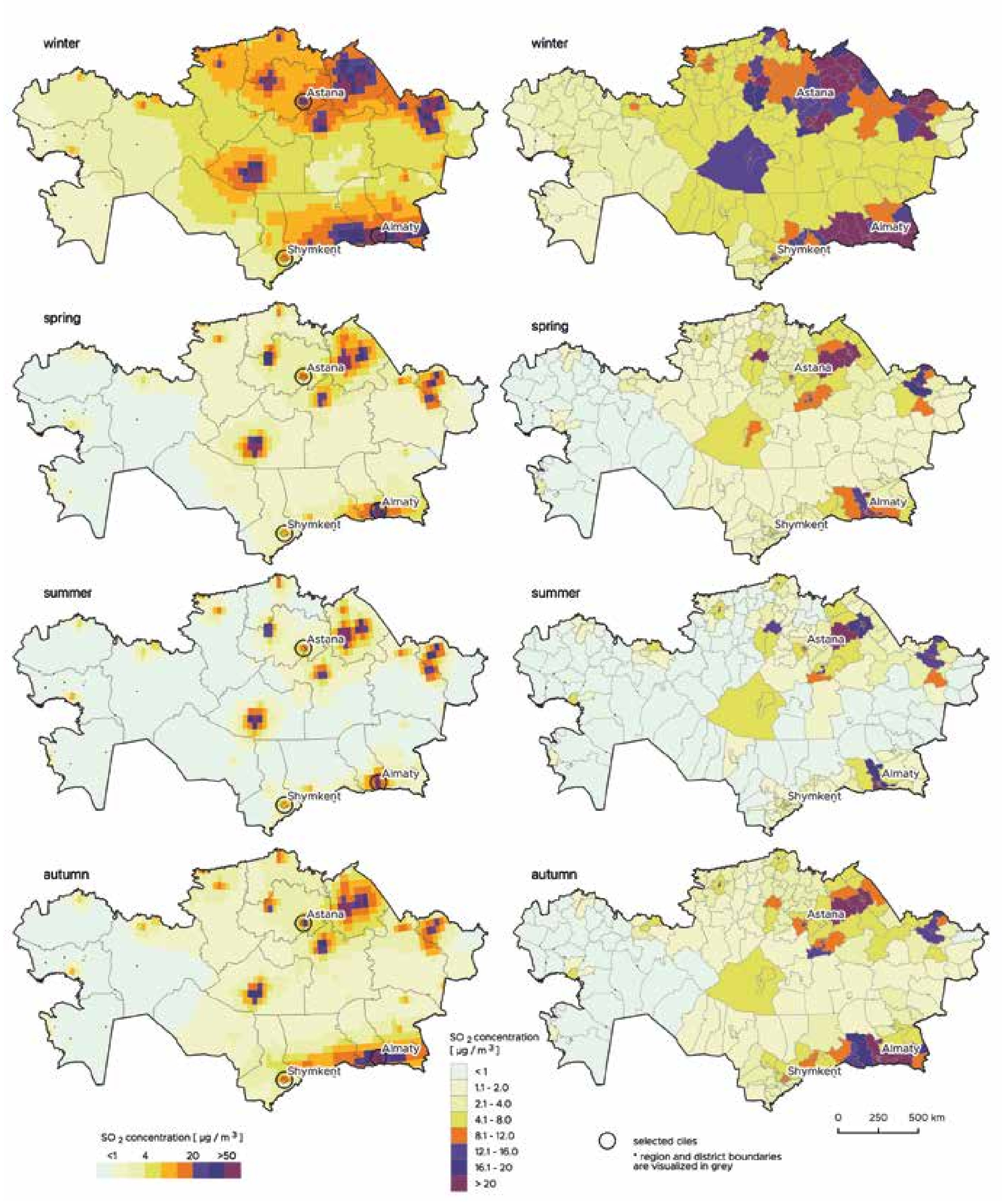

Fig. 26: Average SO_2 concentrations in districts of Kazakhstan calculated for seasons between May 2018 and December 2022 (right), based on per pixel values (left) obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022.

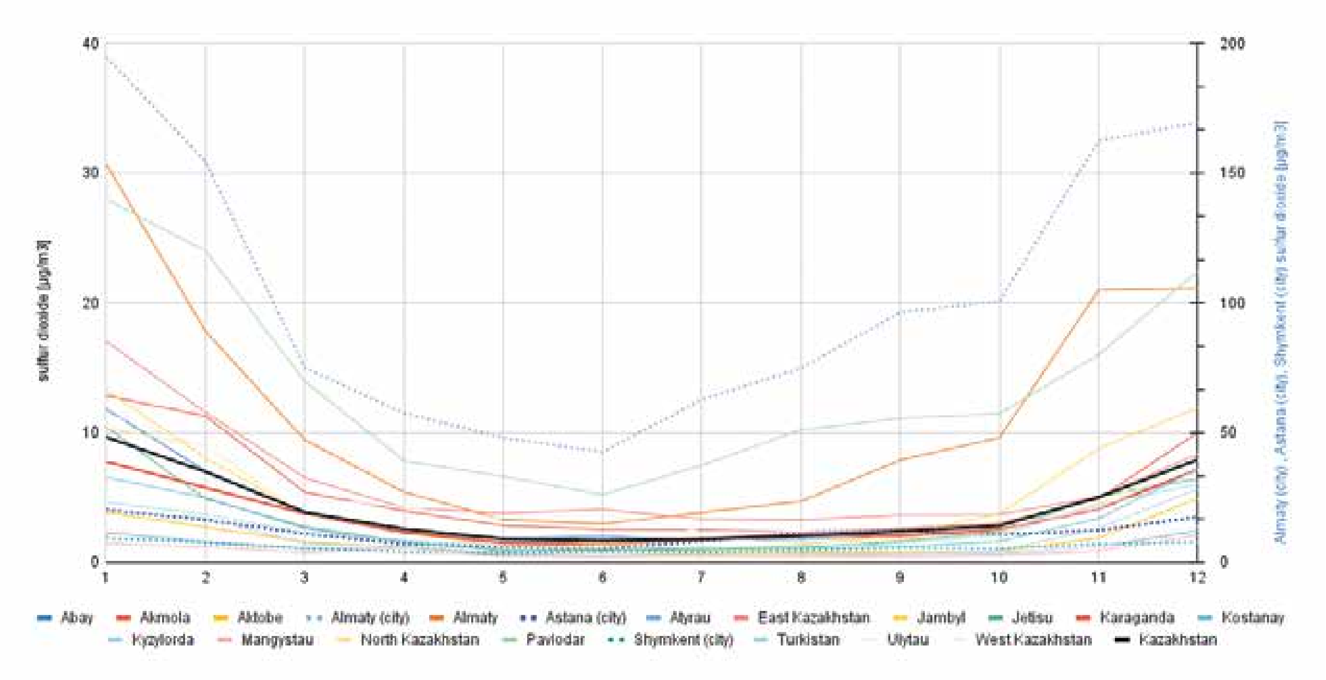

Fig. 27: Average monthly concentrations of SO_2 in regions of Kazakhstan between May 2018 and December 2022, obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022). Note: The right vertical axis refers to the cities of Astana, Almaty, and Shymkent, while the left vertical axis refers to other regions.

are shown in Fig. 24. The highest concentrations were detected around the town of Ekibastuz (127.4 µg/m^3), where the most powerful coal-fired power plant is currently located. This is similar for other cities with coal-fired power plants, such as Oskemen (66.1 µg/m^3), Pavlodar (47.5 µg/m^3), and Almaty (52.4 µg/m^3).

The average SO_2 concentrations around coal-fired power plants can be observed in Fig. 25. The graph is based on measurements within 10 km of the power plant location. The SO_2 concentrations may not be related only to the exhaust of the power plants but also to their technical condition and the level of modernisation. Some concentrations might be influenced by the combination of exhausts from multiple power plants because of their mutual closeness and the S5P resolution.

Seasonality of air pollution

The SO_2 seasonality analysis (Fig. 26) shows that the concentrations peak in the winter season. This is probably the result of both natural and human factors. The high winter concentrations of SO_2 are caused by low deposition resulting from the absence of vegetation and low amounts of precipitation. At the same time, there are higher emissions from intensified house heating in residential areas during the colder months (Mackiewicz-Walec et al., 2014). In some places, SO_2 concentrations are consistently high throughout the year and exceed the WHO limits in every season, as well as Kazakhstan's quality standards. Concentrations in many places in the cities of Almaty, Pavlodar, Ekibastuz, and Karaganda exceed the national limit of 50 µg/m^3 even during the summer season.

The seasonal pattern of the monthly average SO_2 values for each region can be seen in Fig. 27. The graph is supplemented with the average value for the whole territory of Kazakhstan. The lowest values occur in the summer months in almost all regions. In terms of regional distribution, the highest concentrations throughout the year are in the city of Almaty; nonetheless, the whole Almaty Region reaches very high values. The cities of Astana and Shymkent also reach higher values than other regions. Without city-regions, the highest year-round concentrations occur in the Pavlodar Region, where coal-fired power plants and the mining industry are located.

Particulate matter (PM_{10})

Basic analysis

High concentrations of PM_{10} occur especially in the south and the southeast of Kazakhstan. This is related to natural sources, such as bare soil and deserts, where dust and other particles are generated. Kazakhstan's high wind-speed conditions, sparse vegetation cover, frequent droughts, and

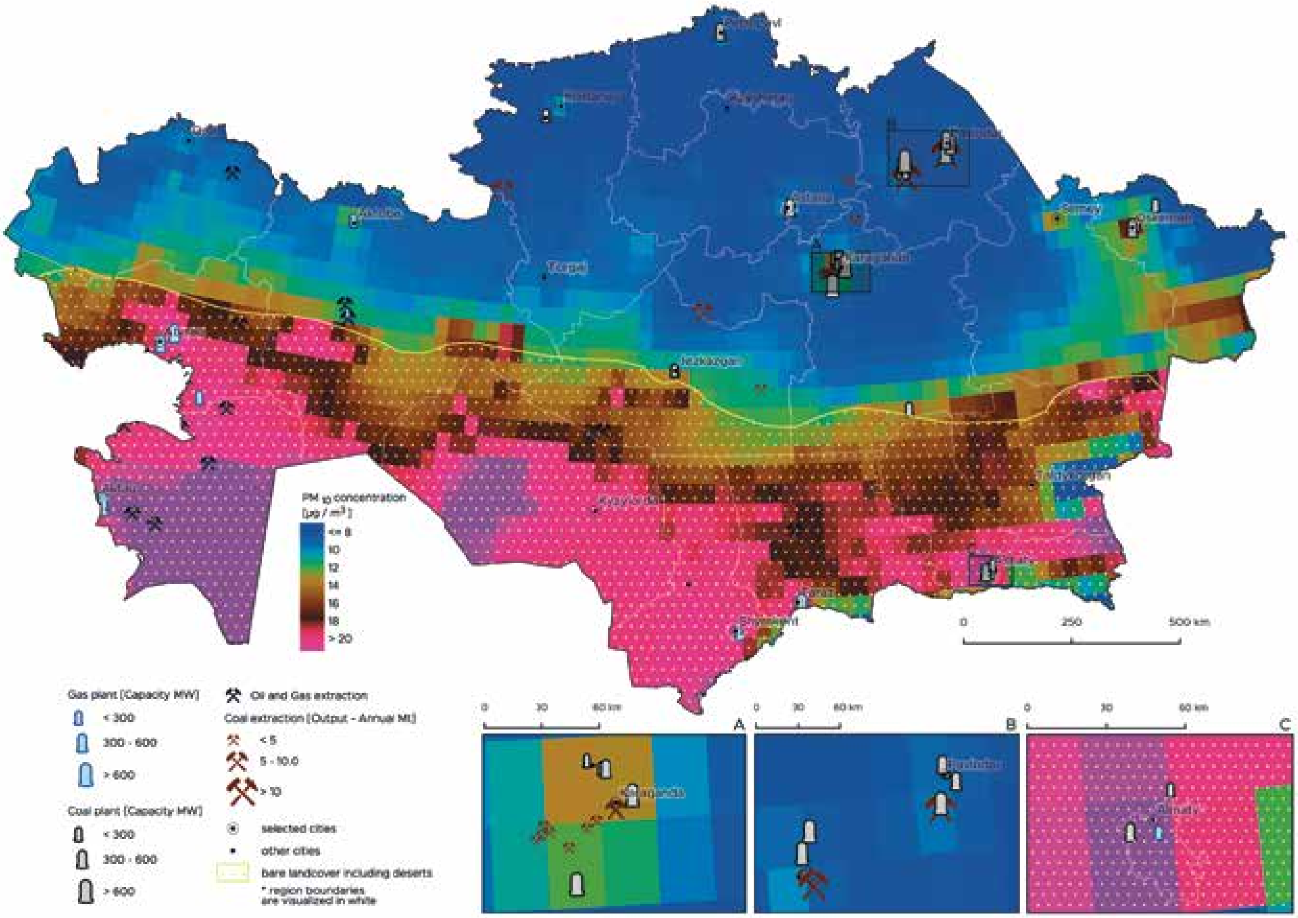

Fig. 28: Median PM_{10} concentrations in Kazakhstan between May 2018 and December 2022, obtained from the Copernicus Atmosphere Monitoring Service. The cities that are focused on are A) Karaganda, B) Pavlodar, C) Almaty. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022; European Commission, 2022.

continental climate create suitable conditions for the development of dust storms throughout the country. Dust storms can pick up fine particles from the ground and transport them over long distances, significantly contributing to the presence of PM_{10} in the air (Issanova & Abuduwaili, 2017). Severe dust storms cause PM_{10} concentrations to exceed 500 or even 1000 µg/m^3 (Issanova et al., 2023). Areas with the natural occurrence of PM_{10} are marked with yellow points in Fig. 28.

It can further be observed that a significant part of Kazakhstan exceeds the WHO limits for annual PM_{10} (20 µg/m^3, marked in pink). Outside the areas with mostly naturally generated PM_{10}, increased concentrations are found in urban areas in the northern part of the country. These are, for example, the cities of Karaganda, Oskemen, Aktobe, Astana, and Kostanay.

The distribution of PM_{10} particles varies each year. The highest concentrations were recorded in 2020, which may be related to natural conditions, such as the frequency of dust storms. Fig. 29 shows the average PM_{10} concentrations within the regions of Kazakh-

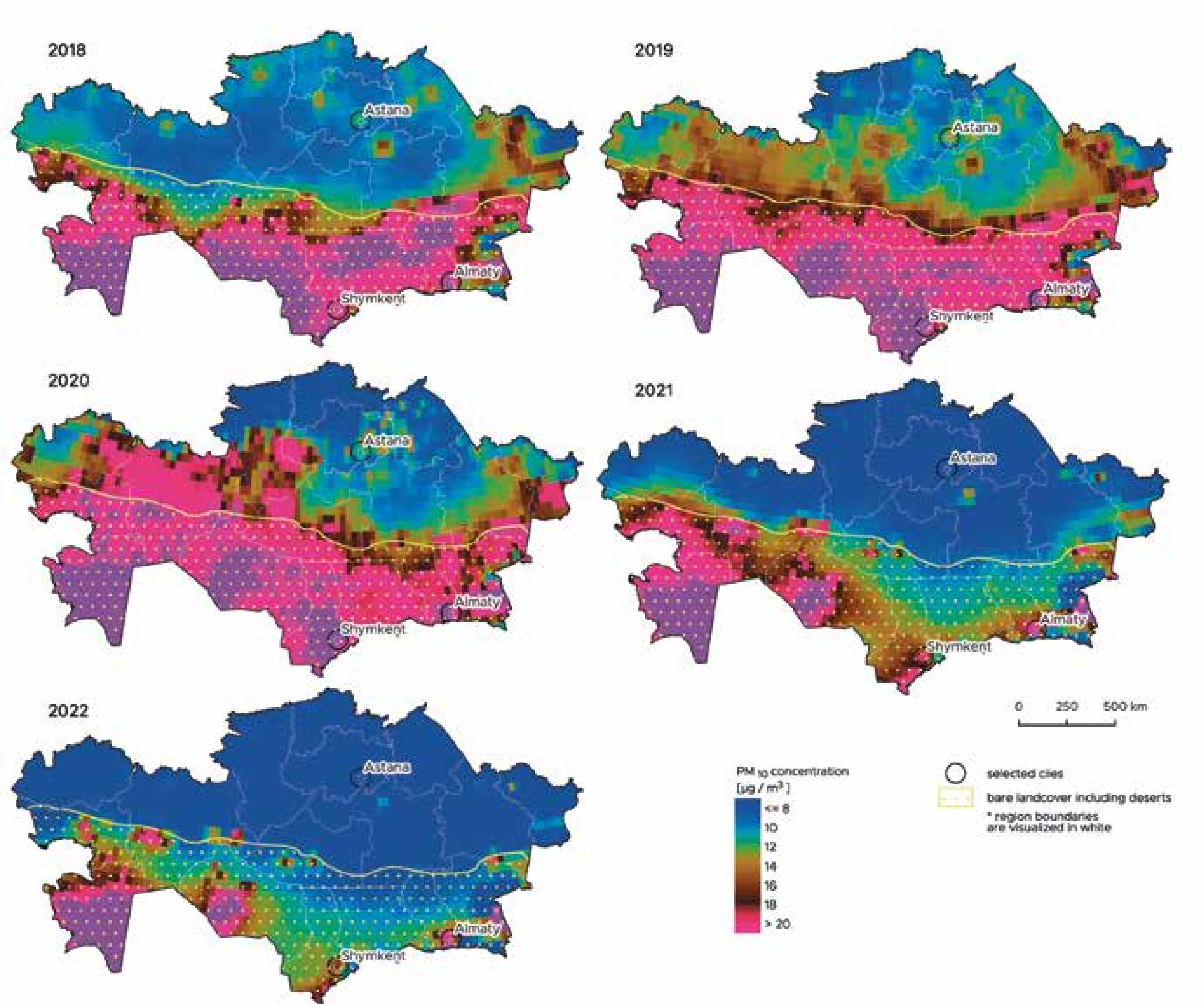

Fig. 29: Median yearly PM_{10} concentrations in Kazakhstan between May 2018 and December 2022, obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022; European Commission, 2022.

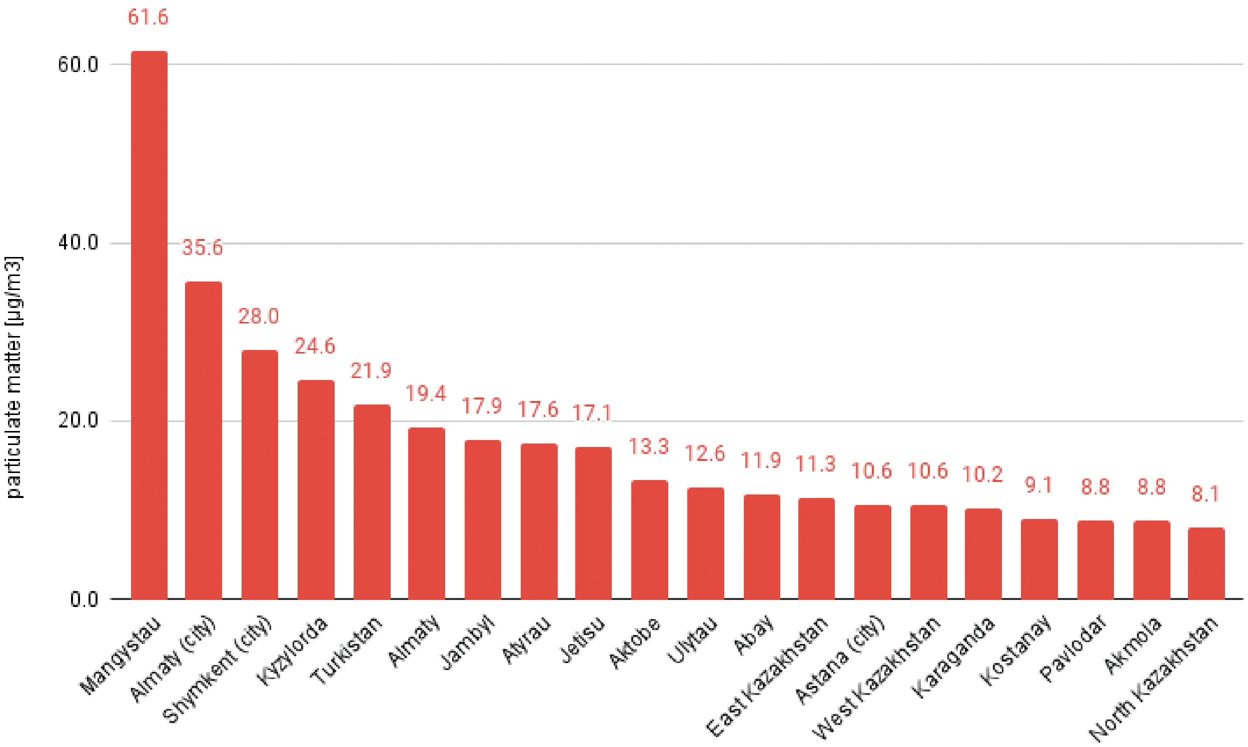

Fig. 30: Median PM_{10} concentrations in the regions of Kazakhstan between May 2018 and December 2022, obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022.

stan. The Mangystau Region in the arid south-western part of the country has the highest values.

Seasonality of air pollution

The changes in PM_{10} concentrations over the whole territory of Kazakhstan are shown in Fig. 31. On the national scale, seasonal changes are mainly influenced by natural conditions, which is the case for the average over the study period. Increased concentrations can be observed irrespective of the season, especially in the south of the country. They are linked to the presence of bare lands with frequent dust storms that most frequently occur in the spring and summer months (Issanova & Abuduwaili, 2017). This is confirmed by the analysis as the concentrations in these months are significantly elevated compared to other months. The lowest natural PM_{10} concentrations can be found in the winter months in the northern part of Kazakhstan. While most pronounced in winter, the effect of anthropogenic activity on higher concentrations can be observed in all seasons (in the areas not so affected by natural conditions). In the cities of Karaganda and Oskemen, the median values do not fall below 13 $\mu g/m^3$ and 15 $\mu g/m^3$, respectively.

The seasonal pattern of the monthly average PM_{10} values for each region can be seen in Fig. 32. The graph is supplemented with the average value for the whole territory of Kazakhstan and it confirms the above-mentioned pattern of PM_{10} concentrations during the year (the effect of anthropogenic activity in the areas not significantly affected by natural conditions). Most regions reach the highest concentrations in the spring to summer months. The Mangystau

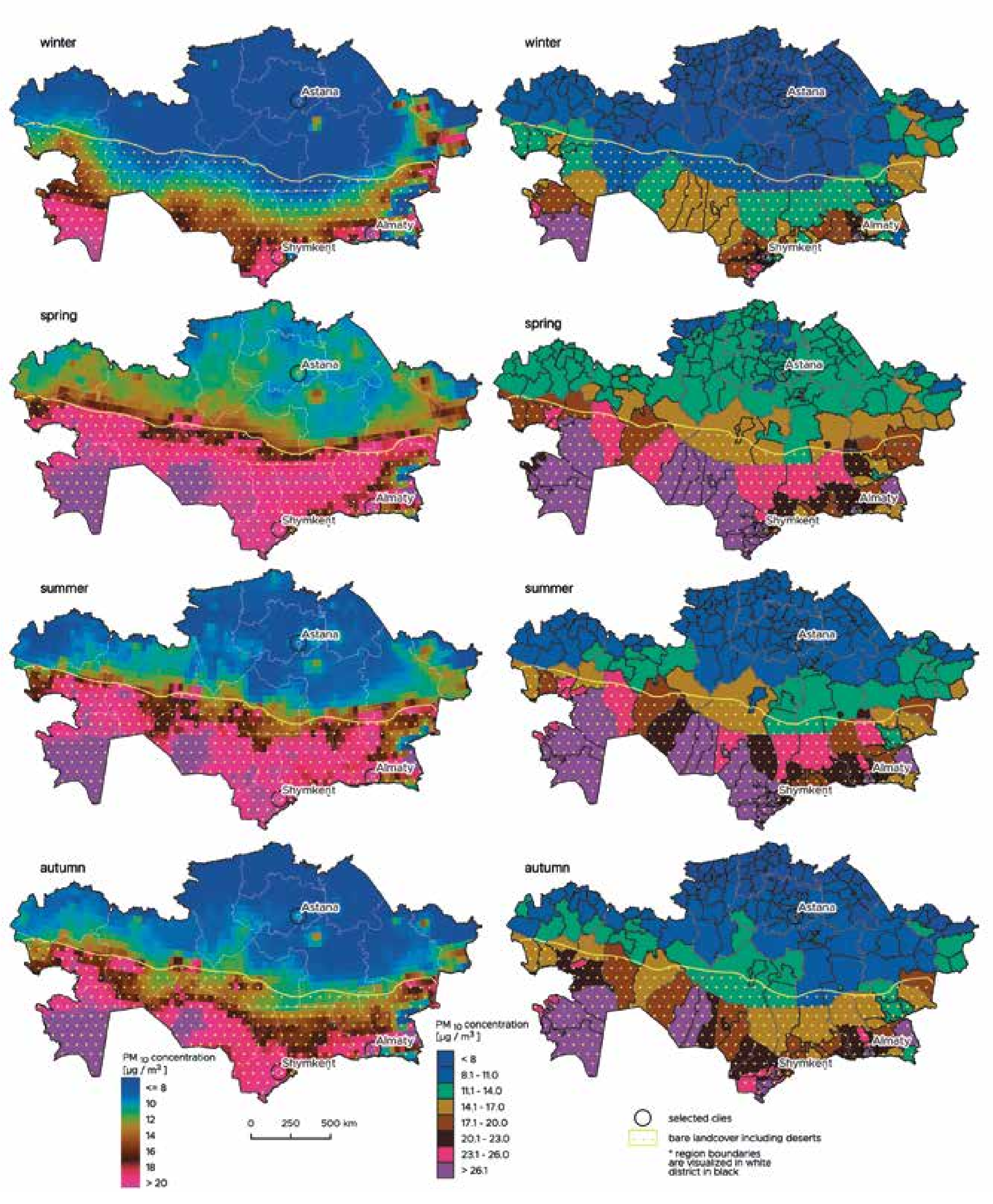

Fig. 31: Median seasonal PM10 concentrations in Kazakhstan in general (left) and for districts (right) between May 2018 and December 2022, obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022; European Commission, 2022.

Region, with extensive bare lands and frequent sandstorms, has significantly higher concentrations than other regions. An increase in PM_{10} for some cities in the winter months is mainly related to anthropogenic activities. Fig. 33 shows significantly higher concentrations in cities where mines or power plants are located.

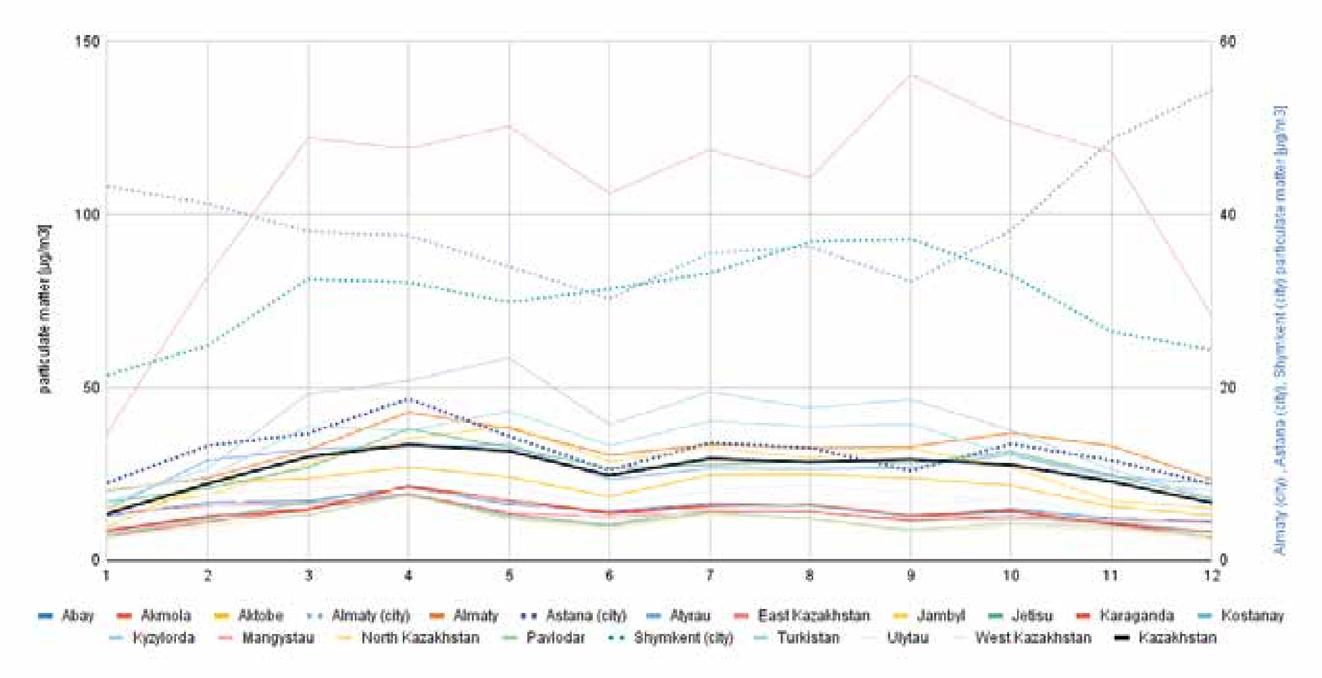

Fig. 32: Average monthly PM$_{10}$ concentrations in the regions of Kazakhstan between May 2018 and December 2022, obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022). Note: The right vertical axis refers to the cities of Astana, Almaty, and Shymkent only, while the left vertical axis refers to other regions.

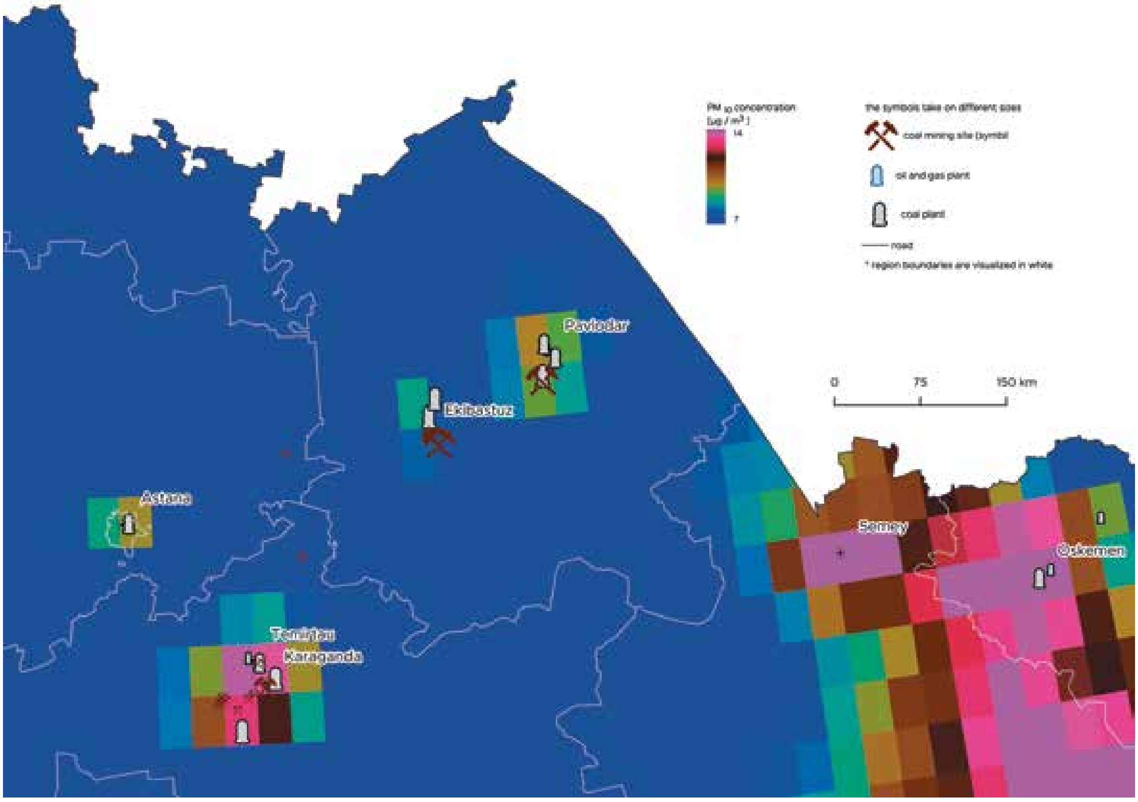

Fig. 33: PM$_{10}$ concentrations in the north-western part of Kazakhstan for the winter season; median of 2018-2022 obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022; Global Energy Monitor, 2022. Note: The colour scale is adjusted to the displayed area and cannot be directly compared with previous maps showing PM$_{10}$.

AIR POLLUTION IN THE KARAGANDA REGION: DETAILED VIEW

The Karaganda Region is located in the central part of Kazakhstan. Its administrative centre is the eponymous city of Karaganda, the fourth largest in the country. After splitting into two regions in 2022 (part of the territory of the Karaganda Region was made into the new Ulytau Region, with an administrative centre in Zhezqazghan), the region now covers an area of approximately 239,000 square kilometres and has a population of around 1.3 million people.

The region is known for its rich mineral resources, including coal, iron, and copper. The Karaganda coal basin is one of the largest in the world and provides the basis for the region's energy and metallurgical industry. Other major industries in the region include chemicals and machinery.

Nitrogen dioxide (NO_2)

Fig. 34 displays the average concentrations of NO_2 in the Karaganda Region measured between May 2018 and December 2022. The highest concentrations are centred around the two largest cities of the region – Karaganda and Temirtau. Karaganda is a centre of coal mining and a major industrial and cultural centre. It is known for its metallurgical and chemical industries, as well as

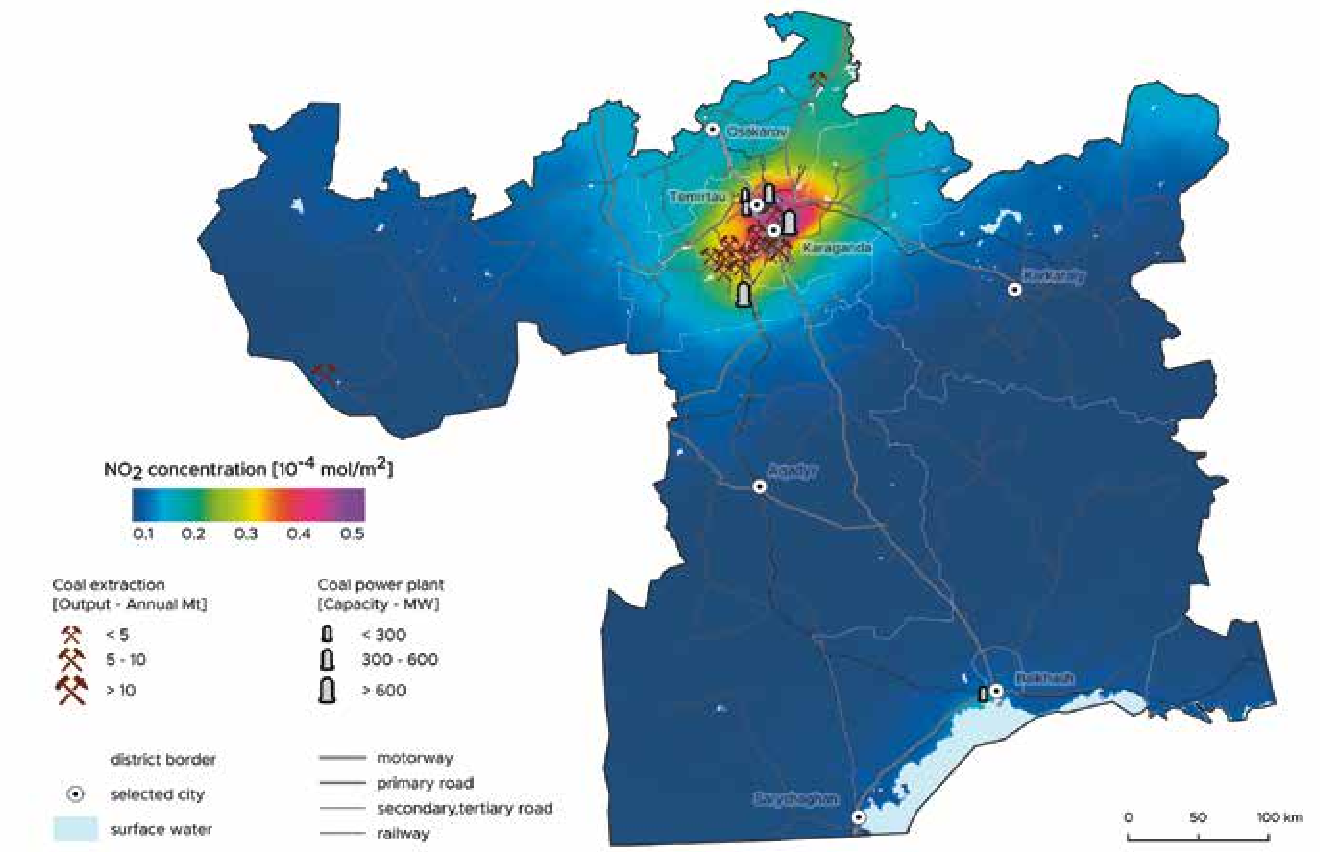

Fig. 34: Average NO_2 concentrations in the Karaganda Region between 2018 and 2022, obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022; Global Energy Monitor, 2022.

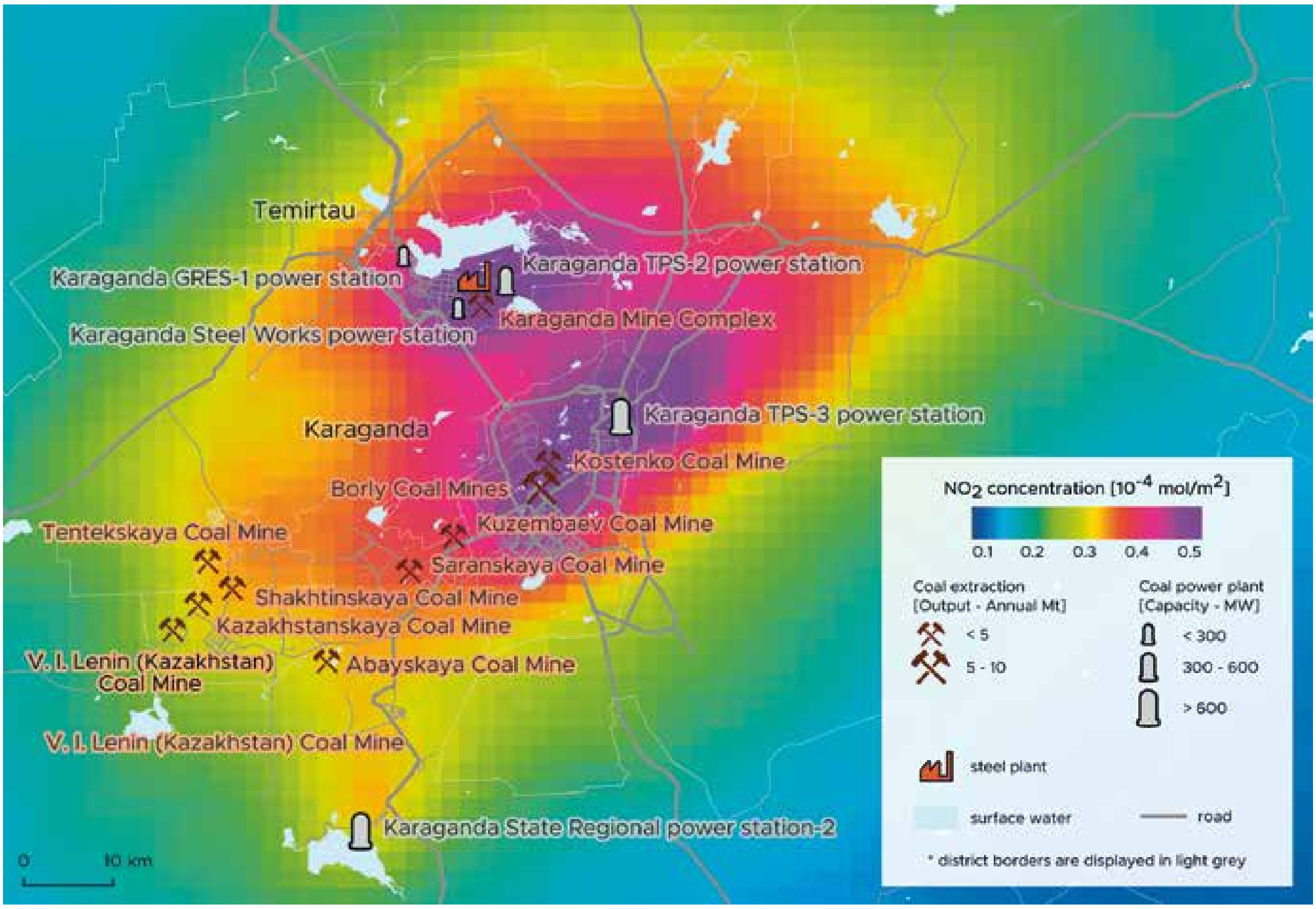

Fig. 35: Average NO_2 concentrations around the cities of Karaganda and Temirtau between 2018 and 2022, obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022; Global Energy Monitor, 2022.

its machine-building and food-processing plants. Temirtau is located around 30 kilometres north of Karaganda and is known for its steel industry, being the main employer in the city. Temirtau's steel plant, owned by the company ArcelorMittal Temirtau JSC, is one of the largest in Kazakhstan and produces a range of steel products for the domestic and international markets. The city also has a number of other industrial enterprises in the machinery, chemical, and construction materials sectors.

Increased concentrations can also be identified between the A17 and P27 roads heading north-east from the city of Karanda to the towns of Ekibastuz and Pavlodar in the neighbouring Pavlodar Region. In a relatively small area, there are also increased values to the west of the town of Balkhash in the south of the region.

Fig. 35 shows the area around the cities of Karaganda and Temirtau in greater detail. This area includes ten coal mines with a total annual mining volume of up to 23 megatons. The largest of the mines (Borly Coal Mine), with an annual mining volume of 7.3 Mt, belongs to Kazakhmys Corporation; the remaining nine mines are under ArcelorMittal Temirtau JSC (Global Energy Monitor, 2022).

There are a further five coal-fired power plants in the area with a combined maximum capacity of more than 2100 megawatts. More than two-thirds of this volume is covered by the Karaganda State Regional power plant 2 (743 MW) and the Karaganda TPS-3

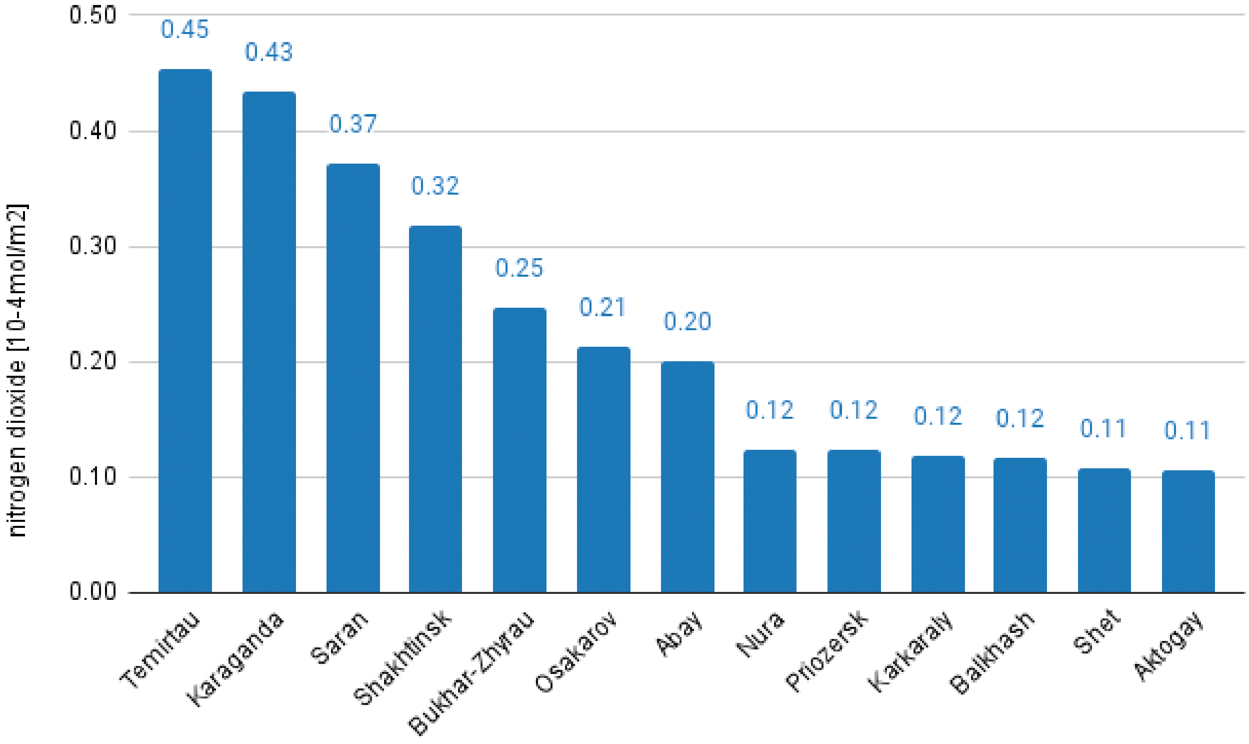

Fig. 36: Average NO_2 concentrations calculated for each district of the Karaganda Region using Sentinel-5P satellite data. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); HDX, 2022.

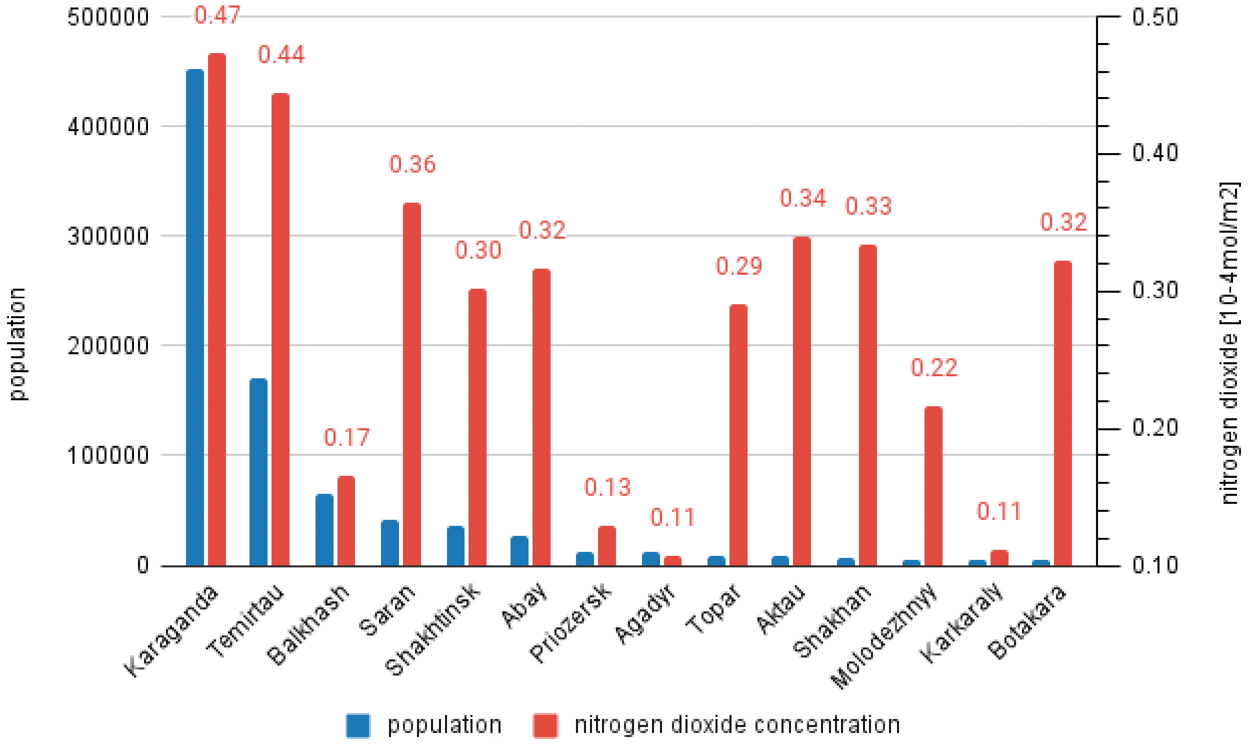

Fig. 37: Average concentrations of NO_2 calculated for cities and towns of the Karaganda Region with populations higher than 5000, using Sentinel-5P satellite data. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); HDX, 2022.

power plant (670 MW) (Global Energy Monitor, 2022).

However, the biggest polluter within this area and, at the same time, one of the biggest in Kazakhstan, is the ArcelorMittal Temirtau steel plant. The annual nominal capacity of this factory in terms of crude steel is approximately 6 Mt (Global Energy Monitor, 2022). The nearest house is 500 metres away from the factory (Arnika, 2022).

The average concentrations of NO_2 in the districts of the Karaganda Region are visualised in Fig. 36. The most polluted districts are Temirtau and Karaganda and the small mining towns of Saran and Shakhtinsk, located west of Karaganda, and the district of Bukhar-Zhyrau, covering the area around the city districts of Temirtau and Karaganda and the area between these cities and the regional border north-west of the cities.

Fig. 37 shows the relationship between population and NO_2 concentrations. In the graph the cities are listed from left to right by population. In the case of the first five cities, we can observe a linear relationship between the population of the cities and the amount of NO_2 in the atmosphere around them. A notable exception is the city of Balkhash, with relatively low NO_2 concentrations with respect to its population. On the other hand, there are towns such as Aktau, Shakhan, or Botakara, with a population of fewer than ten thousand inhabitants, which probably have high concentrations of NO_2 mainly because of the geographical proximity of the regional capital, Karaganda, and the city of Temirtau.

Methane (CH_4)

Fig. 38 shows the median concentrations of CH_4 in the Karaganda Region between May 2018 and December 2022. As the regional variability of the measured values is relatively low within the

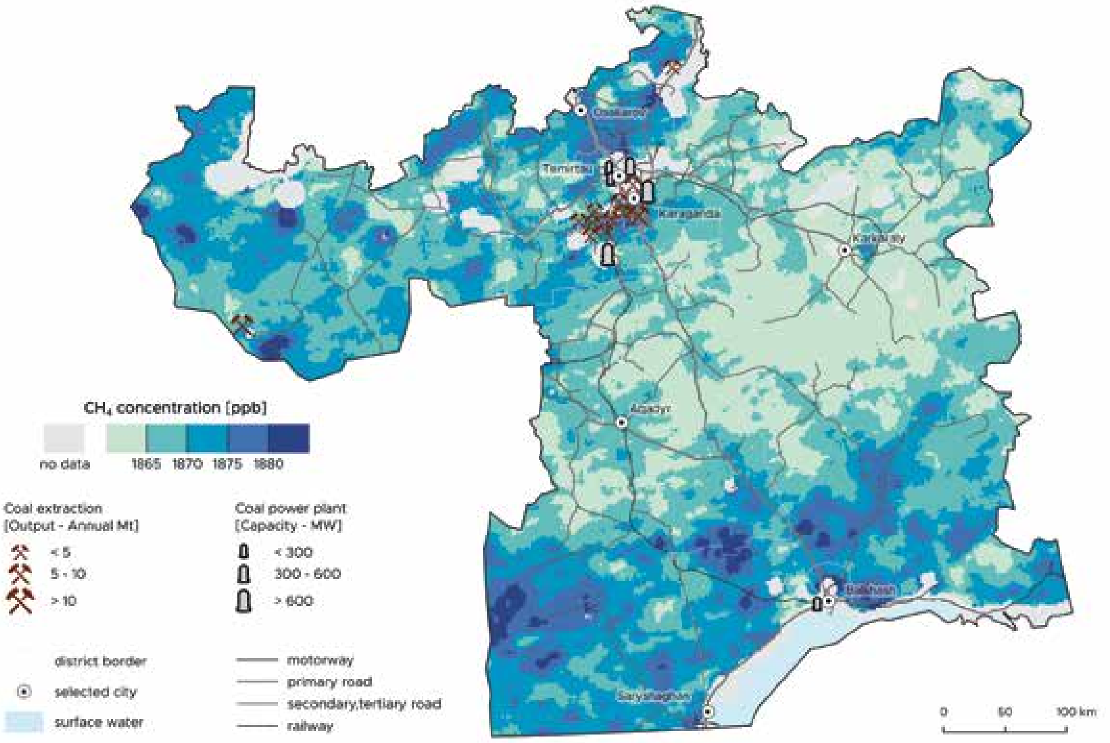

Fig. 38: Average CH_4 concentrations in the Karaganda Region between 2018 and 2022, obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022; Global Energy Monitor, 2022.

region, the values used in the colour scale have been adjusted to highlight the regional differences. The southern part of the region has comparatively higher concentrations, and so does the area around the regional capital and in the north-west of the region.

The districts with the highest CH4 concentrations in the Karaganda Region are Saran and Karaganda. Besides these two districts, the average concentrations are relatively stable at around 1870 ppb. The districts of Priozersk and Temirtau do not have any value in the graph for two reasons: 1) they are small in area and 2) they are located near a large body of water. As previously mentioned, there is a water mask applied to the CH_4 data measured by Sentinel-5P on the side of the data provider because of the quality issues over these areas. Because of the combination of the small size of these districts and their proximity to a body of water, there was not enough valid data to calculate statistics. The uncertainty of the CH_4 modelling over and around bodies of water has to be considered not only in the case of the Priozersk and Temirtau districts but also elsewhere, as there are many bodies of water in the region and even though measures were taken to limit data from these areas its effectiveness is affected by several factors, among which the most important is water freezing.

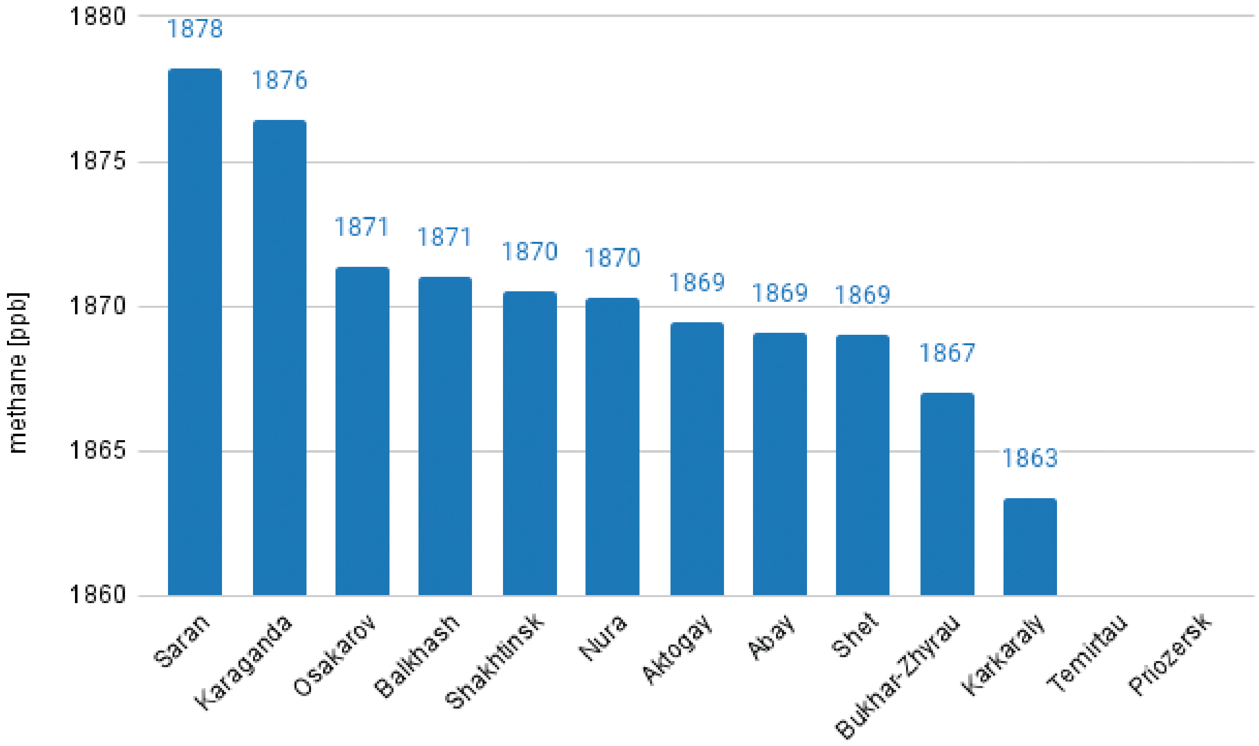

Fig. 39: Average CH_4 concentrations calculated for districts of the Karaganda Region using Sentinel-5P satellite data. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); HDX, 2022.

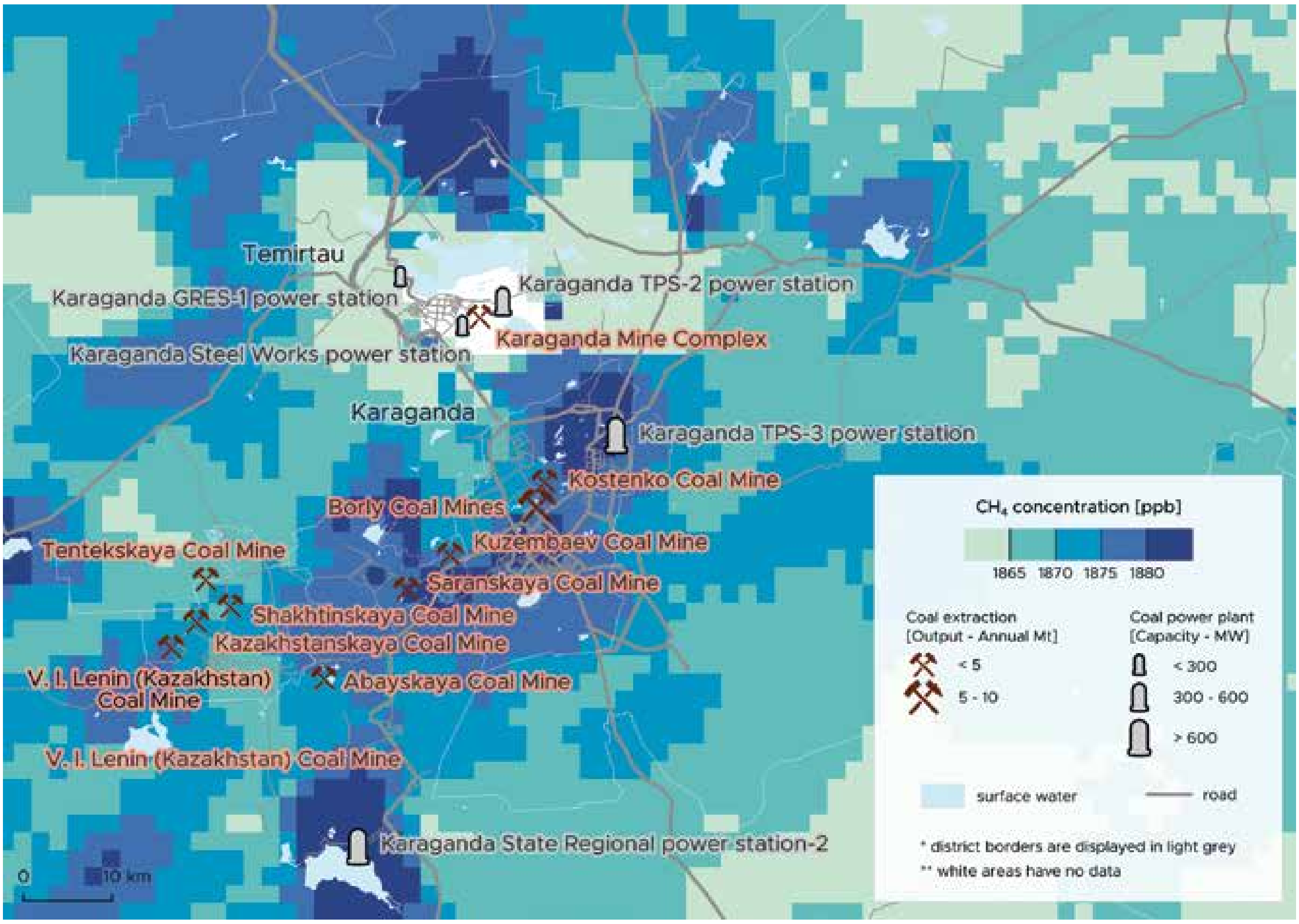

Fig. 40: Average CH_4 concentrations around the cities of Karaganda and Temirtau between 2018 and 2022, obtained from the Sentinel-5P satellite. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022; Global Energy Monitor, 2022.

Fig. 39 shows the average values for each district in the Karaganda Region. The highest concentrations are observed in the Karaganda and Saran districts.

If we take a more detailed look at the Karaganda district in Fig. 40, slightly elevated methane concentrations can be observed above coal mines and in the vicinity of coal-fired power plants – Karaganda Thermal Power Plant 3 and Karaganda State Regional Power Plant 2. However, the latter power plant is located near a body of water where methane concentrations may be affected by invalid data. In contrast, elevated methane levels are observed around the other three coal-fired power plants located north of the city of Karaganda.

Fig. 41 shows the relationship between population and CH_4 concentrations. In the graph the cities are listed from left to right by population. In the case of this pollutant, no pattern and no relationship with the number of inhabitants in a given city can be observed.

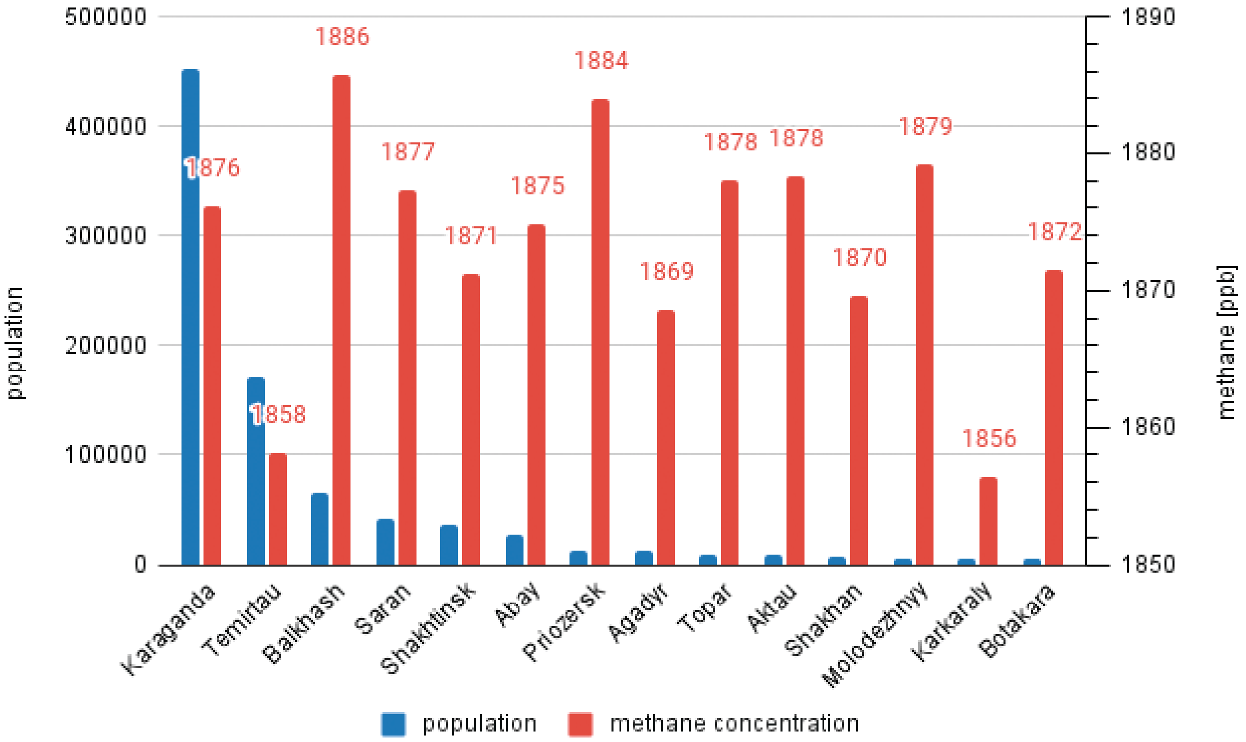

Fig. 41: Average CH_4 concentrations calculated for cities and towns of the Karaganda Region with a population higher than 5000 using Sentinel-5P satellite data. Sources: Copernicus Sentinel data (ESA, 2018–2022; modified); OpenStreetMap contributors, 2022; HDX, 2022.

Sulfur dioxide (SO_2)

In Fig. 42, SO_2 concentrations in the Karaganda Region measured between May 2018 and December 2022 can be observed. A similar regional distribution of pollution concentrations can be identified as in the case of NO_2. The highest concentrations are centred around the two largest cities of the region – Karaganda and Temirtau. As mentioned above, this area is a centre of coal mining and other industrial activities in the region. However, because of the lower spatial resolution of the SO_2 model data, the palette is not as detailed in the pollution distribution. But it is still possible to observe a north-easterly direction of increased concentrations from the town of Karaganda to the town of Ekibastuz.

Average concentrations of SO_2 in the districts of the Karaganda Region are visualised in Fig. 43. The Temirtau district has the highest average concentration. Very similarly high concentrations were also detected in the Karaganda, Saran, and Shakhtinsk districts. In other districts, lower values are detected.

Fig. 44 shows the relationship between population and SO_2 concentrations. In the graph the cities are listed from left to right by population. In the

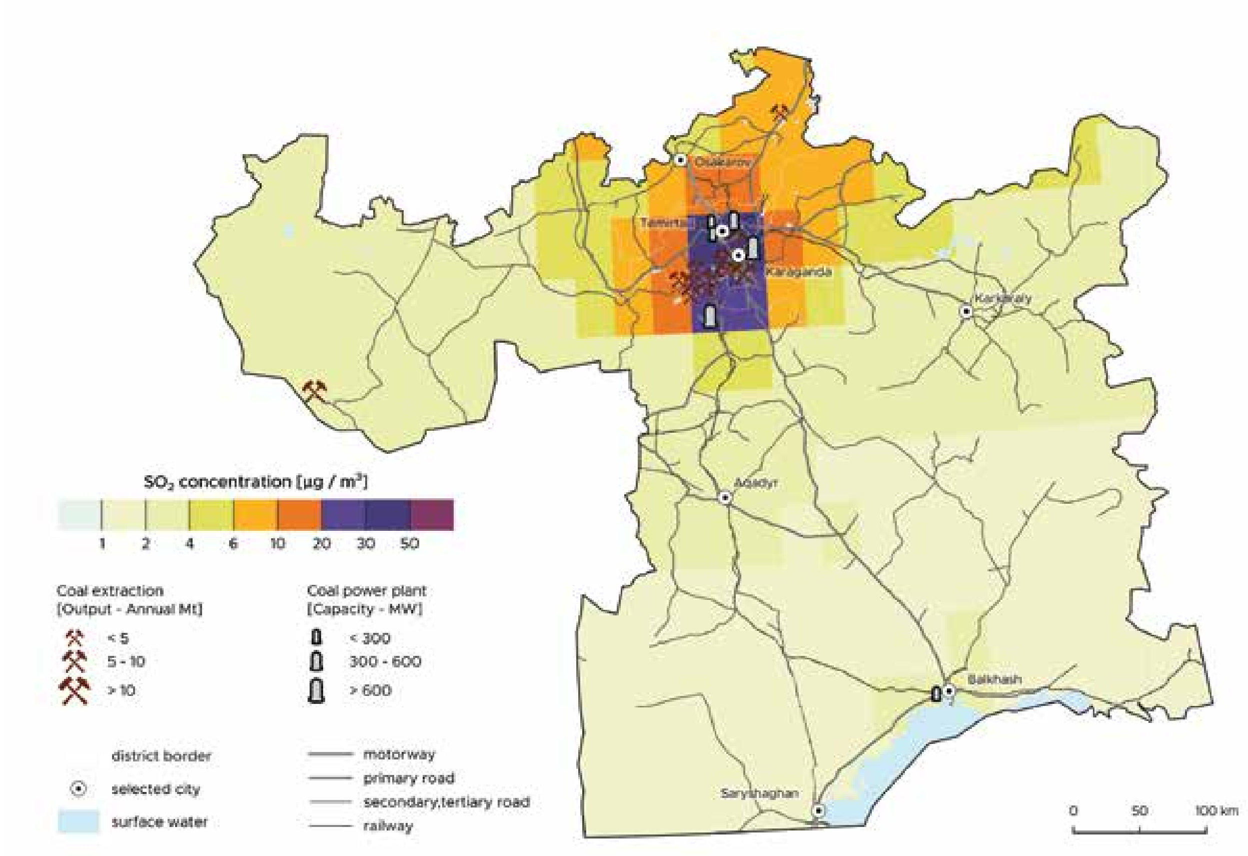

Fig. 42: Average SO2 concentrations in the Karaganda Region between 2018 and 2022, obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022; Global Energy Monitor, 2022.

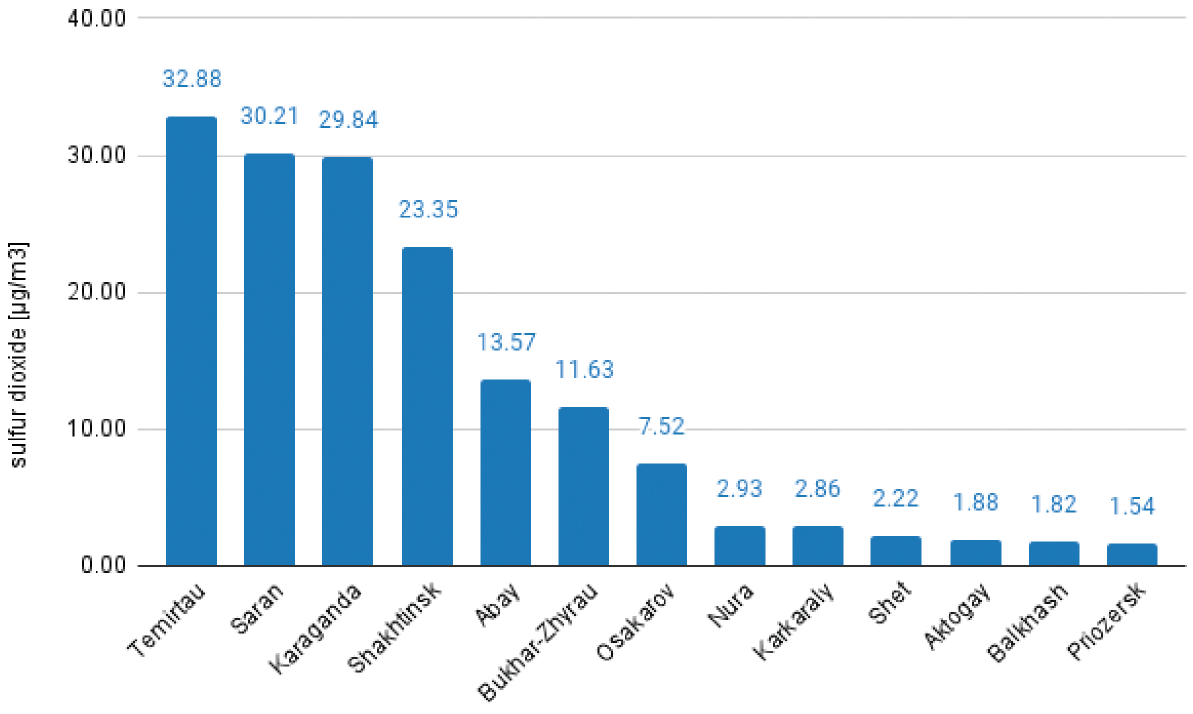

Fig. 43: Average SO$_2$ concentrations calculated for each district of the Karaganda Region, obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022; HDX, 2022.

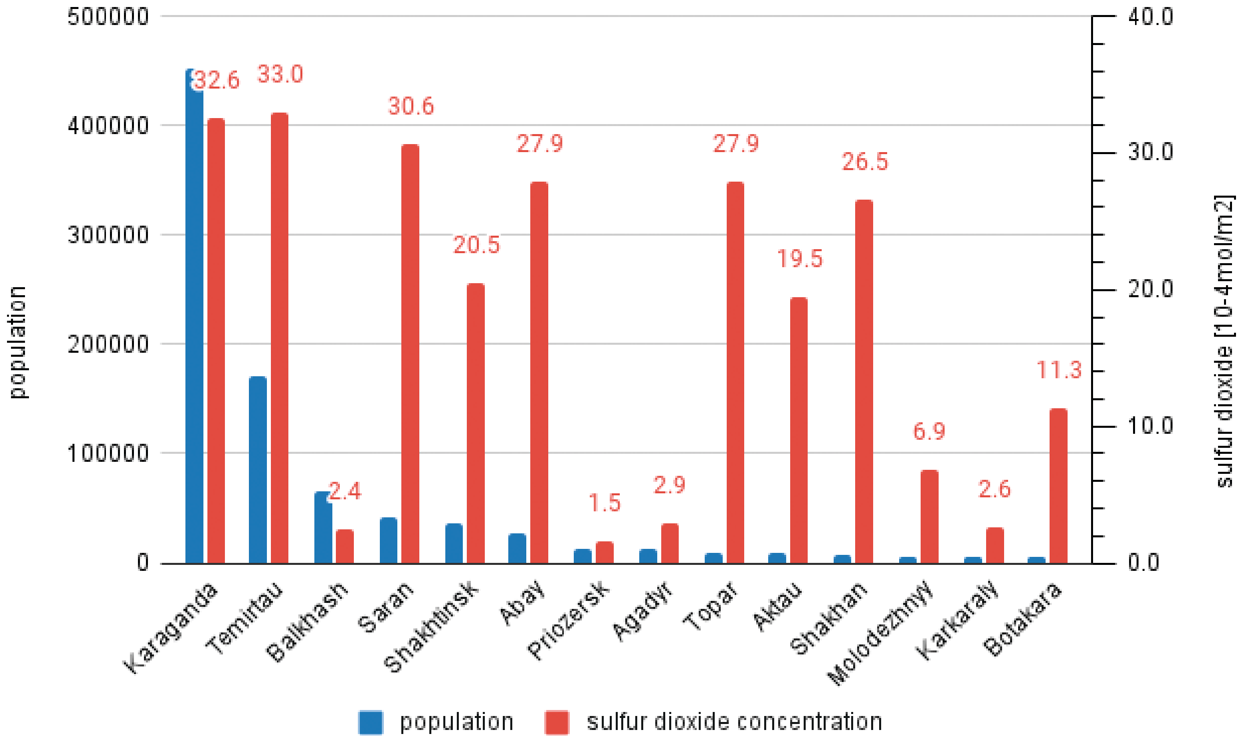

Fig. 44: Average SO2 concentrations calculated for cities and towns of the Karaganda Region with a population higher than 5000, obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022; HDX, 2022.

case of this pollutant, no pattern and no relationship with the number of inhabitants in a given city can be observed. In most cities, concentrations reach high levels. Seven of them exceed the WHO daily limits – 20 µg/m^3 (Karaganda, Temirtau, Saran, Abay, Shakhtinsk, Topar, Shakhan).

The analysis does not reveal an increase in concentrations over the city of Balkhash, although Assanov (2021) classifies it as a pollution hotspot. Despite the presence of the Balhashcvetmet Ferrous Metallurgy plant in the region, which is known for its potential to generate pollution, the analysis does not indicate a corresponding increase in concentrations over the city of Balkhash.

Particulate matter (PM$_{10}$)

In Fig. 45, both anthropogenic and natural influences on the distribution of PM$_{10}$ concentrations can be observed. As mentioned in the chapter focusing on the distribution of PM$_{10}$ throughout Kazakhstan, much of the territory is influenced by natural sources of PM$_{10}$. Especially in the summer months, concentrations of this pollutant increase almost throughout the southern part as a result of the bare land cover. The Karaganda Region is located at the interface of this significant natural source. Therefore, elevated values related to natural origin can be observed in the southern part of the region. On the contrary, in the northern part, a significant anthropogenic influence can be observed. The combination of mining, metallurgy, and coal power plants increases PM$_{10}$

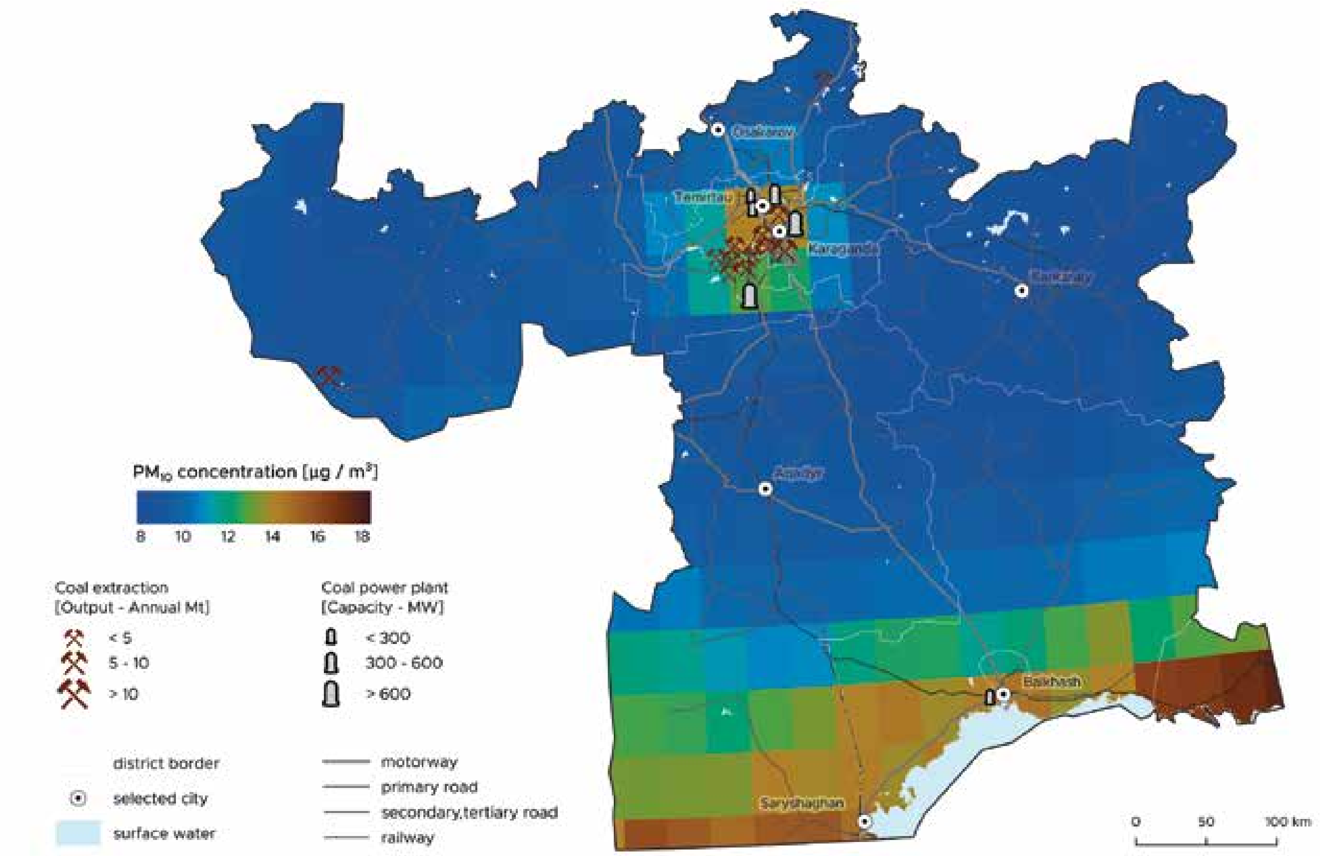

Fig. 45: Average PM$_{10}$ concentrations in the Karaganda Region between 2018 and 2022, obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022; Global Energy Monitor, 2022.

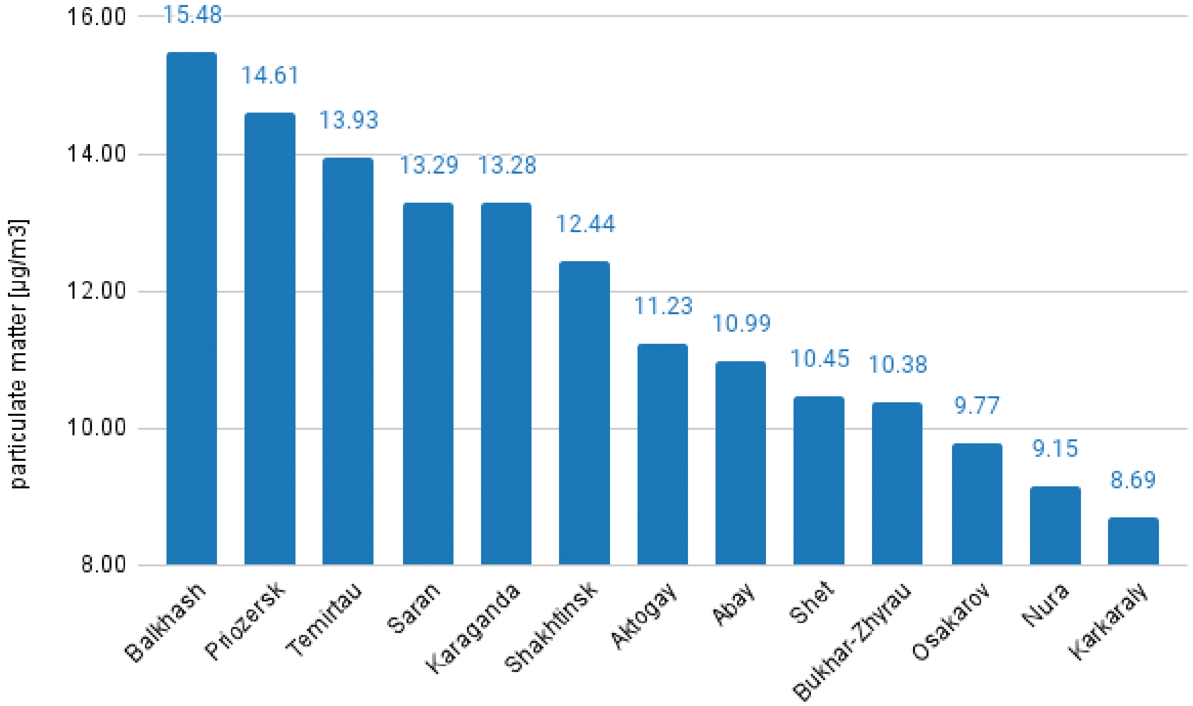

Fig. 46: Average PM$_{10}$ concentrations calculated for each district of the Karaganda Region using the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022; HDX, 2022.

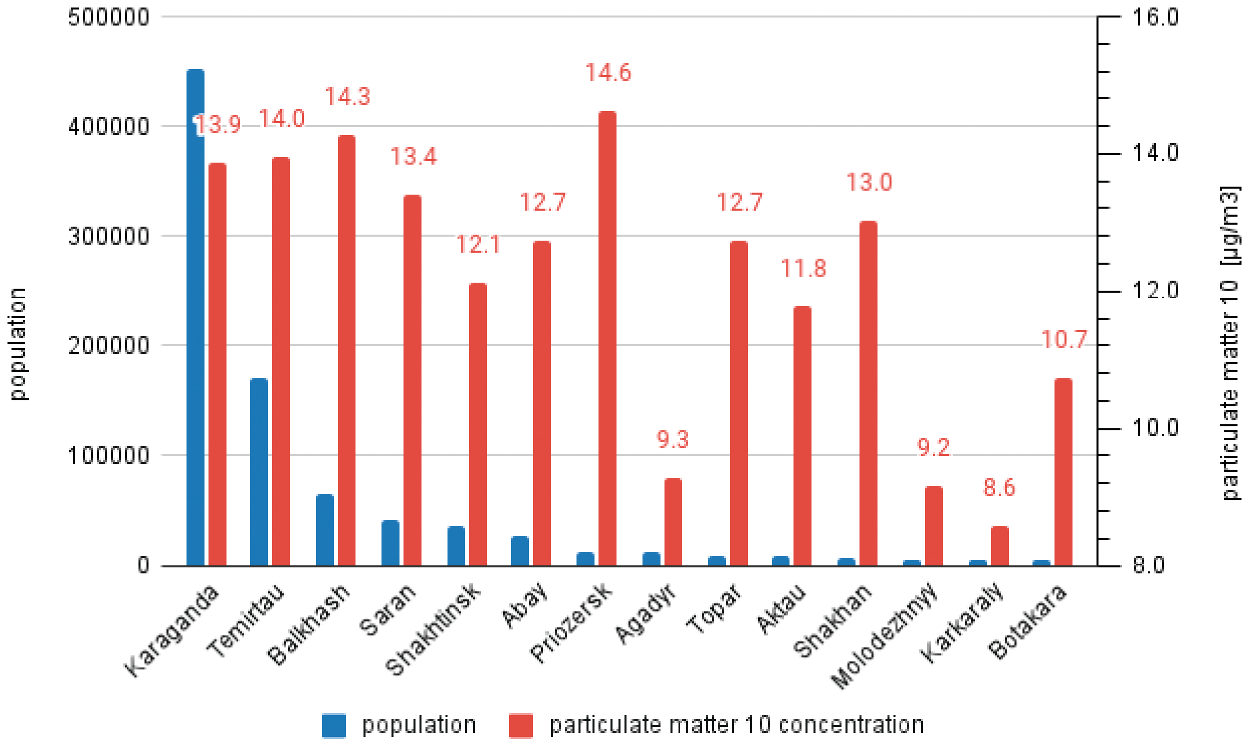

Fig. 47: Average PM_{10} concentrations calculated for cities and towns of the Karaganda Region with a population higher than 5000, obtained from the Copernicus Atmosphere Monitoring Service. Sources: Copernicus Atmosphere Monitoring Service data (CAMS, 2022); OpenStreetMap contributors, 2022); HDX, 2022.

concentrations around the cities of Karaganda and Temirtau all year round.

The average PM_{10} concentrations per district within the Karaganda Region can be observed in Fig. 46. As mentioned above, the districts around the city of Karaganda and Temirtau reach the highest concentrations because of anthropogenic sources of pollution. Conversely, districts located in the south achieve high values because of natural factors.

Fig. 47 shows the relationship between population and PM_{10} concentrations. In the graph the cities are listed from left to right by population. It can be observed that for most cities PM_{10} concentrations are comparable to each other. In contrast to the previous pollutants, towns in the south of the Karaganda Region also reach high levels. In Balkhash, the likely reason for this is the activities of Balhashcvetmet Ferrous Metallurgy, as well as other natural sources. In Priozersk, it is primarily attributed to natural sources.

RECOMMENDATIONS

Air pollution and climate change are firmly interconnected, with both posing significant risks to human health, ecosystems, and economic stability. The impacts of these issues are felt globally, but are especially visible in resource-rich nations such as Kazakhstan. Recognising the complex situation, Kazakhstan updated its environmental protection code in 2021. This amendment solidifies the country's commitment to mitigating air pollution through the adoption of best available technologies (BAT) as cited by the IEA in 2022, and charts its path towards achieving carbon neutrality by 2060. Additionally, 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.

However, the large reserves of earth materials in Kazakhstan have historically steered its economy towards mining, resource processing, and heavy industries. While these sectors have been instrumental in driving economic growth, they also intensify the challenges related to improving air quality and addressing climate change mitigation. As the nation copes with this duality, the interplay between its economic drivers and environmental commitments is becoming crucial. The sections below delve into the recommended strategies to harmonise these objectives.

Strengthen air quality monitoring and data collection

The National Hydrometeorological Service of Kazakhstan (Kazhydromet) is responsible for owning and operating the National Air Quality Monitoring Network (NAQMN) in Kazakhstan. As there is a limited number of measuring stations, it is essential to **expand the monitoring infrastructure** by establishing more strategically located stations in urban, industrial, and rural areas, including near the major pollution sources mentioned in this study.

These stations should be equipped with high-quality instruments capable of measuring a wide range of pollutants accurately. Regular maintenance, calibration, and quality assurance procedures are crucial to ensure reliable data. Enhancing data quality and validation through standardised measurement techniques and robust quality control protocols is also necessary. 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.

Leveraging the potential of **citizen monitoring networks** such as AirKaz.org can provide additional insights into the problem. By engaging the public to contribute data on air pollution through various tools and applications, a larger volume of data can be collected, offering a more comprehensive understanding of the air quality landscape across different areas. Moreover, data reporting should be accessible and user-friendly, with real-time data made available through online portals and mobile platforms.

Regular utilisation of satellite monitoring and data from services such as the Copernicus Atmosphere Monitoring Service can provide a broader perspective on the overall progress and spatial-temporal changes in pollution distribution, including the problem with transborder polluters.

Ramp down coal use and renewable energy deployment

The key activities should focus on **preventing the building of new fossil fuel power plants**, gradual reduction of the share of fossil fuels, and diversification of the energy production among renewable sources.

On the evidence of examples from coal transition regions in the EU and US, it is important to initiate engagement with businesses and communities affected by the coal industry to develop a **comprehensive plan for gradually reducing coal consumption** as soon as possible. This plan should align with the country's climate targets and transition towards cleaner energy sources. Collaboration with coal plant operators, miners, and relevant stakeholders is essential to ensure a just, fair, and smooth transition. (World Bank, 2022)

A phased retirement approach can be adopted for coal plants, with consideration being given to their economic life and the availability of alternative energy sources. Planning for the exit of coal plants and coal mines should take into account the **upstream impact on the coal mining sector**, including potential job losses and the need for alternative livelihood opportunities for the communities that are affected. Support programmes, such as retraining initiatives and diversification of local economies, should be implemented to start facilitating a successful transition away from coal.

Given Kazakhstan's heavy reliance on oil and gas production, it is crucial to focus on maximising the decarbonisation of this sector. Efforts should be made to **maximally reduce flaring and venting**, as well as minimise leaks during the handling and transportation of oil and gas products. Preferably, the country's natural gas reserves could be utilised as a transitional fuel towards renewable energy sources. The country can explore the potential of using gas to balance the fluctuations in renewable energy generation, especially in areas with solar and wind energy potential, such as desert regions.

Investing in solar and wind farms, along with improving the transmission and energy storage infrastructure, can facilitate the speedy integration of renewable energy sources into the grid. To attract business interest in the renewable energy sector, it is recommended to establish supportive policies, feed-in tariffs, and investment incentives to attract private sector involvement in renewable energy projects.

A specific focus should be put on **efficient district heating and cooling** to support a clean and decarbonised heat and cooling supply. There is a pressing need to prioritise the renovation and improvement of residential, commercial, and public buildings in terms of energy efficiency. Approximately 55% of residential houses in Kazakhstan rely on individual heating systems, with coal accounting for 55% of these systems, followed by gas at 35%, and other fuels at 10%. In smaller towns, central heating infrastructure is nonexistent, further contributing to the prevalence of individual heating methods. Moreover, a significant percentage of residential buildings, particularly panel housing, lack proper insulation and energy-saving measures. Upgrading heating systems, enhancing insulation, and promoting energy-efficient practices can contribute to reducing energy consumption and improving indoor air quality.

In addition, attention should be paid to smaller towns and cities where the central heating infrastructure is insufficient or unavailable, leading to a higher dependence on individual heating systems fuelled by coal and other pollutants. **Introducing centralised heating systems** or alternative clean energy options can help address this issue and improve energy efficiency on a larger scale. The government, in cooperation with regional authorities, should also explore the establishment of subsidy programmes to assist individual homeowners in enhancing their insulation and heating systems. Funds accrued from pollution-related charges could be allocated for this initiative.

Regulatory frameworks, environmental liability, and local emission inventories

In recent years, Kazakhstan has accelerated its efforts towards more empathetic and uniform environmental policies with the adoption of international climate policy resolutions (e.g. Concept on Transition to Green Economy, Strategy Kazakhstan 2050, or Carbon Neutral Kazakhstan 2060), inter-organisational collaboration, and the updating of the Environmental Code.

Despite the presence of legislation, its implementation and **enforcement remain weak**, and there is inadequate collaboration among different government bodies and organisations, including ministries, which hinders the practical implementation of frameworks. The methods used to establish emission limit values (ELVs) are associated with insufficient environmental quality standards, and there is a lack of monitoring and enforcement of these standards. (Assanov, 2021)

Therefore, it is now vital to strengthen the capacity of the regulatory agencies responsible for environmental protection to enforce the proposed air quality standards and regulations effectively. This requires the allocation of adequate resources, including funding, staffing, training, and technical equipment. Emphasis should be also put on enforcing the legislation which is bound to advances against lobbying and corruption activities. Regular inspections and audits of industries, power plants, and other pollution sources should be performed to verify compliance with environmental regulations. **Stringent but proportional penalties for non-compliance** with air quality standards and regulations should raise awareness among industries and the public about the consequences of non-compliance.

In order to tackle the issue of cross-border emissions from places such as Chelyabinsk, Magnitogorsk, or Tashkent, Kazakhstan should prioritise **establishing bilateral agreements with Russia and Uzbekistan**. These agreements should focus on setting emission reduction targets, sharing information on industrial activities, and implementing joint monitoring and enforcement mechanisms. Additionally, Kazakhstan should enhance its own air quality monitoring systems, particularly in regions prone to cross-border emission overflows.

Local government bodies can utilise emission inventories as a tool to identify significant sources of air pollutants and guide their activities towards addressing the issue. The comprehensive understanding and quantification of local sources of air pollution enable stakeholders to identify key sectors that require rapid and cost-effective mitigation measures. This is particularly crucial for industrial centres and urban areas, where emission inventories should precede the planning of targeted interventions. The development of **clean air plans** at the municipal and regional levels, based on up-to-date inventories, serves as an effective tool for achieving long-term improvements in air quality. These plans should outline specific measures and strategies to be implemented in the upcoming five years.

PM_{10} pollution will remain a persistent challenge in Kazakhstan because of natural factors, including vast areas with limited vegetation cover that facilitate the easy transportation of particles, often in the form of dust storms. However, Kazakhstan can contribute indirectly to combating this problem by focusing on initiatives to **combat climate change and desertification** in other regions.

Energy efficiency and emission control measures for industries

Heavy industry and energy generation in Kazakhstan have the biggest impact on air quality and human health. The challenge arises from **heavy industries or power plants often being in close proximity to cities or even within them**. This highlights the importance of installing high-performance filters and adhering to strict standards.

Implementing **financial instruments** backed by strong energy efficiency rules and obligations based on World Bank recommended policies (World Bank, 2022) can significantly reduce energy consumption and associated emissions in key sectors such as building renovation, industrial processes, and transportation. This should involve promoting energy-efficient equipment, retrofitting buildings, and implementing smart transportation solutions, all of which contribute to reducing air pollution.

Creating an attractive investment environment through incentives such as tax breaks, subsidies, and streamlined administrative processes can encourage private investment in energy efficiency. Any financial support and incentives for industries should be tied to the use of the **best available techniques (BAT)** and the transition to low-carbon processes. Establishing green funding programmes specifically targeted at reducing industrial emissions and supporting the adoption of clean technologies is recommended in order to facilitate these activities.

Encouraging the adoption of **energy management systems**, such as ISO 50001, can help industries in monitoring and optimising their energy consumption. By implementing effective energy management practices, companies can identify energy-saving opportunities, set energy reduction targets, and continuously improve their energy performance.

Sector-specific roadmaps for the reduction of emissions should outline key steps, milestones, and targets for transitioning to more sustainable production. Proper support and technology transfer from international institutions such as the OECD or World Bank can provide guidance and technical support in the development of these roadmaps and progress monitoring. Support for research and development initiatives focused on developing innovative solutions for the reduction of emissions in industries will also foster international competition and provide new business opportunities.

In this regard, Kazakhstan should establish a functional **Pollution Release and Transfer Register** (PRTR) that aligns with the standards outlined in the PRTR Protocol of the Aarhus Convention, which Kazakhstan ratified in 2020. Regular submissions from major polluting entities should undergo verification and be accessible to the public online. The results should affect government systems at different levels, such as state standards of ecological safety, procedures for issuing legal permits for emissions of pollutants, or state regulatory policy.

In areas where consistent monitoring indicates breaches of permissible pollution thresholds, stronger limits must be enforced, accompanied by the issuance of **emission quotas**. These predetermined caps should not only address the existing emission volumes but also proactively deter the introduction of new emission sources.

Public awareness and participation

Public awareness of air quality in Kazakhstan is generally low. Ensuring public access to information is crucial, including data from the state air quality monitoring, timely smog warnings, and details regarding the operation of major pollution sources. It is important for the government to **actively involve the public in decision-making processes**, such as spatial planning and the approval of clean air plans at the municipal and regional levels, as well as conducting Environmental Impact Assessments (EIAs) and permitting procedures for industrial facilities. Public engagement not only has positive effects *Shy* but also helps overcome potential opposition from the public, political entities, or commercial interests regarding planned pollution reduction measures. There should be a further emphasis on public involvement in monitoring the use of state environmental funds, such as revenues from polluter fees or emission trading schemes.

In Kazakhstan there is a significant reliance on passenger car transport, often consisting of old models with poor fuel efficiency. This contributes to air pollution, particularly in cities such as Almaty, Astana, Shymkent, and Pavlodar, where high concentrations of NO_2 and SO_2 were observed. Furthermore, there is widespread use of highly polluting heating methods, including coal, gas, biomass, and heating oils. These practices have a significant impact on air quality and contribute to pollution in residential areas and urban centres. It is essential to address these issues by promoting **public awareness campaigns** and educating the public about the importance of sustainable transportation options, adopting cleaner heating practices in private households, promoting energy conservation, and discouraging the burning of biomass. Government initiatives and incentives can play a crucial role in supporting the transition.

Additionally, establishing an **early warning system** to alert the authorities and the public about such events would prove beneficial in taking timely preventive measures and minimising the adverse effects on air quality and human health. To encourage public participation in decision-making processes and engage stakeholders in the development and implementation of air pollution control measures, user-friendly platforms and tools for accessing and understanding environmental data are crucial.

Specific recommendations for the Karaganda Region

To improve air quality in the Karaganda Region, it is essential to prioritise efforts towards the **coal-related industries** in the area. Specifically, a key focus should be on incentivising coal power stations to adopt advanced pollution control technologies and enforce strict emission standards. For instance, encouraging coal power stations to invest in state-of-the-art flue gas desulphurisation systems, electrostatic precipitators, or fabric filters can capture and remove pollutants effectively before they are released into the atmosphere. These technologies are designed to trap substances such as sulphur dioxide, particulate matter, and other harmful components, thereby mitigating their impact on air quality.

It is also vital to address the issue of coal mines, especially taking measures to mitigate **dust emissions from mining operations**. This can include technologies improving dust suppression, utilising enclosed conveyor systems, and establishing stringent monitoring and enforcement mechanisms. Regular monitoring of dust levels and conducting inspections can help identify areas that require improvement and enable prompt corrective measures to be taken. Additionally, there should be a system in place to monitor the compliance of coal sold on the retail market, which is currently flooded with low-quality surrogates of indeterminate quality.

The **metallurgical industry**, especially steel mills, ferroalloy facilities, and copper smelters, should be specifically addressed as well. Encouraging the adoption of cleaner production technologies, such as electric arc furnaces instead of traditional blast furnaces, can significantly reduce emissions of pollutants such as particulate matter, sulphur dioxide, and nitrogen oxides.

Alongside these measures, it is important to **improve monitoring efforts** in the region. Enhancing the air quality monitoring network by strategically locating monitoring stations equipped with high-quality instruments can provide accurate and real-time data on pollutant levels. This data can then be used to assess the effectiveness of pollution reduction measures and identify areas that require further attention.

As described in detail in the general recommendation section, local government should **involve citizens in decisions** such as spatial planning, approving local clean air plans, conducting EIAs, and permitting industrial activities. Such engagement fosters transparency, mitigates opposition, and allows oversight of fund use.

Obsolete technologies in heavy industry, not complying to the up-to-date standards, are one of the main reasons of excess air pollution. ArcelorMittal Temirtau. (Photo: Ondrej Petrlik / Arnika)

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https://arnika.org

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https://ecomuseum.kz

EcoMuseum was established in Karaganda in 1995. Its mission is to collect and disseminate environmental information on the territory of Central Kazakhstan to increase the role of the public in solving urgent environmental issues and in development of democratic processes in the society. EcoMuseum focuses on raising public awareness, involvement of the public in environmental protection actions, research and introduction of environmentally sound technologies.

https://worldfrom.space

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Lake Balkhash and the Kazakhmys copper smelter, which is the main source air pollution in the area (Photo: Ondrej Petrlik / Arnika)

ArcelorMital Temirtau is one of the largest sources of air pollution throughout the country. View from the Samarkand Reservoir. (Photo: Ondrej Petrlik / Arnika)

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