

# KARTIRANJE PROSTORSKE PORAZDELITVE ONESNAŽEVAL ZRAKA V PROVINCII QUANG NINH (VIETNAM) NA PODLAGI PODATKOV SENTINEL 5P

# MAPPING THE SPATIAL DISTRIBUTION OF AIR POLLUTANTS IN QUANG NINH PROVINCE (VIETNAM) USING SENTINEL 5P DATA

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## IZVLEČEK

Vietnam je država z bogatim rudnim bogastvom, pri čemer so zaloge premoga, ki znašajo približno 8,6 milijarde ton, skoncentrirane predvsem v premogovnem bazenu province Quang Ninh. Poleg gospodarskih in družbenih koristi ima premogovništvo tudi negativne vplive na okolje, kot sta onesnaževanje zraka in vode. Onesnaženost zraka na območjih premogovništva resno vpliva na zdravje ljudi in okolje. V študiji so predstavljeni rezultati kartiranja četrtletnih kart prostorske porazdelitve onesnaževal zraka v provinci Quang Ninh, vključno s CO, NO<sub>2</sub>, O<sub>3</sub> in SO<sub>2</sub>, na podlagi podatkov Sentinel 5P TROPOMI. Podatki Sentinel 5P TROPOMI o četrtletnih koncentracijah onesnaževal zraka v celotnem letu 2023 so bili zbrani s platformo za računalništvo v oblaku Google Earth Engine (GEE) in nato povprečeni po četrtletjih. Rezultati ocene onesnaženosti zraka iz podatkov daljinskega zaznavanja so primerjani z mejnimi vrednostmi osnovnih parametrov v zraku v predpisu QCVN 05:2013/BTNMT (Državni tehnični predpis o kakovosti zraka). Analiza rezultatov kaže, da vse koncentracije CO, NO<sub>2</sub>, O<sub>3</sub> in SO<sub>2</sub> v provinci Quang Ninh leta 2023 presegajo predpisane v QCVN, zlasti v južni regiji, kjer so skoncentrirani veliki premogovniki. Rezultati študije zagotavljajo pravočasne informacije, ki upravljavcem pomagajo spremljati kakovost zraka na območjih premogovništva.

## KLJUČNE BESEDE

onesnaževala zraka, daljinsko zaznavanje, premogovnik, Sentinel 5P TROPOMI, provinca Quang Ninh, Vietnam

## ABSTRACT

Vietnam is a country with rich mineral resources, of which coal reserves are about 8.6 billion tons, concentrated mainly in the coal basin of Quang Ninh province. Besides the economic and social benefits, coal mining has negative impacts on the environment, such as air and water pollution. Air pollution in coal mining areas seriously affects human health and the environment. This study presents the results of mapping the quarterly spatial distribution maps of air pollutants in Quang Ninh province, including CO, NO<sub>2</sub>, O<sub>3</sub> and SO<sub>2</sub> from Sentinel 5P TROPOMI data. Sentinel 5P TROPOMI data on four air pollutant concentrations in the entire year 2023 was collected using the Google Earth Engine (GEE) cloud computing platform and then averaged over the quarters. The results of air pollution assessment from remote sensing data are compared with the limit values of basic parameters in the air in QCVN 05:2013/BTNMT National technical regulation on air quality. Analysis of the achieved results show that the concentrations of CO, NO<sub>2</sub>, O<sub>3</sub> and SO<sub>2</sub> in Quang Ninh province in 2023 are all high compared to regulations in QCVN, especially in the southern region where large coal mines are concentrated. The results received in this study provide timely information to help managers monitor air quality in coal mining areas.

## KEY WORDS

air pollutants, remote sensing, coal mine, Sentinel 5P TROPOMI, Quang Ninh province, Vietnam

## 1 INTRODUCTION

Vietnam has big reserves of fossil energy with 10 billion tons of anthracite coal, more than 200 billion tons of brown coal in the northern delta area (Luu & Nguyen, 2009). Coal has served as a fundamental pillar in energy production in Vietnam for decades, providing energy for industries and human activities. Despite its important role in socio-economic development, coal exploitation and use has caused negative impacts on the environment and public health (Gopinathan et al., 2023). The environmental consequences of coal extraction and transportation are extensive, changing land cover and polluting the air and water. Air quality in many coal mining areas around the world has seriously degraded, greatly affecting the health of surrounding people (Krishnan et al., 2022; Li et al., 2023; Trinh, 2016; Xia et al., 2022). Air pollution from coal mines is mainly due to the emission of particulate matter and gases, in which the major air pollutants are methane ( $\text{CH}_4$ ), sulfur dioxide ( $\text{SO}_2$ ), carbon monoxide (CO) (Trenchev et al., 2023) and oxides of nitrogen ( $\text{NO}_x$ ) (Chen et al., 2018). Estimating and monitoring the concentration of air pollutants in coal mining areas is an urgent issue, providing timely information to help managers respond to environmental pollution.

Traditional research methods have used in situ data at measuring stations to evaluate air pollution. However, this method has major limitations because the number of observation stations is not large enough, leading to incomplete information on the distribution of air pollutants. Since the beginning of the 21st century, many studies have used remote sensing data such as Landsat and MODIS multispectral images to monitor air pollution in big cities (Ozelkan et al., 2015; Jivani, 2017; Saraswat et al., 2017; Liang, Gong, 2020) as well as mineral exploitation areas (Huertas et al., 2012; Saini et al., 2016; Oparin et al., 2017; Xia et al., 2022). Most of these studies evaluate dust pollution (mainly PM10 parameter) in coal mining areas based on the relationship between atmospheric reflectance determined from remote sensing images and dust content in the air. However, multispectral remote sensing data such as Landsat and MODIS images are not effective in estimating the concentration of other air pollutants, including  $\text{CH}_4$ , CO,  $\text{NO}_x$ , and  $\text{SO}_x$ ..., because these parameters do not have a close relationship with atmospheric reflection.

Sentinel-5 Precursor (Sentinel-5P) is the first Copernicus mission dedicated to monitoring the atmosphere. Sentinel-5P carries a single instrument TROPOMI (TROPOspheric Monitoring Instrument) to map a multitude of trace gases such as nitrogen dioxide, ozone, formaldehyde, sulphur dioxide, methane, carbon monoxide and aerosols (ESA, 2024). These characteristics of Sentinel 5P satellite data allow us to overcome the limitations of other optical remote sensing data in air pollution monitoring. With high temporal resolution and wide coverage area, Sentinel 5P data has been widely and effectively used in monitoring the concentration of air pollution parameters in many different regions of the world (Amiri et al., 2023; Hassaan et al., 2023; Halder et al., 2023; Mehrabi et al., 2023). Many studies also use Sentinel 5P data to monitor the changes in air quality under the influence of the Coronavirus Pandemic, which shows that the air quality in many largest cities has improved significantly under conditions of pandemic lockdown (Mejia et al., 2023; Morozova et al., 2022; Pham & Phan, 2024; Virghileanu et al., 2020).

Sentinel 5P data is also used in mapping the spatial and temporal distribution of air pollutants such as  $\text{CH}_4$ , CO,  $\text{NO}_2$ ,  $\text{SO}_2$ , HCHO in coal mining areas. Trenchev et al. used Sentinel 5P data

for 2018-2022 to detect large-scale CH<sub>4</sub>, NO<sub>2</sub> and CO emissions from coal mines in the Kuznetsk basin (Kemerovo region), the largest coal mining region in Russia. The results showed that methane (CH<sub>4</sub>) emissions from coal mines worldwide were higher than those from the oil and gas industry (Tranchev et al., 2023). The study (Peng et al., 2023) also used Sentinel 5P data in monitoring methane emissions in the coal mining area in Shanxi (China). Analysis of data from more than a thousand individual coal mines in Shanxi province shows that the estimated emission factor increases significantly with coal mining depth and that ongoing deeper coal mining increases emissions intensity of coal mine methane in the future (Peng et al., 2023). In Europe, Sentinel-5P satellite data has been used to detect methane plumes over some largest methane-emitting coal mines. According to the European Commission and the European Environment Agency, the 10 largest coal mines in Europe (all in Poland) emitted about 282,300 tons of methane into the atmosphere in 2020 (ESA, 2022). In Vietnam, up to now there have been a number of studies using Sentinel 5P satellite data to monitor the concentration of air pollutants in some large cities such as Hanoi capital (Do et al., 2022), Thai Nguyen city (Luu et al., 2023) construction material exploitation area in Mong Cai city, Quang Ninh province (Luong et al., 2023). The above studies show the advantages of Sentinel 5P TROPOMI data in monitoring the changes in air quality and mapping the spatial-temporal distribution of air pollutants.

This article presents the results of mapping the concentration distribution of air pollutants in the Quang Ninh coal mining area, the largest coal basin in Vietnam, from Sentinel 5P satellite data. Sentinel 5P TROPOMI data in the study area in 2023 was collected to build quarterly and annual average concentration maps for 4 air pollutants, including CO, NO<sub>2</sub>, O<sub>3</sub> and SO<sub>2</sub>. Methane (CH<sub>4</sub>) and formaldehyde (HCHO) data in the study area are not enough for quarterly analysis, so they will not be presented in this article. The results received in the study are objective and timely information, helping managers monitor and respond to air pollution in coal mining areas. In addition, the concentration distribution maps of air pollutants can also be used as input data for environmental models.

## 2 MATERIALS AND METHODOLOGY

### 2.1 Study area and Materials

**Study area.** Quang Ninh is a province located in northeastern Vietnam, at geographical coordinates from 20°40' to 21°39'49.8" north latitude and from 106°26' to 108°31' east longitude (Figure 1). Quang Ninh has a natural area of 6,120,79 km<sup>2</sup> and a population of nearly 1,400,000 people in 2022. The province has a border of more than 118 km with China and has a coastline of 250 km. Quang Ninh has rich mineral resources, most notably coal reserves accounting for 95% of the country's coal reserves (coal reserves of about 8.8 billion tons).

With huge coal resources, Quang Ninh has become the largest coal mining and power production center in Vietnam (Quang Ninh Portal, 2024). In the period 2016 - 2021, on average each year, Vietnam exploits and consumes about 39 - 42 million tons of raw coal, of which the majority is in the Quang Ninh coal basin. Besides the benefits it brings to local socio-economic development, coal mining also negatively affects the environment in Quang Ninh. Open-pit mining sites generate large amounts of dust and toxic

gases from the mining sites. In addition, increasing the area and scale of waste dumps also causes loss of vegetation, causing significant dust. Coal transportation activities from mines to consumption are also the cause of air pollution along traffic routes. In addition, Quang Ninh province is also one of the localities with the largest number of coal-fired power plants in Vietnam. Currently, the province has 7 coal-fired power plants, with a total capacity of 4,150 MW, accounting for 16% of the country's total electricity output. Every year, coal-fired power plants release millions of tons of ash and slag into the environment, increasing dust pollution in Quang Ninh province.

Currently, there are more than 10 air quality monitoring stations in Quang Ninh province, mainly distributed in coal mines and urban areas. These monitoring stations provide information about air quality through the AQI (Air Quality Index) index. The number of air quality monitoring stations in the study area is not much and accessing data is difficult. Therefore, using Sentinel 5P TROPOMI satellite data to evaluate the air quality in Quang Ninh province is a feasible and appropriate solution.

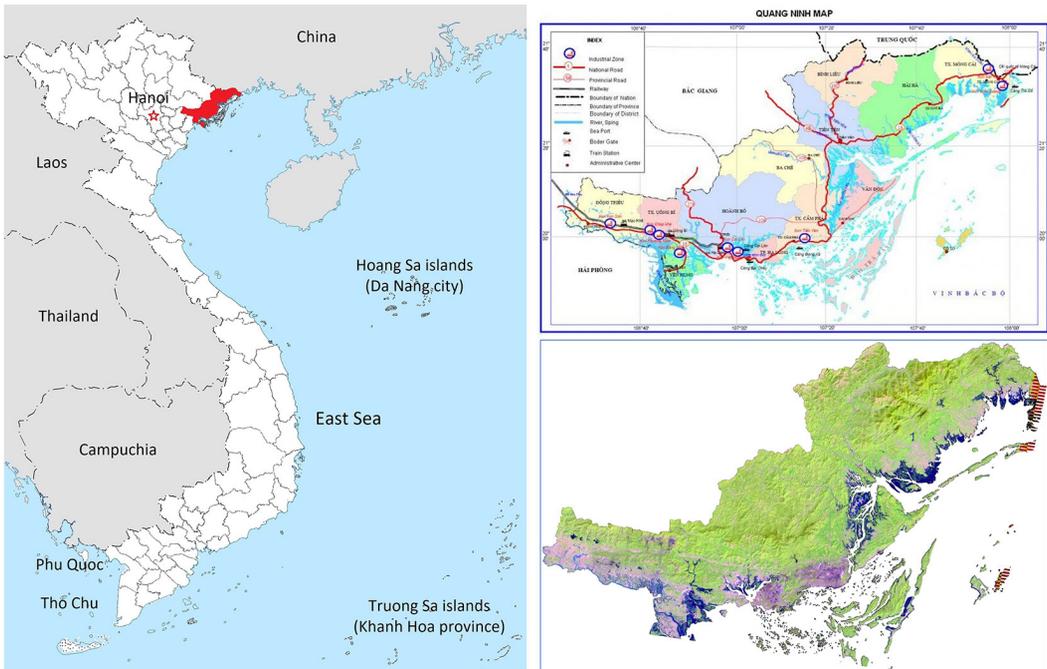


Figure 1: Geographic location of Quang Ninh province (northern Vietnam)

**Materials.** In this study, Sentinel 5P TROPOMI data collected continuously in 2023 in Quang Ninh province are used to build content distribution maps of 4 air pollution parameters, including CO, NO<sub>2</sub>, O<sub>3</sub> and SO<sub>2</sub>. Sentinel 5P TROPOMI data characteristics are shown in Table 1 (ESA, 2023). The Google Earth Engine (GEE) platform was used to collect and process Sentinel 5P data using the harpconverbin\_spatial tool. Post-processed data at the L3 level, which removed pixels with QA values less than 80% for AER\_AI, 75% for the tropospheric\_NO<sub>2</sub>\_column\_number\_density band of NO<sub>2</sub> and 50% for all other datasets except for O<sub>3</sub> and SO<sub>2</sub> (Gopikrishnan et al., 2022).

Table 1: Sentinel 5P TROPOMI bands characteristics (ESA, 2023)

Bands	Spectrometer	Spectral range (nm)	Temporal resolution	Spatial resolution (km)	Swath (km)
1	Ultraviolet - UV	270 - 300	Daily	7 × 28	~ 2600
2		300 - 320	Daily	7 × 3.5	
3	Ultraviolet-visible UVIS	320 - 405	Daily	7 × 3.5	~ 2600
4		405 - 500	Daily	7 × 3.5	
5	Near Infrared - NIR	625 - 725	Daily	7 × 3.5	~ 2600
6		725 - 775	Daily	7 × 3.5	
7	Shortwave Infrared - SWIR	2305 - 2345	Daily	7 × 7	~ 2600
8		2345 - 2385	Daily	7 × 7	

## 2.2 Methodology

Sentinel 5P TROPOMI data in NetCDF format (L2 level) collected from the Copernicus database, then processed on the GEE platform to achieve L3 level and converted to TIFF format based on the `harpconverbin_spatial` tool.

Google Earth Engine is a cloud-based geospatial analysis platform that allows users to visualize and analyze satellite image data. GEE operates through an online JavaScript application interface (API) - Code Editor. In the Code Editor interface, users can write and run scripts to process and analyze spatial data. GEE archives remote sensing data from satellite systems over the past 40 years, including data from the Sentinel system as well as the computational tools needed to analyze the data without downloading to a computer. GEE is an efficient and powerful tool when processing multi-temporal remote sensing data, such as with Sentinel 5P images.

The CO, NO<sub>2</sub>, O<sub>3</sub> and SO<sub>2</sub> concentration calculated from Sentinel 5P data has the unit of mol/m<sup>2</sup>, while the unit according to Vietnamese standards is µg/m<sup>3</sup>, so after processing it is necessary to convert the measurement unit according to the formula (Savenets, 2021):

$$C = \frac{C_{col}}{H} \times M \times A \quad (1)$$

Where: C - the air pollutants concentration in unit µg/m<sup>3</sup>;

$C_{col}$  - the pollutant column content in unit mol/m<sup>2</sup>;

H - tropospheric height in mid latitude (10000 m);

A - constant for conversion from (g/m<sup>3</sup>) to (µg/m<sup>3</sup>) (equals to 1000000).

M - the molar mass of air pollutants (g/mol).

Formula (1) is also used in many different studies in Vietnam to convert the Sentinel 5P data unit from mol/m<sup>2</sup> to µg/m<sup>3</sup> (Do et al., 2022; Luu et al., 2023; Luong et al., 2023). In many scientific projects of the Ministry of Natural Resources and Environment of Vietnam (Nghiem, 2022; Pham, 2023), the authors also used formula (1) to evaluate air pollution in Bac Ninh province, Northern Vietnam. In addition, Savenets' formula was also used in the study of Nagy et

al. to build a concentration distribution map of air pollution parameters in Sharkia Governorate (Egypt's Eastern Nile Delta) (Nagy et al., 2024). The most common air pollutants in the troposphere (Nakhjiri and Kakroodi, 2024) at altitudes of 8 to 12 km, therefore, the average altitude of 10 km is used in the studies of the concentration distribution of CO, NO<sub>2</sub>, O<sub>3</sub> and SO<sub>2</sub> from Sentinel 5P satellite data.

Finally, the content of air pollution parameters determined from Sentinel 5P data was compared with Regulations QCVN 05:2013/BTNMT National technical regulation on ambient air quality to evaluate air quality in the study area (Table 2).

Table 2: The limit values ( $\mu\text{g}/\text{m}^3$ ) of air pollutants in QCVN 05:2013/BTNMT (MONRE, 2023)

No.	Air pollutant	Average 1 hour	Average 8 hour	Average 24 hour	Annual average
1	CO	30000	10000	-	-
2	NO <sub>2</sub>	200	-	100	40
3	O <sub>3</sub>	300	120	-	-
4	SO <sub>2</sub>	350	-	125	50

### 3 RESULTS AND DISCUSSION

Sentinel 5P TROPOMI data for the whole year of 2023, after collection and processing, is used to build the average concentration distribution maps of CO, NO<sub>2</sub>, O<sub>3</sub> and SO<sub>2</sub> by quarter and year using ArcGIS 10 software. The concentration unit of air pollutant gases is also converted from mol/m<sup>2</sup> to  $\mu\text{g}/\text{m}^3$  according to formula (1) (Savenets, 2021).

#### *a) The spatio-temporal distribution maps of CO concentration*

Figure 2 shows the quarterly spatial distribution maps of CO concentration for 2023 in Quang Ninh province from Sentinel 5P data. It can be seen that the CO concentration in Quang Ninh has a big difference between quarters of the 2023 year, in which the CO concentration is highest in the first quarter (shown in yellow and dark brown in Figure 2) with values ranging from 12242.9  $\mu\text{g}/\text{m}^3$  to 17091.8  $\mu\text{g}/\text{m}^3$ . The areas with the highest CO concentrations are located in the southwest of Quang Ninh province, where there are large coal mines in Dong Trieu, Uong Bi, and Cam Pha districts. In the second quarter, the CO concentration in the air of Quang Ninh province was the second highest (from 11385.7  $\mu\text{g}/\text{m}^3$  to 18406.5  $\mu\text{g}/\text{m}^3$ ), in which the areas with the highest CO concentrations are distributed in coastal areas and some near-shore islands. During the third quarter, the concentration of CO in the air reached its lowest (from 7975.8  $\mu\text{g}/\text{m}^3$  to 10150.6  $\mu\text{g}/\text{m}^3$ ), shown by the purple color in Figure 2. In general, the CO concentration in the air in Quang Ninh province in the third quarter of 2023 is mostly below 10000  $\mu\text{g}/\text{m}^3$ . The carbon oxide concentration increased in the 4th quarter of 2023 (from 9830.1  $\mu\text{g}/\text{m}^3$  to 12891.3  $\mu\text{g}/\text{m}^3$ ), but remained lower than the CO concentration in the 2<sup>nd</sup> and 1<sup>st</sup> quarters.

Although QCVN 05:2013/BTTMT does not stipulate quarterly and annual average CO concentration limit values, through comparison with Table 2 shows that the CO concentration in Quang Ninh is very high, the lowest from about 8000  $\mu\text{g}/\text{m}^3$  (nearly equal to the limit value according to the 8-hour average in QCVN 05:2013/BTTMT).

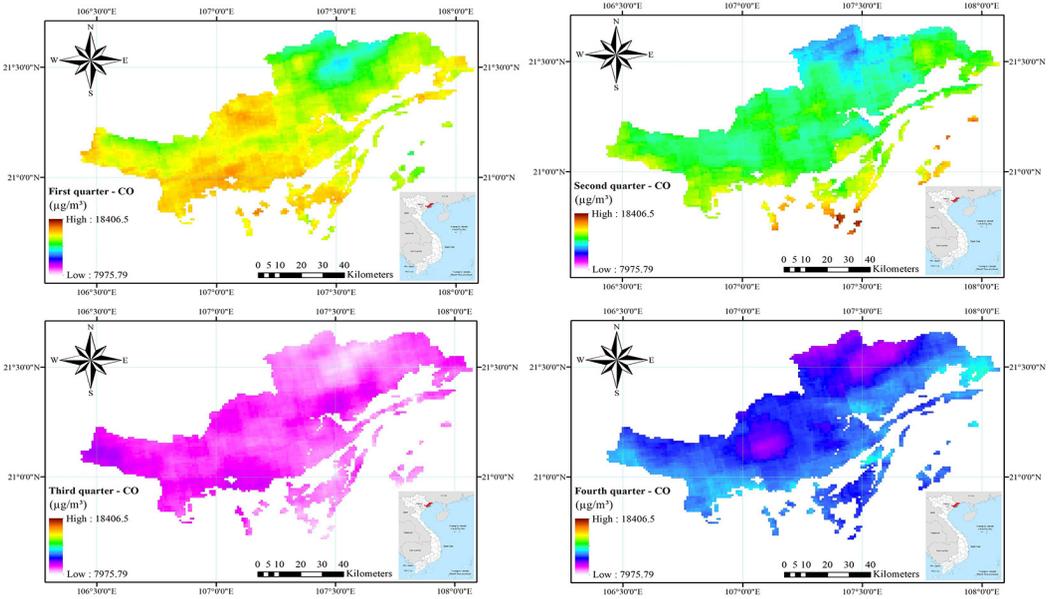


Figure 2: The quarterly 2023 spatial distribution map of CO in Quang Ninh province

In addition, this study also built the map of annual average carbon oxide concentrations (CO) for 2023 in Quang Ninh province (Figure 3). Figure 3 shows that the annual average CO concentration for 2023 in Quang Ninh province ranges from 10716.5  $\mu\text{g}/\text{m}^3$  to 13485.6  $\mu\text{g}/\text{m}^3$ , even higher than the limit value of average CO concentration in 8 hours according to QCVN 05:2013/BTTTT. It can be seen throughout the year 2023, the CO concentration is highest in the southern region, where large coal mines are located.

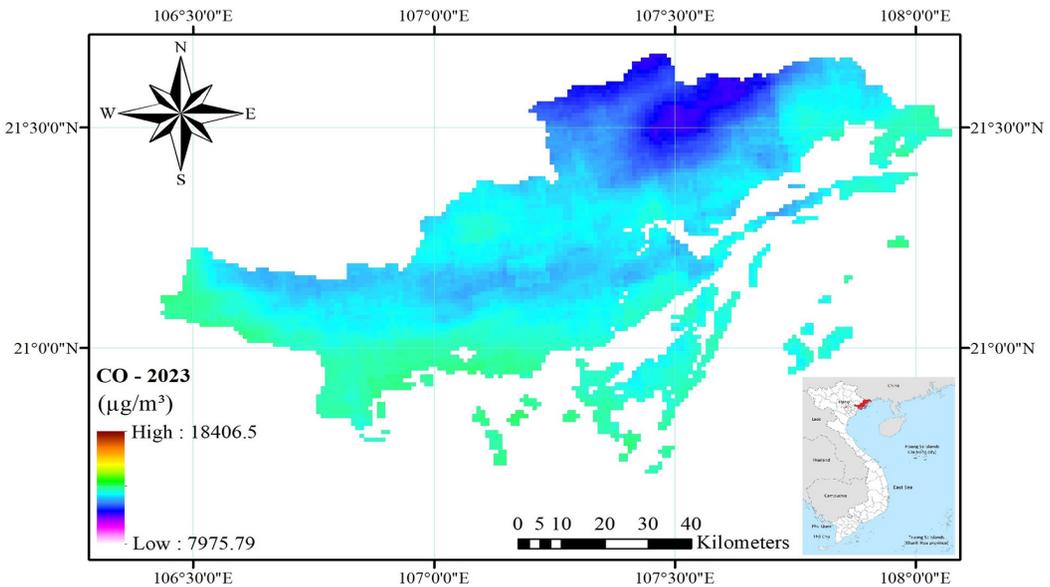


Figure 3: Map of annual average carbon oxide concentrations (CO) for 2023 in Quang Ninh province

**b) The spatio-temporal distribution maps of NO<sub>2</sub> concentration**

Figure 4 shows the quarterly spatial distribution maps of nitrit (NO<sub>2</sub>) concentration for 2023 in Quang Ninh province. The results showed that similar to the CO pollutant, the NO<sub>2</sub> concentration was highest in the areas of Dong Trieu, Uong Bi, Quang Yen and Cam Pha districts - where there are large coal mines (shown by yellow and dark brown in Figure 4). The average NO<sub>2</sub> concentrations in the first quarter of 2023 ranged from 31.31 µg/m<sup>3</sup> to 75.70 µg/m<sup>3</sup>, while in the second quarter they ranged from 34.90 µg/m<sup>3</sup> to 75.12 µg/m<sup>3</sup>. In the third quarter of 2023, the average NO<sub>2</sub> concentrations decreased (similar to CO concentrations), with values ranging from 26.56 µg/m<sup>3</sup> to 59.71 µg/m<sup>3</sup>, in which the highest quarterly average NO<sub>2</sub> concentration is still distributed in the area of large coal mines in Quang Ninh province (southwest region). The average NO<sub>2</sub> concentrations increased again in the fourth quarter of 2023, with values ranging from 25.06 µg/m<sup>3</sup> to 72.77 µg/m<sup>3</sup>.

The map of the annual average NO<sub>2</sub> concentration for 2023 in Quang Ninh province is presented in Figure 5, in which the annual average NO<sub>2</sub> concentration range from 30.46 µg/m<sup>3</sup> to 69.11 µg/m<sup>3</sup>. The areas with the highest annual average NO<sub>2</sub> concentrations are located in the west and southwest of Quang Ninh province (where there are large coal mines). The annual average NO<sub>2</sub> concentration for 2023 in large coal mine areas is also significantly higher than the limit value for the NO<sub>2</sub> parameter according to QCVN 05:2023/BTNMT (50 µg/m<sup>3</sup>).

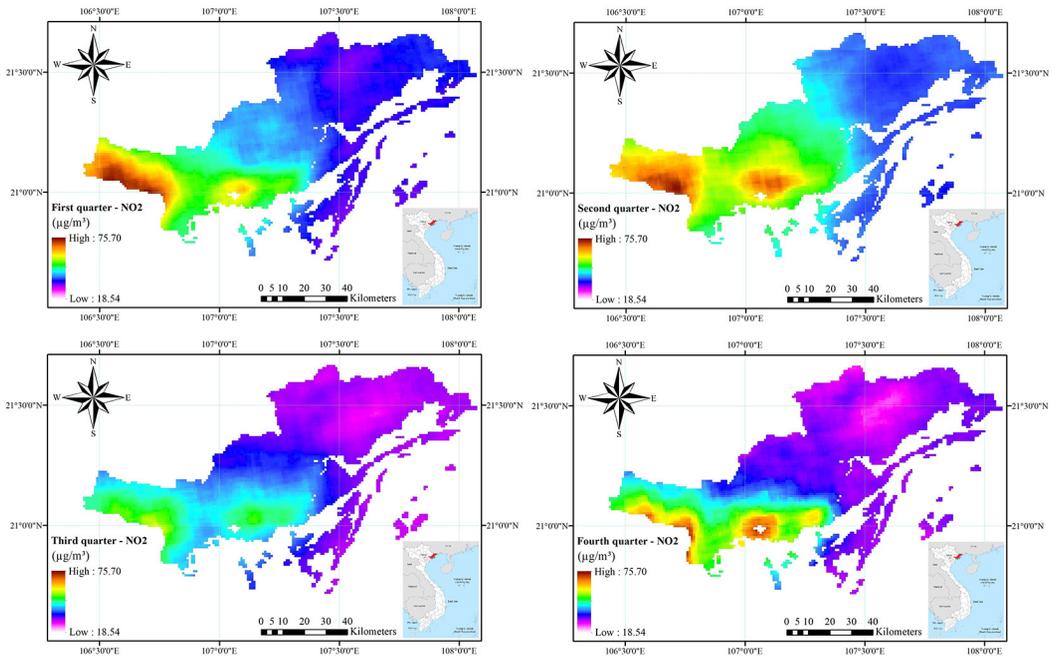


Figure 4: The quarterly 2023 spatial distribution map of NO<sub>2</sub> in Quang Ninh province

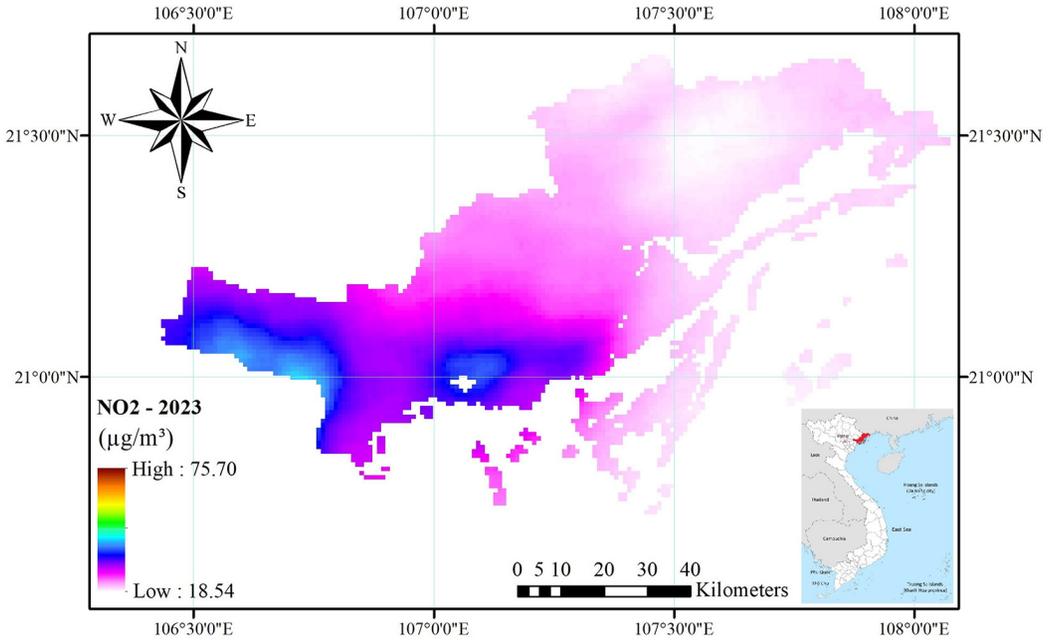


Figure 5: Map of annual average nitrite concentrations ( $\text{NO}_2$ ) for 2023 in Quang Ninh province

*c) The spatio-temporal distribution maps of  $\text{O}_3$  concentration*

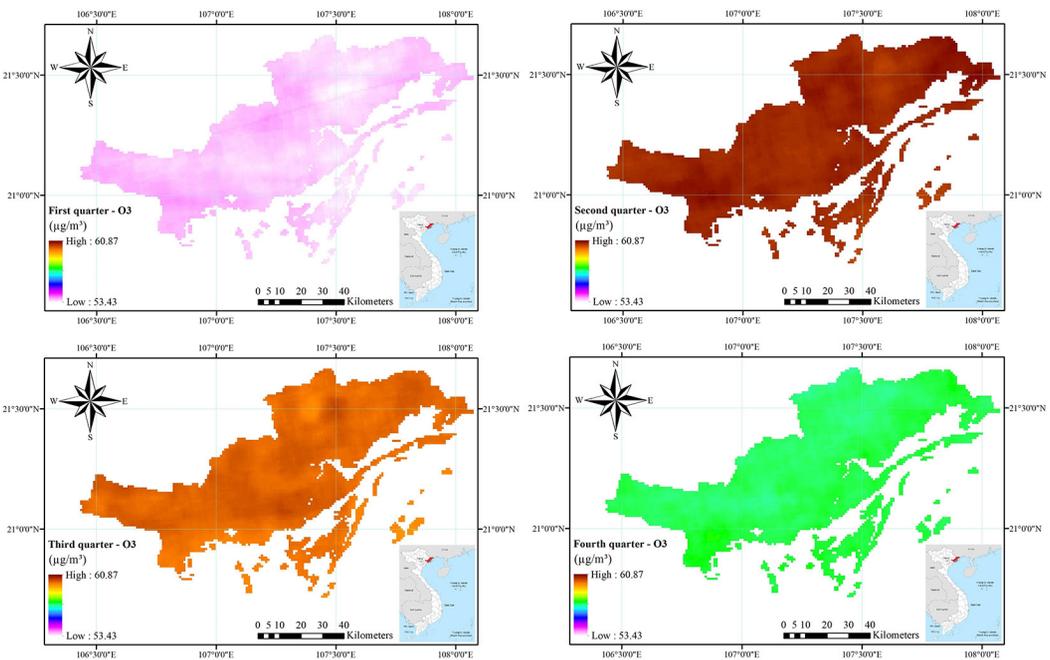


Figure 6: The quarterly 2023 spatial distribution map of  $\text{O}_3$  in Quang Ninh province

The maps of quarterly and annual average ozone ( $O_3$ ) concentrations for 2023 in Quang Ninh province are presented in Figures 6 and 7. It can be seen that ozone concentrations in Quang Ninh province do not have significant differences between different areas in all 4 quarters as well as the whole year 2023. The quarterly average  $O_3$  concentration in for 2023 ranges from  $53.43 \mu\text{g}/\text{m}^3$  to  $54.00 \mu\text{g}/\text{m}^3$  (1st quarter),  $60.24 \mu\text{g}/\text{m}^3$  to  $60.88 \mu\text{g}/\text{m}^3$  (2nd quarter),  $59.63 \mu\text{g}/\text{m}^3$  to  $60.30 \mu\text{g}/\text{m}^3$  (3rd quarter) and  $57.05 \mu\text{g}/\text{m}^3$  to  $57.76 \mu\text{g}/\text{m}^3$  (4th quarter). The annual average  $O_3$  concentration for 2023 ranges from  $57.74 \mu\text{g}/\text{m}^3$  to  $58.13 \mu\text{g}/\text{m}^3$ . In general, the average  $O_3$  concentration in the 2nd and 3rd quarters of 2023 is higher than in the 1st and 4th quarters.

The standard QCVN 05:2023/BTNMT does not stipulate the limit value of annual and quarterly  $O_3$  concentration (Table 2), however, compared to the limit value of  $O_3$  concentration in 1 hour ( $300 \mu\text{g}/\text{m}^3$ ) and 8 hours ( $120 \mu\text{g}/\text{m}^3$ ), the  $O_3$  concentration in Quang Ninh province in 2023 is basically within the allowable level.

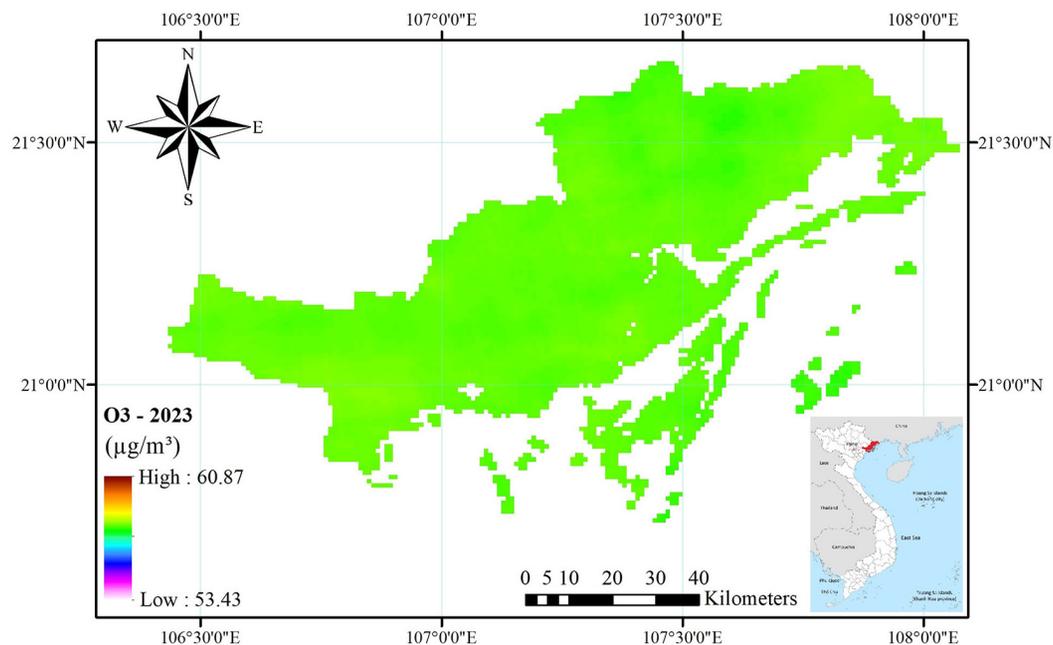


Figure 7: Map of annual average ozone concentrations ( $O_3$ ) for 2023 in Quang Ninh province

#### ***d) The spatio-temporal distribution maps of $SO_2$ concentration***

The map of quarterly average  $SO_2$  concentration for 2023 in Quang Ninh province is presented in Figure 8. The obtained results showed that the  $SO_2$  concentration in the study area reached its lowest in the third quarter of 2023 (from 0 to  $282.02 \mu\text{g}/\text{m}^3$ ). The average  $SO_2$  concentration in the first (from 0 to  $291.55 \mu\text{g}/\text{m}^3$ ), second (from 0 to  $154.27 \mu\text{g}/\text{m}^3$ ), and fourth quarters (from 0 to  $292.06 \mu\text{g}/\text{m}^3$ ) of 2023 is quite similar and significantly higher than the third quarter. It can be said that the sulfur dioxide concentration in the air in Quang Ninh province is high when compared to QCVN 05:2013/BTNMT, higher than the limit value of average  $SO_2$  concentration in 24 hours ( $125 \mu\text{g}/\text{m}^3$ ).

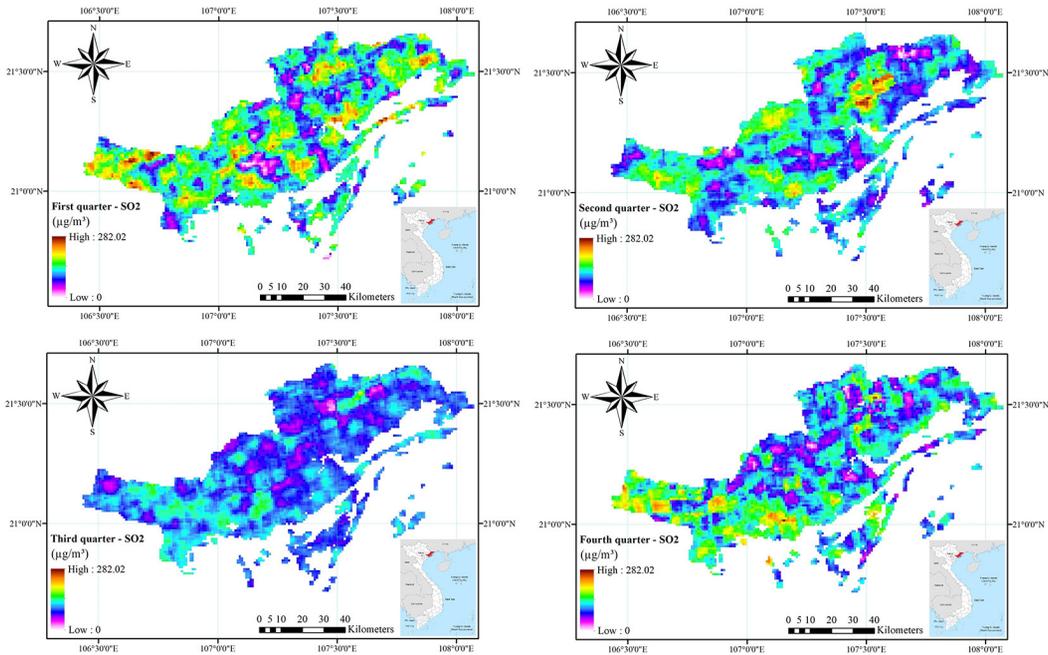


Figure 8: The quarterly 2023 spatial distribution map of SO<sub>2</sub> in Quang Ninh province

In addition, this study also built a map of the annual average SO<sub>2</sub> concentration from Sentinel 5P TROPOMI data (Figure 9), in which the annual average SO<sub>2</sub> concentration for 2023 in Quang Ninh province ranges from 0 to 180.12 µg/m<sup>3</sup>. Comparison with Vietnam standards on air quality (QCVN 05:2013/BTNMT) shows that the annual concentration of SO<sub>2</sub> for 2023 in Quang Ninh is much higher than the limit value in the standard (50 µg/m<sup>3</sup>). Most of the study area has an annual average SO<sub>2</sub> concentration in 2023 that exceeds the allowable standard in QCVN 05:2023. Areas with average SO<sub>2</sub> concentrations in 2023 within the allowable value in QCVN 05:2013/BTNMT are negligible, as shown by the purple colour in Figure 9. Analyzing the distribution of average SO<sub>2</sub> concentration in 2023 in Quang Ninh province also shows that SO<sub>2</sub> concentration is higher in the western and southwestern regions. This is also consistent with the concentration distribution of other air pollutants in Quang Ninh province such as CO, O<sub>3</sub> and NO<sub>2</sub>. Thus, it can be said that the coal mining process in Quang Ninh has a great influence on the concentration distribution of air pollutants, including carbon oxide, nitrite, ozone and sulfur dioxide.

To evaluate the accuracy of the results of calculating CO, NO<sub>2</sub>, O<sub>3</sub> and SO<sub>2</sub> concentration from Sentinel 5P data, in the study using air quality data in 2023 at 4 ground monitoring stations: 03 stations in Cam Pha city (the largest coal basin in Quang Ninh province) and 01 station in Ha Long city (the administrative, economic, socio-cultural center of Quang Ninh province). The results show that the concentrations of air pollution parameters determined from Sentinel 5P TROPOMI data have high similarities with data at monitoring stations. However, the concentration values of CO, NO<sub>2</sub>, O<sub>3</sub> and SO<sub>2</sub> calculated from remote sensing data are generally lower than the actual values measured at the stations. This is because the CO, NO<sub>2</sub>, O<sub>3</sub> and SO<sub>2</sub> concentrations calcu-

lated on the image is the average value of an image pixel, much larger than the monitoring range of a measuring station.

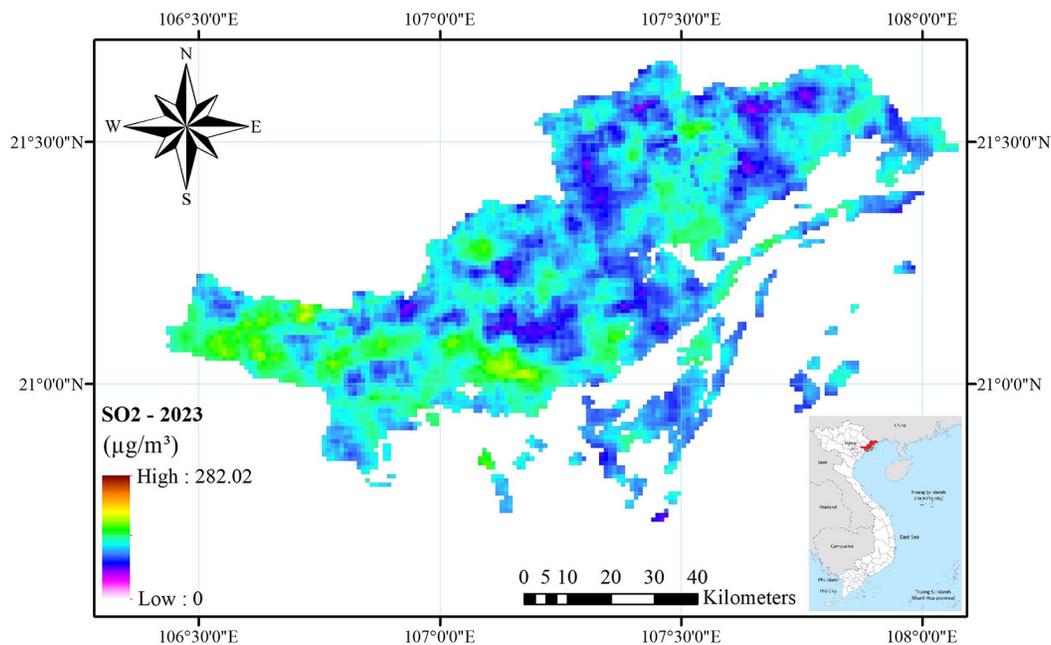


Figure 9: Map of annual average sulfur dioxide concentrations ( $\text{SO}_2$ ) for 2023 in Quang Ninh province

#### 4 CONCLUSION

This study presents the results of applying Sentinel-5P TROPOMI satellite data for mapping the spatio-temporal distribution of 04 air pollutants concentration ( $\text{CO}$ ,  $\text{NO}_2$ ,  $\text{O}_3$  and  $\text{SO}_2$ ) in the Quang Ninh province - a key area for coal exploitation and use in Vietnam. From Sentinel 5P data, this study built the quarterly and annual average maps of air pollutants concentration for 2023, including  $\text{CO}$ ,  $\text{NO}_2$ ,  $\text{O}_3$  and  $\text{SO}_2$ , then compared with the limit values in Vietnamese standard on air quality (QCVN 05:2013/ BTNMT). The results show that the concentrations of  $\text{CO}$ ,  $\text{NO}_2$ ,  $\text{O}_3$  and  $\text{SO}_2$  in Quang Ninh province in 2023 are all high compared to regulations in QCVN, of which the highest concentration is in the first quarter.

In addition, the concentration distribution maps of air pollutants obtained in this study are objective and timely information, allowing managers to assess the level of air pollution as well as identify sources of air emissions in the study area. With a wide coverage area, Sentinel-5P TROPOMI data can be used effectively in air pollution monitoring and assessment, saving time and costs compared to traditional research methods.

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