Periódico Eletrônico Fórum Ambiental da Alta Paulista
Electronic Journal Environmental Forum of Alta Paulista
ISSN 2966-2931 Suporte Online / *Online Support* - ISSN 1980-0827 Suporte CD-ROM / *CD-ROM Support*

Edição em Português e Inglês / *Edition in Portuguese and English* - v. 21, n. 2, 2025

Use of the TROPOMI sensor to detect atmospheric pollutants from forest fires moving toward southern Brazil

Luana Pasquetti
Master's student in Architecture and Urbanism, ATITUS Educação, Brasil
luanapasquetti@gmail.com
ORCID iD: 0009-0002-5539-5786

Guilherme Peterle Schmitz
PhD candidate in Architecture and Urbanism, ATITUS Educação, Brasil.
guilhermepeterle99@gmail.com
ORCID iD: 0009-0005-0457-6394

Alcindo Neckel
Professor PhD, ATITUS Educação, Brazil.
alcindo.neckel@atitus.edu.br
ORCID iD: 0000-0001-5435-3096

Caliane Christie Oliveira de Almeida Silva
Professor PhD, ATITUS Educação, Brazil.
caliane.silva@atitus.edu.br
ORCID iD: 0000-0002-8477-389X

Grace Tibério Cardoso
Professor PhD, ATITUS Educação, Brazil.
grace.cardoso@atitus.edu.br
ORCID iD: 0000-0002-1779-4631

Submissão: 13/11/2024
Aceite: 19/07/2025
PASQUETTI , Luana; SCHMITZ , Guilherme Peterle; NECKEL , Alcindo; SILVA, Caliane Christie Oliveira de Almeida; CARDOSO , Grace Tibério. Uso do sensor TROPOMI na detecção de poluentes atmosféricos originados em incêndios florestais que se movimentam para o Sul do Brasil. **Periódico Eletrônico Fórum Ambiental da Alta Paulista**, *[S. l.]*, v. 21, n. 2, 2025. DOI: 10.17271/1980082721220225876. Disponível em: https://publicacoes.amigosdanatureza.org.br/index.php/forum_ambiental/article/view/5876.
Licença de Atribuição CC BY do Creative Commons https://creativecommons.org/licenses/by/4.0/

Periódico Eletrônico Fórum Ambiental da Alta Paulista
Electronic Journal Environmental Forum of Alta Paulista
ISSN 2966-2931 Suporte Online / *Online Support* - ISSN 1980-0827 Suporte CD-ROM / *CD-ROM Support*

Edição em Português e Inglês / *Edition in Portuguese and English* - v. 21, n. 2, 2025

Uso do sensor TROPOMI na detecção de poluentes atmosféricos originados em incêndios florestais que se movimentam para o Sul do Brasil

RESUMO
Objetivo - O objetivo geral deste estudo é quantificar a poluição atmosférica no Estado do Rio Grande do Sul (Brasil), durante o período de janeiro de 2021 a setembro de 2024.
Metodologia – Foi utilizado o método qualitativo quantitativo, combinando análise ambiental e Sensoriamento Remoto em relação a disponibilização das imagens, utilizando o satélite Sentinel-5P acoplado ao TROPOspheric Monitoring Instrument (TROPOMI) de domínio da Agência Espacial Europeia (ESA) para análise dos poluentes atmosféricos. Bem como o processamento das imagens coletadas pelos softwares SNAP (Sentinel Application Platform) e QGIS (Quantum GIS), além da geração de planilhas de dados aplicada à metodologia de agrupamento K-means no software JASP (versão 0.18.3.0).
Originalidade/relevância - contribuir com a criação de políticas públicas ambientais voltadas à mitigação dos níveis de poluição atmosfera.
Resultados - Os resultados demonstram níveis de CO de 0,0244 mol/m², revela-se que no dia 11 de setembro de 2024 foram ≈5,9 vezes (490,16%) maiores do que os níveis médios normais. Os níveis de NO2 de 2024 atingiu um valor de 1.11E-5 mol/m², originando-se níveis ≈6,65 vezes (565,76%) maiores que os níveis médios decorrentes registrados.
Contribuições teóricas/metodológicas - O presente estudo contribui teoricamente ao aprofundar a compreensão sobre a aplicação de técnicas de Sensoriamento Remoto na análise da poluição atmosférica em escala regional. Metodologicamente, destaca-se pela integração de diferentes ferramentas analíticas e computacionais — como o uso conjunto dos softwares SNAP, QGIS e JASP — e pela adoção do algoritmo de agrupamento K-means como técnica estatística para a interpretação de dados ambientais. Essa abordagem interdisciplinar oferece um modelo replicável de monitoramento ambiental que pode ser adaptado a outras regiões e contextos de estudo.
Contribuições sociais e ambientais - o estudo fornece dados concretos e atualizados sobre os níveis de poluentes atmosféricos no Estado do Rio Grande do Sul, fortalecendo a base científica necessária para a formulação de políticas públicas ambientais. Ao evidenciar picos críticos de poluição e sua variação temporal, a pesquisa subsidia ações de mitigação voltadas à saúde pública, controle de emissões e gestão territorial sustentável. Além disso, estimula a conscientização da população e dos gestores sobre os impactos da poluição atmosférica, promovendo práticas voltadas ao desenvolvimento sustentável.

PALAVRAS-CHAVE: Qualidade do ar. Poluição atmosférica. Incêndios florestais.

Using the TROPOMI sensor to detect atmospheric pollutants originating from forest fires moving towards southern Brazil

ABSTRACT
Objective - The general objective of this study is to quantify air pollution in the State of Rio Grande do Sul (Brazil), during the period from January 2021 to September 2024.
Methodology - The quantitative qualitative method was used, combining environmental analysis and Remote Sensing in relation to the availability of images, using the Sentinel-5P satellite coupled to the TROPOspheric Monitoring Instrument (TROPOMI) under the domain of the European Space Agency (ESA) to analyze atmospheric pollutants. As well as the processing of the images collected using the SNAP (Sentinel Application Platform) and QGIS (Quantum GIS) software, in addition to the generation of data sheets applied to the K-means clustering methodology in the JASP software (version 0.18.3.0).
Originality/relevance - to contribute to the creation of public environmental policies aimed at mitigating atmospheric pollution levels.
Results - The results show that CO levels of 0.0244 mol/m² on September 11, 2024 were ≈5.9 times (490.16%) higher than normal average levels. NO2 levels in 2024 reached a value of 1.11E-5 mol/m², giving rise to levels ≈6.65 times (565.76%) higher than the average levels recorded.
Theoretical/methodological contributions - This study contributes theoretically by deepening our understanding of the application of remote sensing techniques in the analysis of atmospheric pollution on a regional scale.

Methodologically, it stands out for its integration of different analytical and computational tools - such as the joint use of SNAP, QGIS and JASP software - and for its adoption of the K-means clustering algorithm as a statistical technique for interpreting environmental data. This interdisciplinary approach offers a replicable environmental monitoring model that can be adapted to other regions and study contexts.
Social and environmental contributions - the study provides concrete, up-to-date data on the levels of atmospheric pollutants in the state of Rio Grande do Sul, strengthening the scientific basis needed to formulate public environmental policies. By highlighting critical pollution peaks and their temporal variation, the research supports mitigation actions aimed at public health, emissions control and sustainable land management. It also stimulates awareness among the population and managers about the impacts of air pollution, promoting practices aimed at sustainable development.

KEYWORDS: Air quality. Atmospheric pollution. Forest fires.

Uso del sensor TROPOMI para detectar contaminantes atmosféricos procedentes de incendios forestales que se desplazan hacia el sur de Brasil

RESUMEN
Objetivo - El objetivo general de este estudio es cuantificar la contaminación atmosférica en el Estado de Rio Grande do Sul (Brasil), durante el período comprendido entre enero de 2021 y septiembre de 2024.
Metodología - Se utilizó el método cualitativo cuantitativo, combinando el análisis ambiental y la Teledetección en relación a la disponibilidad de imágenes, utilizando el satélite Sentinel-5P acoplado al TROPOspheric Monitoring Instrument (TROPOMI), de dominio de la Agencia Espacial Europea (ESA), para analizar los contaminantes atmosféricos. Así como el procesado de las imágenes recogidas mediante el software SNAP (Sentinel Application Platform) y QGIS (Quantum GIS), además de la generación de hojas de datos aplicadas a la metodología de clustering K-means en el software JASP (versión 0.18.3.0).
Originalidad/Relevancia - Contribuir a la creación de políticas públicas ambientales destinadas a mitigar los niveles de contaminación atmosférica.
Resultados - Los resultados muestran que los niveles de CO de 0,0244 mol/m² el 11 de septiembre de 2024 fueron ≈5,9 veces (490,16%) superiores a los niveles medios normales. Los niveles de NO2 en 2024 alcanzaron un valor de 1,11E-5 mol/m², dando lugar a niveles ≈6,65 veces (565,76%) superiores a los niveles medios registrados.
Aportaciones teóricas/metodológicas - Este estudio contribuye teóricamente al profundizar en el conocimiento de la aplicación de las técnicas de teledetección en el análisis de la contaminación atmosférica a escala regional. Metodológicamente, destaca por la integración de diferentes herramientas analíticas y computacionales -como el uso conjunto de los softwares SNAP, QGIS y JASP- y por la adopción del algoritmo de agrupamiento K-means como técnica estadística para la interpretación de datos ambientales. Este enfoque interdisciplinar ofrece un modelo de vigilancia ambiental replicable que puede adaptarse a otras regiones y contextos de estudio.
Contribuciones sociales y ambientales - el estudio proporciona datos concretos y actualizados sobre los niveles de contaminantes atmosféricos en el estado de Rio Grande do Sul, fortaleciendo la base científica necesaria para formular políticas públicas ambientales. Al destacar los picos críticos de contaminación y su variación temporal, la investigación subvenciona acciones de mitigación dirigidas a la salud pública, el control de emisiones y la gestión territorial sostenible. También estimula la concienciación de la población y de los gestores sobre los impactos de la contaminación atmosférica, promoviendo prácticas orientadas al desarrollo sostenible.

PALABRAS CLAVE: Calidad del aire. Contaminación atmosférica. Incendios forestales.

Periódico Eletrônico Fórum Ambiental da Alta Paulista
Electronic Journal Environmental Forum of Alta Paulista
ISSN 2966-2931 Suporte Online / *Online Support* - ISSN 1980-0827 Suporte CD-ROM / *CD-ROM Support*
Edição em Português e Inglês / *Edition in Portuguese and English* - v. 21, n. 2, 2025

GRAPHICAL ABSTRACT

1 INTRODUCTION

Atmospheric pollutants originating from fires and other polluting sources cause significant changes to the environment across large geographical regions, and have worsened in recent years as a result of intensified human actions, through the release of gaseous chemical elements capable of threatening air quality on a global scale (Bodah *et al.*, 2022). These quantities of pollutants emitted into the atmosphere also originate daily from industries and motor vehicles due to the burning of fossil fuels and agricultural and farming activities, not forgetting natural causes such as volcanic eruptions and fires (Kuśmierczyk-Michulec; Baré, 2024).

Sun *et al.* (2021) and Fadairo *et al.* (2024) emphasize that the materials emitted into the atmosphere are characterized as: particulate matter (PM), carbon monoxide (CO), sulphur dioxide (SO_2), hydrocarbons (HC), nitrogen oxide (NO), carbon dioxide (CO_2) and nitrogen dioxide (NO_2). These gaseous chemical pollutants contain mostly ultrafine particles that have a harmful impact on human health and the quality of the environment. These air pollutants are responsible for 99% of the global population breathing contaminated air, according to data from the World Health Organization (WHO, 2021). These atmospheric pollutants have been quantitatively analyzed in 117 countries around the world by the Organization, attesting that they affect global human health and contribute to a decrease in the population's quality of life in general (WHO, 2021).

More precisely, it should be remembered that the WHO, in its 2021 report, estimated that around 7 million premature lives were lost due to air pollution (WHO, 2021). These contaminants are made up of microparticles - smaller than 2.5 micrometers called $PM_{2.5}$ which have high penetrability in the lungs and are capable of reaching the bloodstream, causing respiratory damage, cerebrovascular (stroke), developmental problems, cardiovascular diseases, as well as affecting other organs that trigger other respiratory diseases (WHO, 2021; Bodah *et al.*, 2022).

According to the World Meteorological Organization's (WMO) annual climate and air quality bulletin, which analyzed air quality in the year 2023, forest fires have a major impact on air quality through the mass emission in a short period of polluting nanoparticles, causing irreversible damage in the short term and deaths in prolonged exposure at their peak (WMO, 2023). In Brazil, around 186,692 fire outbreaks were recorded from January 2024 to September 16, 2024, representing 51.2% of the outbreaks of fire in the whole of South America in the same period. Around 59,641 outbreaks were recorded from September 1 to 16, 2024 alone, reaching the highest level in 17 years and covering around 60% of Brazilian territory in smoke (INPE, 2024).

Given the alarming data, forest fires are a global problem due to air currents. The cloud of pollution moves through the atmosphere, affecting other regions - as happened in the state of Rio Grande do Sul in September 2024, when carbon monoxide levels reached an all-time high (Bodah *et al.*, 2022; ESA, 2024), and may represent a warning of the harmfulness of the quality of the environment to human health. This atmospheric pollution, when caused by forest fires in the Midwest and North of Brazil, can transport these contaminants by air masses to the South of Brazil, mainly due to the corridor of atmospheric water vapor and low-altitude winds that

Periódico Eletrônico Fórum Ambiental da Alta Paulista
Electronic Journal Environmental Forum of Alta Paulista
ISSN 2966-2931 Suporte Online / *Online Support* - ISSN 1980-0827 Suporte CD-ROM / *CD-ROM Support*
Edição em Português e Inglês / *Edition in Portuguese and English* - v. 21, n. 2, 2025

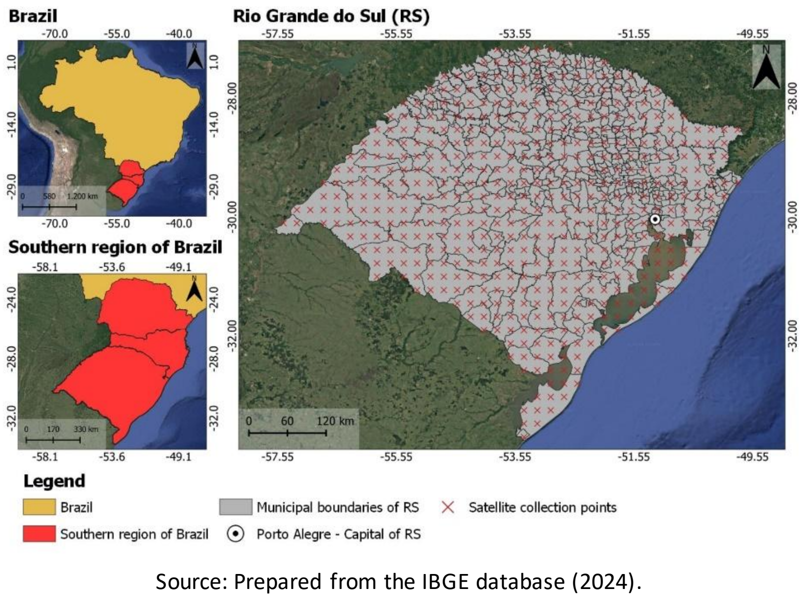
forms in the Amazon and reaches the South; a standard climate system in South America, to the east of the Andes, responsible for the rainfall regime and commonly called “flying rivers”.

Given this context, the general objective of this study is to quantify atmospheric pollution in the state of Rio Grande do Sul (Brazil), during the period from January 2021 to September 2024, a period of great aggravation of fires in the country, by means of Remote Sensing, using the Sentinel-5P satellite coupled to the TROPOspheric Monitoring Instrument (TROPOMI) under the domain of the European Space Agency (ESA) aimed at detecting levels of carbon monoxide (CO) and nitrogen dioxide (NO_2). The Sentinel-5P satellite was used specifically for monitoring the atmosphere with high spatial and temporal resolution. This study is of fundamental importance as it uses the TROPOspheric Monitoring Instrument (TROPOMI) (Bodah *et al.*, 2022), in the analysis of air quality related to the consequences of the Brazilian forest fires, which are capable of displacing contaminants (NO_2 and CO) to the south of Brazil, potentially causing severe risks to human health, as proven by the World Health Organization. (WHO, 2021).

2 MATERIAL AND METHODS

The state of Rio Grande do Sul (RS), located in the southern region of Brazil (Figure 1), has a territorial area of 281,748 km². Its estimated population is 11.4 million inhabitants, spread over 497 municipalities. The city of Porto Alegre, which is the state capital, stands out as the main political, economic, and cultural center. From a climatic point of view, Rio Grande do Sul has a subtropical climate, characterized by hot summers and harsh winters, with significant temperature variations throughout the year (IBGE, 2024).

Figure 1 – Location of the state of Rio Grande do Sul in Brazil, in relation to the cloud of detection points via TROPOMI.



Source: Prepared from the IBGE database (2024).

Using the Sentinel-5P satellite, coupled with the TROPOMI sensor, the distribution of collection points was generated by Irregular Triangulation Network (TIN) (Neckel *et al.*, 2022), resulting in a total of 522 points, spaced 25km apart, located in the state of Rio Grande do Sul (Figure 1). The data collected with the TROPOMI sensor covers the variables of the pollutants CO (carbon monoxide) and NO_2 (nitrogen dioxide), for the years 2021 and 2024, in the summer (January) and winter (September) seasons, with the collections carried out over 4 days in each month analyzed, taking into account the good quality of the images selected for sampling, with the minimum reduction of clouds, as determined by the studies by Chen *et al.* (2024) and Maheshwarkar *et al.* (2024).

It should be remembered that the choice of the study period (2021 and 2024) is justified on the basis of data from the European Space Agency, which identified that these years recorded the highest peak concentrations of the pollutants analyzed (ESA, 2024). With regard to the CO and NO_2 data detected via TROPOMI, spatial resolutions of 25 km x 25 km were used, with a normalization of 0.83 µg/mg and a maximum error of 6.62%, allowing for a detailed analysis of the different regions studied. The dates chosen for this study were selected according to the degree of contaminants over the period studied, which were updated daily, allowing the creation of time series to observe variations over time. Data collection is based on remote sensing images from the Sentinel-5P satellite, obtained through the Copernicus Browser platform, which provides free access to the satellite's raw data.

The collection process followed these steps (Bodah *et al.*, 2022; Maheshwarkar *et al.*, 2024): a) Image download: the daily images were downloaded and filtered for data corresponding to the geographical area of Rio Grande do Sul; b) Collection period: the analysis period covers the months of January 2021 to September 2024, covering three and a half years of observations. This period allowed for the analysis of seasonal patterns and correlation with specific events, such as fires and industrial activities; c) Atmospheric correction and processing: after downloading the images, atmospheric correction and data processing were carried out using the ESA SNAP (Sentinel Application Platform) software to ensure the accuracy of the measurements.

The data collected by detection via TROPOMI was organized in a geospatial database, allowing for the analysis of time series and the visualization of maps of the spatial distribution of pollutants (Bodah *et al.*, 2022; Maheshwarkar *et al.*, 2024). In this context, data interpolation was carried out using kriging to fill in measurement gaps, providing a continuous visualization of pollutant levels in the state (Chen *et al.*, 2024). Daily, monthly, and seasonal averages of CO and NO_2 levels were used to realize temporal variations for the averages and standard deviations. This facilitated the analysis of seasonal and anomalous patterns, with comparing pollutant levels over different seasons and identifying anomalies that could be related to specific events, as emphasized by Filonchyk and Peterson (2024).

Data modeling was carried out using QGIS (Quantum GIS) software, which enabled geospatial visualization and analysis and prepared the maps in this study. The methodology used was carefully designed to provide a comprehensive analysis of air pollution in the state of Rio Grande do Sul, using the data provided by the Sentinel-5P satellite, making it extremely important for understanding air quality in large regions (Chen *et al.*, 2024). The use of remote sensing, combined with geospatial analysis techniques and validation with terrestrial data, provides a solid basis for understanding CO and NO_2 concentrations over time in a given region

(Bodah *et al.*, 2022; Maheshwarkar *et al.*, 2024). Despite some limitations related to cloud cover and spatial resolution in urban areas, the proposed method makes it possible to identify emission patterns and their potential impacts on public health (Bodah *et al.*, 2022). This collected data was modeled using the K-means clustering methodology (Hajihosseinlou *et al*. 2024), allowing for a better understanding of the results obtained in this study. This approach offers a valuable contribution to air quality management and environmental monitoring in large regions, with the potential for future expansion with the application of more detailed studies.

3 RESULTS AND DISCUSSION

The results showed a set of data collected by the TROPOMI sensor in the study area (Table 1). For the CO variable, we first analyzed the averages, which were stable throughout 2021, with the highest value on January 11, 2021, with an average of 0.0244 mol/m² (Figure 2 (B)), compared to the other periods this year. In the summer (Figure 2 (A, C and D)), the highest average values were found this year in the winter season (Figure 2 (I, J, K and L)).

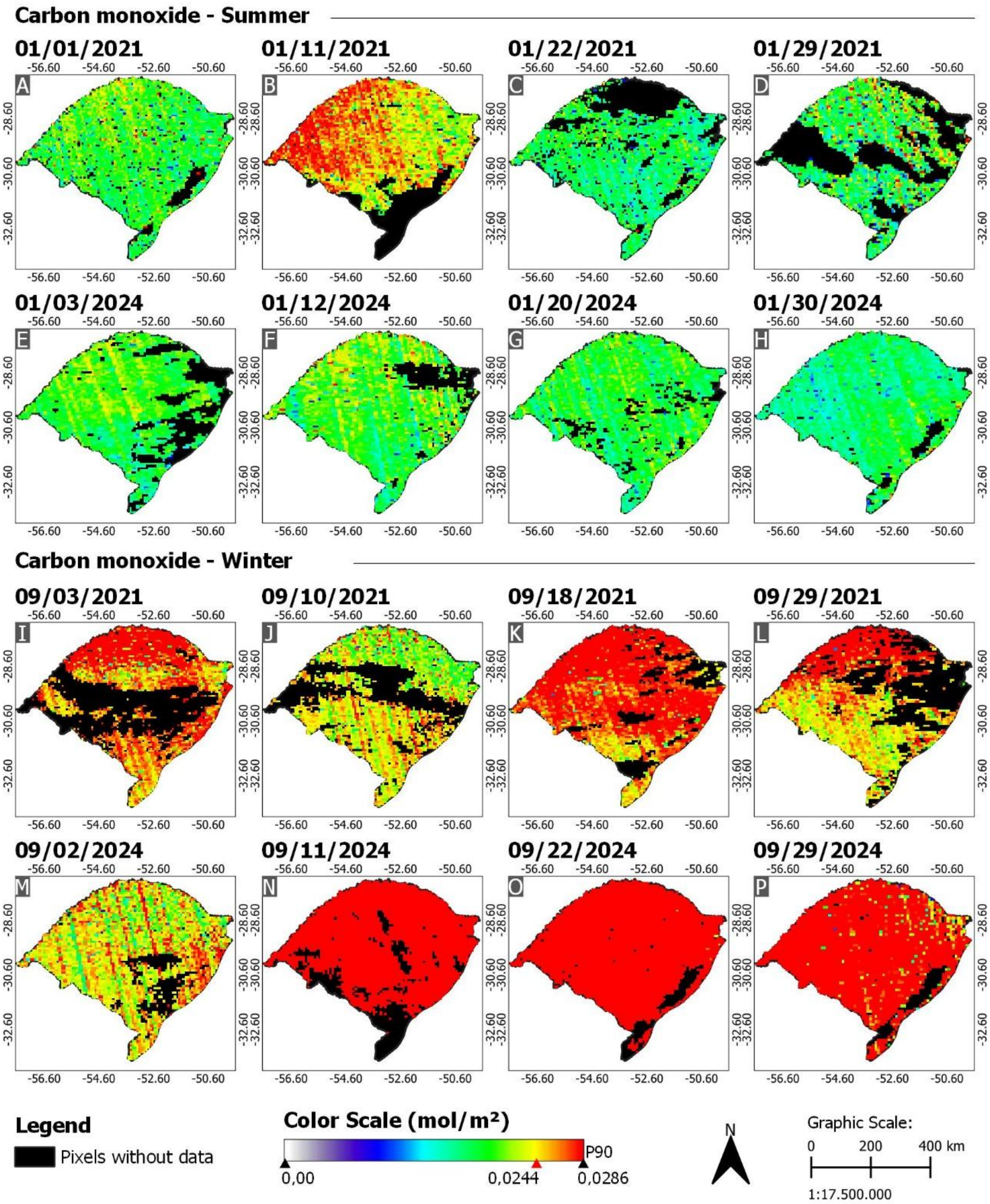
Table 1 - Descriptive statistics of the data collected from satellite images, referring to the CO and NO_2 variables captured with the TROPOMI sensor applied to the study area in the state of Rio Grande do Sul.

Satellite images	**Valid**	**Lost**	**Average**	**Standard Deviation**	**Variance**	**Minimum**	**Maximum**
CO_SUM_2021_01_01	522	0	0.02	0.005	2.51E-05	0	0.111
CO_SUM_2021_01_11	522	0	0.025	0.004	1.29E-05	0	0.053
CO_SUM_2021_01_22	522	0	0.017	0.003	7.78E-06	0	0.027
CO_SUM_2021_01_29	522	0	0.019	0.005	2.19E-05	0	0.044
CO_WIN_2021_09_03	522	0	0.028	0.004	1.33E-05	0.01	0.047
CO_WIN_2021_09_10	522	0	0.023	0.003	9.21E-06	0.002	0.031
CO_WIN_2021_09_18	522	0	0.029	0.004	1.77E-05	0.011	0.046
CO_WIN_2021_09_29	522	0	0.027	0.004	1.59E-05	0.014	0.043
CO_SUM_2024_01_03	522	0	0.02	0.002	4.65E-06	0.01	0.027
CO_SUM_2024_01_12	522	0	0.02	0.003	8.83E-06	0	0.031
CO_SUM_2024_01_20	522	0	0.019	0.002	5.46E-06	0.005	0.025
CO_SUM_2024_01_30	522	0	0.017	0.002	5.19E-06	0.003	0.028
CO_WIN_2024_09_02	522	0	0.024	0.003	1.10E-05	0.005	0.035
CO_WIN_2024_09_11	522	0	0.144	0.044	0.002	0.064	0.255
CO_WIN_2024_09_22	522	0	0.077	0.022	4.82E-04	0.032	0.126
CO_WIN_2024_09_29	522	0	0.035	0.006	3.88E-05	0.007	0.056
NO2_SUM_2021_01_01	522	0	5.87E-05	5.59E-06	3.12E-11	4.09E-05	8.13E-05
NO2_SUM_2021_01_11	522	0	6.26E-05	5.24E-06	2.75E-11	3.56E-05	8.11E-05
NO2_SUM_2021_01_22	522	0	5.60E-05	6.03E-06	3.63E-11	3.28E-05	8.30E-05
NO2_SUM_2021_01_29	522	0	5.70E-05	4.55E-06	2.07E-11	4.49E-05	7.10E-05
NO2_WIN_2021_09_03	522	0	5.46E-05	5.21E-06	2.71E-11	4.26E-05	7.78E-05
NO2_WIN_2021_09_10	522	0	5.25E-05	4.31E-06	1.86E-11	3.80E-05	7.03E-05
NO2_WIN_2021_09_18	522	0	6.03E-05	5.33E-06	2.84E-11	4.58E-05	7.80E-05
NO2_WIN_2021_09_29	522	0	5.69E-05	4.75E-06	2.25E-11	4.36E-05	7.26E-05
NO2_SUM_2024_01_03	522	0	6.79E-05	5.31E-06	2.82E-11	5.24E-05	8.26E-05
NO2_SUM_2024_01_12	522	0	6.20E-05	5.10E-06	2.61E-11	4.57E-05	7.44E-05
NO2_SUM_2024_01_20	522	0	6.19E-05	5.06E-06	2.56E-11	4.57E-05	7.38E-05
NO2_SUM_2024_01_30	522	0	6.08E-05	3.97E-06	1.58E-11	4.95E-05	7.42E-05
NO2_WIN_2024_09_02	522	0	5.61E-05	7.07E-06	5.00E-11	3.85E-05	9.58E-05
NO2_WIN_2024_09_11	522	0	7.39E-05	6.35E-06	4.03E-11	5.23E-05	9.37E-05
NO2_WIN_2024_09_22	522	0	6.95E-05	6.77E-06	4.58E-11	5.10E-05	9.29E-05
NO2_WIN_2024_09_29	522	0	6.55E-05	6.15E-06	3.79E-11	4.54E-05	1.05E-04
CO_SUM_2021_01_01	522	0	0.02	0.005	2.51E-05	0	0.111
CO_SUM_2021_01_11	522	0	0.025	0.004	1.29E-05	0	0.053
CO_SUM_2021_01_22	522	0	0.017	0.003	7.78E-06	0	0.027
CO_SUM_2021_01_29	522	0	0.019	0.005	2.19E-05	0	0.044

Source: Data detected from geospatial collections by TROPOMI (ESA, 2024).

During the year 2024, CO averages were also stable in summer (Figure 2 (E, F, G and H)), with a drastic increase in winter (Figure 2 (M, N, O and P)). Within the period observed in Table 1, for winter 2024, it is notable that on September 11, 2024, average CO levels were significantly high (0.144 mol/m²). Considering that the average CO level for the region of the state of Rio Grande do Sul over the last 5 years has been 0.0244 mol/m², it can be seen that on September 11, 2024 (Figure 2 (N)) CO levels were ≈5.9 times (490.16%) higher than the normal average levels for the study area, making it the highest average recorded in the 5 years studied (ESA, 2024).

Figure 2 – Representation of carbon monoxide (CO) levels collected in this study via TROPOMI.



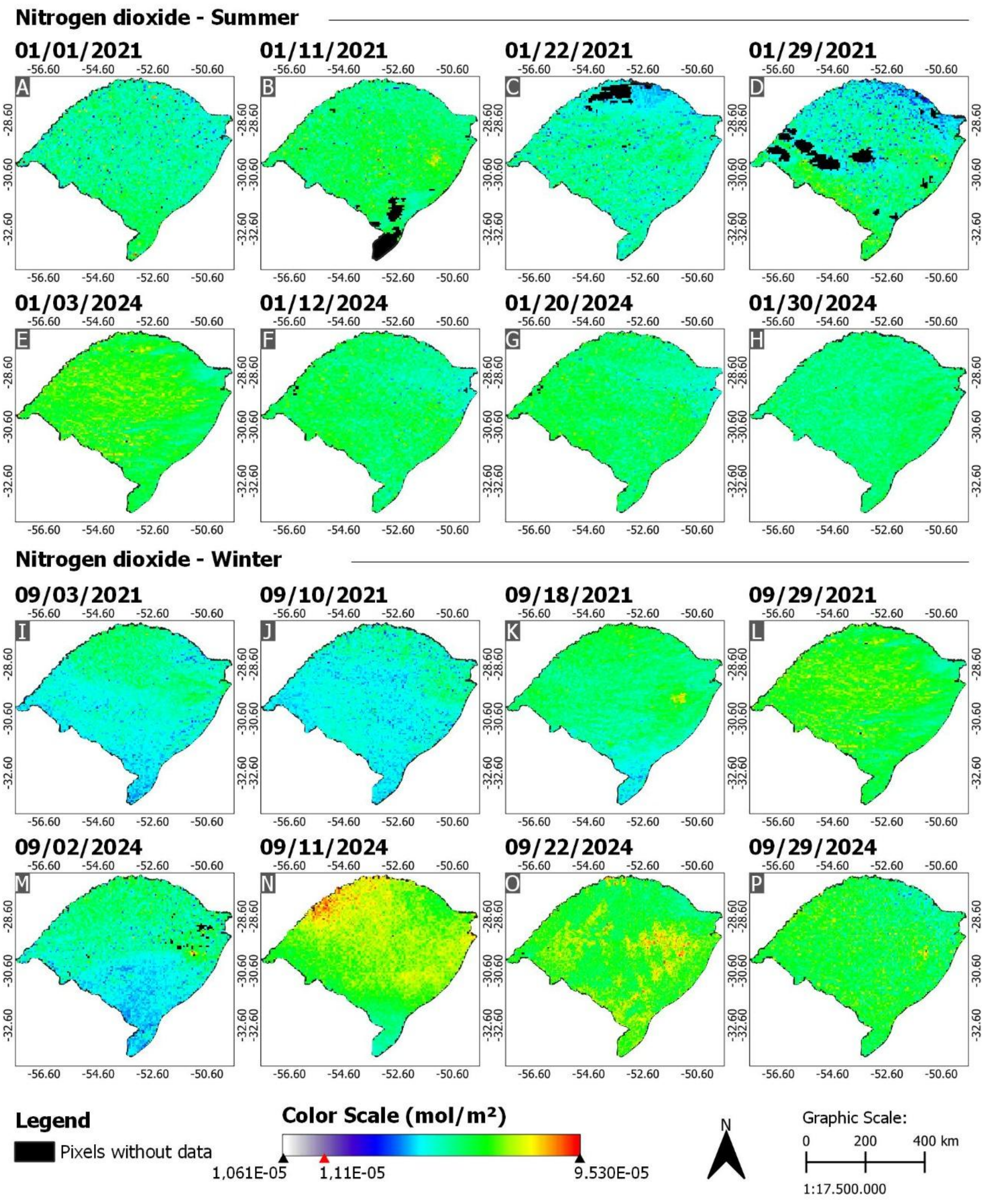
Source: Maps based on data detected via TROPOMI (ESA, 2024).

Table 1 shows the values of the NO_2 variable, making it possible to understand the averages, in which greater stability was observed in 2021, with a higher average value in

Periódico Eletrônico Fórum Ambiental da Alta Paulista
Electronic Journal Environmental Forum of Alta Paulista
ISSN 2966-2931 Suporte Online / *Online Support* - ISSN 1980-0827 Suporte CD-ROM / *CD-ROM Support*
Edição em Português e Inglês / *Edition in Portuguese and English* - v. 21, n. 2, 2025

summer, reaching 6.26E-05 mol/m² on 01/11/2021 (Figure 3 (B)), compared to the other periods of the year in the same season (Figure 3 (A, C and D)). In winter, the collections on 08/18/2021 and 09/29/2021 (Figure 3 (K and L)) recorded higher concentrations of NO_2. These 2021 results indicate a balance in NO2 concentrations between the two observed stations. The difference in understanding and comprehension of this data can foster government agents' decision-making aimed at the future mitigation of the quantities generated by atmospheric pollution. (Bodah *et al.*, 2022; Maheshwarkar *et al.*, 2024).

Figure 3 – Representation of the nitrogen dioxide (NO_2) levels collected in this study via TROPOMI.



Source: Maps based on data detected via TROPOMI (ESA, 2024).

The 2024 data showed that during the summer (Figure 3 (E, F, G and H)), NO_2 averages were higher compared to the two seasons analyzed in 2021. In the winter of 2024 (Figure 3 (M, N, O and P)), there was a significant increase in NO_2 concentrations compared to the previous dates. Table 1 shows that on September 11, 2024, the average NO_2 values were high (7.39E-05 mol/m²), similar to the analysis of the CO pollutant. This NO_2 data for the years 2021 and 2024 turned out to be significantly above average for the region of the state of Rio Grande do Sul, taking into account that within the last 5 years, this average has reached a value of 1.11E-5 mol/m². On September 11, 2024 (Figure 3 (N)), high NO_2 values were detected, with ≈6.65 times (565.76%) higher than the normal average levels for the region analyzed (ESA, 2024).

To analyze the spatial distribution of pollutant gases in the atmosphere of the state of Rio Grande do Sul, the K-means clustering methodology was applied (Hajihosseinlou *et al*. 2024), which revealed the model's performance in dividing the data set collected by the TROPOMI sensor into groups. It can be seen that the data from the 522 collection points was divided into 5 clusters. This generated an R^2 of 0.180, which determined the K-means model. The high AIC (13.998) and BIC (14.680) indices reveal a cluster with a Silhouette index of 0.050, representing a model with spatially dispersed data.

With regard to the performance of the statistical model (Hajihosseinlou *et al*. 2024), Table 2 provides data on the characteristics of each individual cluster. Cluster 1, with 67 points, has an explained proportion of 0.142, a sum of squares of 1.936 and a Silhouette index of 0.054, indicating a reasonable separation from the other clusters. Cluster 4, with 89 points, has an explained proportion of 0.205, a sum of squares of 2.803 and the lowest Silhouette index (0.018), indicating little distinction from the other clusters. Cluster 2, with 104 points, has an explained proportion of 0.212, a sum of squares of 2.905 and a Silhouette index of 0.047, suggesting moderate cohesion. Cluster 5, with 126 points, has an explained proportion of 0.200, a sum of squares of 2.730, and the highest Silhouette index of 0.084, indicating a clearer, more precise definition. Finally, Cluster 3, the largest with 136 points, has the highest explained proportion of 0.242, a sum of squares of 3.304 and a Silhouette index of 0.036, showing moderate separation and less definition than Cluster 5.

Table 2 - Statistical information of the 5 clusters generated from data collected from the TROPOMI sensor.

Clusters	**1**	**2**	**3**	**4**	**5**
Size	67	104	136	89	126
Explained proportion of heterogeneity within the cluster	0.142	0.212	0.242	0.205	0.2
Sum of internal squares	1.936	2.905	3.304	2.803	2.730
Silhouette score	0.054	0.047	0.036	0.018	0.084

Source: Statistical modeling of data detected from geospatial collections by TROPOMI (ESA, 2024).

Table 3 shows the averages for each of the 5 clusters analyzed in relation to the data set. Cluster 1 tends to have higher CO values (Figure 3 (E and H)). The pollutant NO2's lowest values were grouped together (Figure 3 (U, W, AC and AD)). Cluster 2 has predominantly low values for both variables, with the lowest CO averages standing out (Figure 3 (O and P)), as well as some of the lowest NO_2 averages (Figure 3 (Z and AA)). Cluster 3 shows mixed values for CO and NO_2, with data varying around the data set's average. Cluster 4 reveals the highest peaks of

Periódico Eletrônico Fórum Ambiental da Alta Paulista
Electronic Journal Environmental Forum of Alta Paulista
ISSN 2966-2931 Suporte Online / *Online Support* - ISSN 1980-0827 Suporte CD-ROM / *CD-ROM Support*
Edição em Português e Inglês / *Edition in Portuguese and English* - v. 21, n. 2, 2025

NO_2 (Figure 3 (T, U, W, X, AC and AD)) and CO (Figure 3 (G and O)), showing primarily moderate CO values, with high data mainly in winter, indicating a seasonal variation. Cluster 5 maintains low CO values (Figure 3 (H and I)) and a higher NO_2 variation predominantly in summer (Figure 3 (R, Z and AA)).

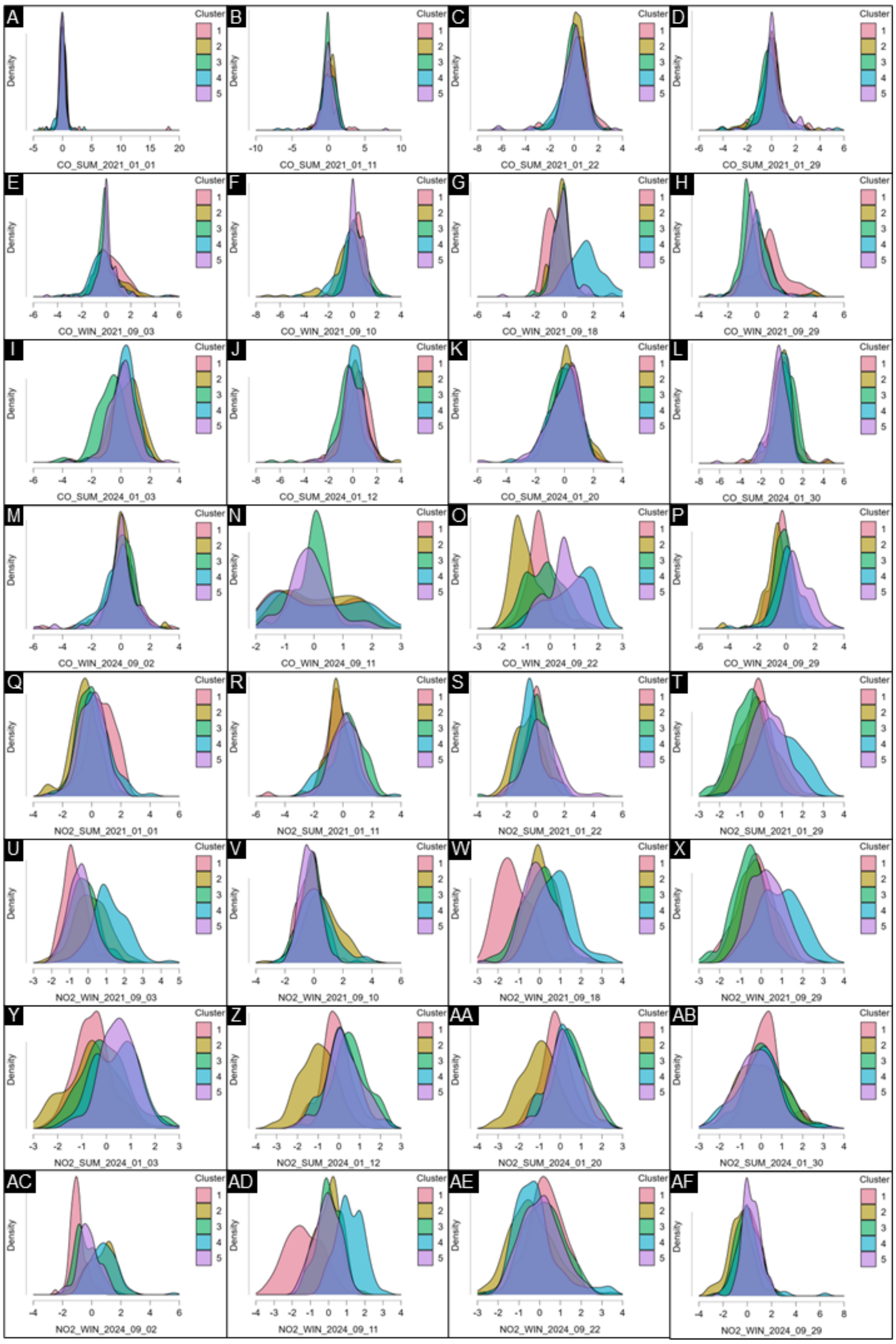
Table 3 - Averages of the 5 clusters in relation to the data set of CO and NO_2 variables collected from the TROPOMI sensor.

Satellite images	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 5**
CO_SUM_2021_01_01	0.378	-2.52E+01	-0.018	-0.053	-0.145
CO_SUM_2021_01_11	0.168	0.203	-0.062	-0.045	-0.159
CO_SUM_2021_01_22	0.239	0.112	-0.053	-0.071	-0.112
CO_SUM_2021_01_29	0.009	0.051	0.254	-0.032	-0.299
CO_WIN_2021_09_03	0.566	0.096	0.016	-0.213	-0.247
CO_WIN_2021_09_10	0.178	-0.614	0.291	-0.276	0.294
CO_WIN_2021_09_18	-0.751	-0.223	-0.155	1.430	-0.258
CO_WIN_2021_09_29	1.014	0.200	-0.232	0.096	-0.522
CO_SUM_2024_01_03	0.176	0.392	0.081	0.351	-0.753
CO_SUM_2024_01_12	0.321	0.159	-0.032	0.180	-0.395
CO_SUM_2024_01_20	0.110	0.135	-0.067	-0.075	-0.045
CO_SUM_2024_01_30	0.204	-0.048	-0.422	-0.098	0.456
CO_WIN_2024_09_02	-0.048	0.078	-0.086	-0.209	0.202
CO_WIN_2024_09_11	-0.078	0.214	-0.128	0.092	-0.062
CO_WIN_2024_09_22	-0.330	-1.052	0.599	0.911	-0.246
CO_WIN_2024_09_29	-0.419	-0.721	0.823	0.164	-0.186
NO2_SUM_2021_01_01	0.673	-0.508	-0.001	0.277	-0.133
NO2_SUM_2021_01_11	-0.375	-0.343	0.120	-0.178	0.479
NO2_SUM_2021_01_22	0.133	-0.558	0.396	-0.271	0.153
NO2_SUM_2021_01_29	-0.326	-0.198	0.326	0.891	-0.645
NO2_WIN_2021_09_03	-0.748	0.189	-0.377	1.188	-0.190
NO2_WIN_2021_09_10	-0.243	0.561	-0.299	0.227	-0.171
NO2_WIN_2021_09_18	-1.268	0.106	0.072	0.760	-0.028
NO2_WIN_2021_09_29	-0.331	-0.186	0.269	0.907	-0.602
NO2_SUM_2024_01_03	-0.557	-0.560	0.498	0.378	-0.046
NO2_SUM_2024_01_12	-0.149	-1.050	0.277	0.126	0.558
NO2_SUM_2024_01_20	-0.171	-1.061	0.306	0.171	0.515
NO2_SUM_2024_01_30	0.227	0.021	-0.223	-0.090	0.167
NO2_WIN_2024_09_02	-0.976	0.644	-0.197	0.802	-0.366
NO2_WIN_2024_09_11	-1.387	-0.031	-0.086	1.161	0.036
NO2_WIN_2024_09_22	0.306	-0.385	0.059	-0.210	0.239
NO2_WIN_2024_09_29	0.098	-0.568	0.325	0.233	-0.099
CO_SUM_2021_01_01	0.378	-2.52E+01	-0.018	-0.053	-0.145
CO_SUM_2021_01_11	0.168	0.203	-0.062	-0.045	-0.159
CO_SUM_2021_01_22	0.239	0.112	-0.053	-0.071	-0.112
CO_SUM_2021_01_29	0.009	0.051	0.254	-0.032	-0.299

Source: Statistical modeling based on geospatial data collected by TROPOMI (ESA, 2024).

Periódico Eletrônico Fórum Ambiental da Alta Paulista
Electronic Journal Environmental Forum of Alta Paulista
ISSN 2966-2931 Suporte Online / *Online Support* - ISSN 1980-0827 Suporte CD-ROM / *CD-ROM Support*
Edição em Português e Inglês / *Edition in Portuguese and English* - v. 21, n. 2, 2025

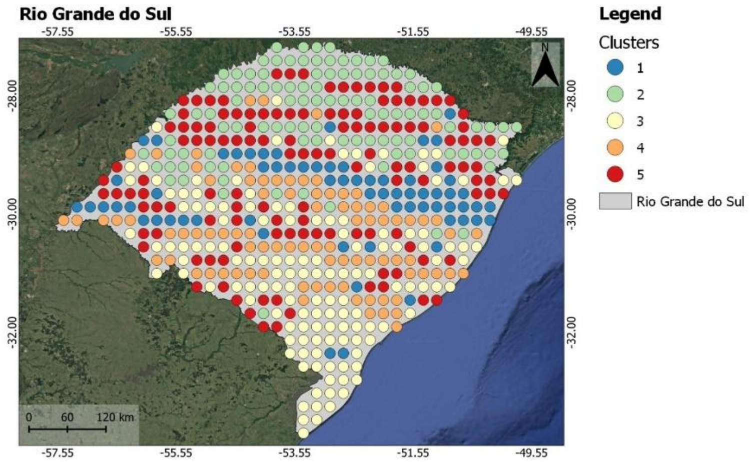
Figure 4 – Representation of the clusters related to CO and NO_2 levels modeled via TROPOMI.



Source: Clusters represented from geospatial collections by TROPOMI (ESA, 2024).

The cluster data reveals the intensity of the data dispersion between the 522 points analyzed, which indicates the great complexity of the spatial arrangement of gases in the atmosphere of the state of Rio Grande do Sul, given the great inherent variability of this dynamic. Figure 5 shows observations where cluster 1 is arranged heterogeneously in the center of the state, indicating that these locations have higher CO values, while there are low NO_2 values. Cluster 2 is located predominantly in the north of the state, indicating low concentrations of both pollutants in this location. Cluster 3 is mostly located from the center to the south of the study area, indicating values close to the average of the data set. Cluster 4 is heterogeneously located in the center of the state, revealing that the highest concentrations of the pollutants analyzed are dispersed in the center of Rio Grande do Sul by shifting air masses. Cluster 5 is dispersed throughout the study area, showing mixed values of CO and NO_2.

Figure 5 – Overlapping clusters in the state of Rio Grande do Sul in relation to CO and NO_2 levels detected via TROPOMI.



4 CONCLUSION

This study revealed results with quantitative CO levels of 0.0244 mol/m², attesting that on September 11, 2024, concentrations were ≈5.9 times (490.16%) higher than normal average levels. NO_2 levels in 2024 reached a value of 1.11E-5 mol/m², giving rise to levels ≈6.65 times (565.76%) higher than the resulting average levels.

From the data detected via TROPOMI, it can be seen that the pollutants showed a pattern of increasing atmospheric concentrations in the state of Rio Grande do Sul. The periods analyzed with the highest CO and NO_2 averages in the region were the same as those recorded during major fires in the Amazon, Pantanal, and other locations in South America, whose pollutants may have been transported by the prevailing direction of the winds on the continent, contributing to the high concentration of these pollutants in the study area. Therefore, it is confirmed that fires are the central hypothesis about the possible causes of the high value of atmospheric pollutants in the state of Rio Grande do Sul.

In this context, it is suggested that future studies be carried out in other Brazilian states, capable of assessing more quantitative proportions of atmospheric pollutants, including aerosols. In this sense, it is worth emphasizing that TROPOMI has proved to be a capable and effective tool for detecting geospatial data that will contribute to the creation of new effective public policies capable of mitigating the continuation of forest fires in Brazil.

The authors would like to thank the European Space Agency (ESA) for providing the unpublished data from the Sentinel-5P (TROPOMI) satellite. We would also like to thank the Center for Studies and Research in Urban Mobility (NEPMOUR+S/ATITUS); the Meridional Foundation; the National Council for Scientific and Technological Development (CNPq), Brazil for awarding the CNPq Research Productivity Grant - Level 2.

5 REFERENCES

BODAH, Brian William; NECKEL, Alcindo; MACULAN, Laércio Stolfo; MILANES, Celene B.; KORCELSKI, Cleiton; RAMÍREZ, Omar; MENDEZ-ESPINOSA, Juan F.; BODAH, Eliane Thaines; OLIVEIRA, Marcos L.S. Sentinel-5P TROPOMI satellite application for NO2 and CO studies aiming at environmental valuation. **Journal Of Cleaner Production**, [S.L.], v. 357, p. 131960, jul. 2022.

CHEN, Cheng; LITVINOV, Pavel; DUBOVIK, Oleg; BINDREITER, Lukas; MATAR, Christian; FUERTES, David; LOPATIN, Anton; LAPYONOK, Tatyana; LANZINGER, Verena; HANGLER, Andreas. Extended aerosol and surface characterization from S5P/TROPOMI with GRASP algorithm. Part II: global validation and intercomparison. **Remote Sensing Of Environment**, [S.L.], v. 313, p. 114374, nov. 2024.

ESA (European Space Agency). Applications: TROPOMI. 2024. Disponível em: https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P/Tropomi.

FADAIRO, Adebayo Afolabi; WONG, Pak Kin; IP, Weng Fai; GHADIKOLAEI, Meisam Ahmadi; CAI, Zhe; NG, Kar Wei; LIAN, Zhen Dong. Impact of neem oil biodiesel blends on physical and chemical properties of particulate matter emitted from diesel engines. **Environmental Pollution**, [S.L.], v. 362, p. 124972, dez. 2024.

FILONCHYK, Mikalai; PETERSON, Michael P. Changes in aerosol properties at the El Arenosillo site in Southern Europe as a result of the 2023 Canadian forest fires. **Environmental Research**, [S.L.], v. 260, p. 119629, nov. 2024.

Instituto Brasileiro de Geografia e Estatística (IBGE). **Cidades e Estados**. 2024. Disponível em: https://www.ibge.gov.br/cidades-e-estados/rs.html.

Instituto Nacional de Pesquisas Espaciais (INPE). **Programa Queimadas do INPE:** BDQUEIMADAS, 2024. https://terrabrasilis.dpi.inpe.br/queimadas/bdqueimadas/.

KUśMIERCZYK-MICHULEC, Jolanta; BARÉ, Jonathan. Global atmospheric monitoring of radionuclides and noble gases: insights into the interhemispheric transport of anthropogenic emissions. **Atmospheric Environment**, [S.L.], v. 319, p. 120304, fev. 2024.

MAHESHWARKAR, Prem; CUESTA, Juan; FORMENTI, Paola; LEMMOUCHI, Farouk. Three-dimensional distribution of aerosols of multiple types at daily scale using TROPOMI spaceborne observations. **Science Of The Total Environment**, [S.L.], v. 955, p. 177037, dez. 2024.

NECKEL, Alcindo; OLIVEIRA, Marcos L.S.; DOTTO, Guilherme L.; MACULAN, Laércio Stolfo; BODAH, Brian William; SILVA, Luis F.O. Sentinel-3B OLCI satellite imagery and advanced electron microscopy of nanoparticle analysis in a marine estuary and watershed: robust multi-analytics and geospatial assessment of key contaminants. **Journal Of Hydrology**, [S.L.], v. 612, p. 128278, set. 2022.

SUN, Jian; SHEN, Zhenxing; ZHANG, Bin; ZHANG, Leiming; ZHANG, Yue; ZHANG, Qian; WANG, Diwei; HUANG, Yu; LIU, Suixin; CAO, Junji. Chemical source profiles of particulate matter and gases emitted from solid fuels for residential cooking and heating scenarios in Qinghai-Tibetan Plateau. **Environmental Pollution**, [S.L.], v. 285, p. 117503, set. 2021.

World Health Organization (WHO). WHO Global Air. **Quality guidelines: particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulphur dioxide and carbon monoxide**; WHO: Genebra, 2021. Disponível em: https://www.who.int/publications/i/item/9789240034228.

World Meteorological Organization's (WMO). **Os Impactos da Matéria Particulada na Produção Agrícola: Mecanismos, Quantificação e Opções para Mitigação (OMM-No. 1340).** Genebra, 2023.

World Meteorological Organization's (WMO). **Boletim de Qualidade do Ar e Clima da OMM**, n.º 2; OMM: Genebra, 2022.

STATEMENTS

EACH AUTHOR'S CONTRIBUTION

When describing the participation of each author in the manuscript, use the following criteria:

- **Study conception and design**: Luana Pasquetti and Guilherme Peterle Schmitz
- **Data Curation**: Luana Pasquetti
- **Formal Analysis**: Grace Tibério Cardoso
- **Research**: Grace Tibério Cardoso
- **Methodology**: Guilherme Peterle Schmitz and Alcindo Neckel
- **Writing - Initial Draft**: Caliane Christie Oliveira de Almeida
- **Writing - Critical Review**: Caliane Christie Oliveira de Almeida
- **Proofreading and Final Editing**: Alcindo Neckel
- **Supervision**: Alcindo Neckel and Caliane Christie Oliveira de Almeida

DECLARATION OF CONFLICTS OF INTEREST

We, **Luana Pasquetti**, **Guilherme Peterle Schmitz**, **Alcindo Neckel**, **Caliane Christie Oliveira de Almeida** and **Grace Tibério Cardoso**, declare that the manuscript entitled “Use of the TROPOMI sensor to detect atmospheric pollutants from forest fires moving towards southern Brazil”:

1. Financial ties: We have no financial ties that could influence the results or interpretation of the work.

2. Professional Relationships: We have no professional relationships that could have an impact on the analysis, interpretation or presentation of the results.

3. Personal Conflicts: We have no personal conflicts of interest related to the contente of the manuscript.