Monitoring the transport of pollutants derived from forest fires: geotechnologies applied to southern Brazil

Monitoramento do transporte de poluentes derivados de queimadas: geotecnologias aplicadas ao sul do Brasil

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***Abstract**: This study aims to quantify atmospheric pollution in the state of Rio Grande do Sul (Brazil) between January 2021 and September 2024. A qualitative–quantitative approach was adopted, combining environmental and Remote Sensing analysis. Data from the Sentinel-5P satellite, equipped with the TROPOspheric Monitoring Instrument (TROPOMI) from the European Space Agency (ESA), were used. Image processing was carried out using the SNAP and QGIS software. Data spreadsheets were generated from satellite imagery for the subsequent application of the K-means clustering algorithm in the JASP software. The study contributes to environmental public policies aimed at mitigating atmospheric pollution. The results revealed CO levels of 0.0244 mol/m², which on September 11, 2024, were about 5.9 times (490.16%) higher than the average observed in the state. NO_2 concentrations in 2024 reached 1.11E-5 mol/m², representing approximately 6.65 times (565.76%) higher values than the recorded averages. The methodology proved to be a replicable monitoring model, adaptable to other regions. The data indicated that the highest CO and NO_2 values coincided with major wildfires in South America, whose pollutants, transported by winds, suggest these fires as the main cause of atmospheric pollution in the analyzed area.*

***Keywords**: Air quality. Atmospheric pollution. Forest fires. TROPOMI.*

***Resumo**: Este estudo tem como objetivo quantificar a poluição atmosférica no estado do Rio Grande do Sul (Brasil) entre janeiro de 2021 e setembro de 2024. Adotou-se abordagem quali-quantitativa, combinando análise ambiental e de Sensoriamento Remoto. Foram utilizados dados do satélite Sentinel-5P, com o instrumento TROPOspheric Monitoring Instrument (TROPOMI), da Agência Espacial Europeia (ESA). O processamento das imagens foi realizado nos softwares SNAP e QGIS. Planilhas de dados foram geradas a partir das imagens de satélite para posterior aplicação do algoritmo de agrupamento K-means no software JASP. O estudo contribui para políticas públicas ambientais voltadas à mitigação da poluição atmosférica. Os resultados revelaram níveis de CO de 0,0244 mol/m², que em 11 de setembro de 2024 foram cerca de 5,9 vezes (490,16%) superiores à média observada no estado. As concentrações de NO_2 em 2024 atingiram 1,11E-5 mol/m², representando valores aproximadamente 6,65 vezes (565,76%) acima dos níveis médios registrados. A metodologia demonstrou-se modelo replicável de monitoramento, adaptável a outras regiões. A coleta indicou que os maiores valores de CO e NO_2 coincidiram com grandes queimadas na América do Sul, cujos poluentes, transportados pelos ventos, apontam essas queimadas como principal causa da poluição atmosférica no recorte analisado.*

***Palavras-chave**: Qualidade do ar. Poluição atmosférica. Queimadas. TROPOMI.*

Resumen: *Este estudio tiene como objetivo cuantificar la contaminación atmosférica en el estado de Rio Grande do Sul (Brasil) entre enero de 2021 y septiembre de 2024. Se adoptó un enfoque cuali-cuantitativo, combinando análisis ambiental y de Teledetección. Se usaron datos del satélite Sentinel-5P con el instrumento TROPOspheric Monitoring Instrument (TROPOMI) de la Agencia Espacial Europea (ESA). El procesamiento de imágenes se realizó en los programas SNAP y QGIS. Las planillas de datos se generaron a partir de imágenes satelitales para aplicar posteriormente el algoritmo K-means en el software JASP. El estudio contribuye a políticas públicas ambientales orientadas a mitigar la contaminación atmosférica. Los resultados revelaron niveles de CO de 0,0244 mol/m², que el 11 de septiembre de 2024 fueron unas 5,9 veces (490,16%) superiores al promedio estatal. Las concentraciones de NO_2 en 2024 alcanzaron 1,11E-5 mol/m², valores aproximadamente 6,65 veces (565,76%) mayores que los niveles medios registrados. La metodología se demostró como modelo replicable de monitoreo, adaptable a otras regiones. Los datos indicaron que los mayores valores de CO y NO_2 coincidieron con grandes incendios en América del Sur, cuyos contaminantes, transportados por los vientos, señalan estos incendios como la principal causa de la contaminación atmosférica en el área analizada.*

Palabras clave: *Calidad del aire. Contaminación atmosférica. Incendios. TROPOMI.*

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 PM2.5 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 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).

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).

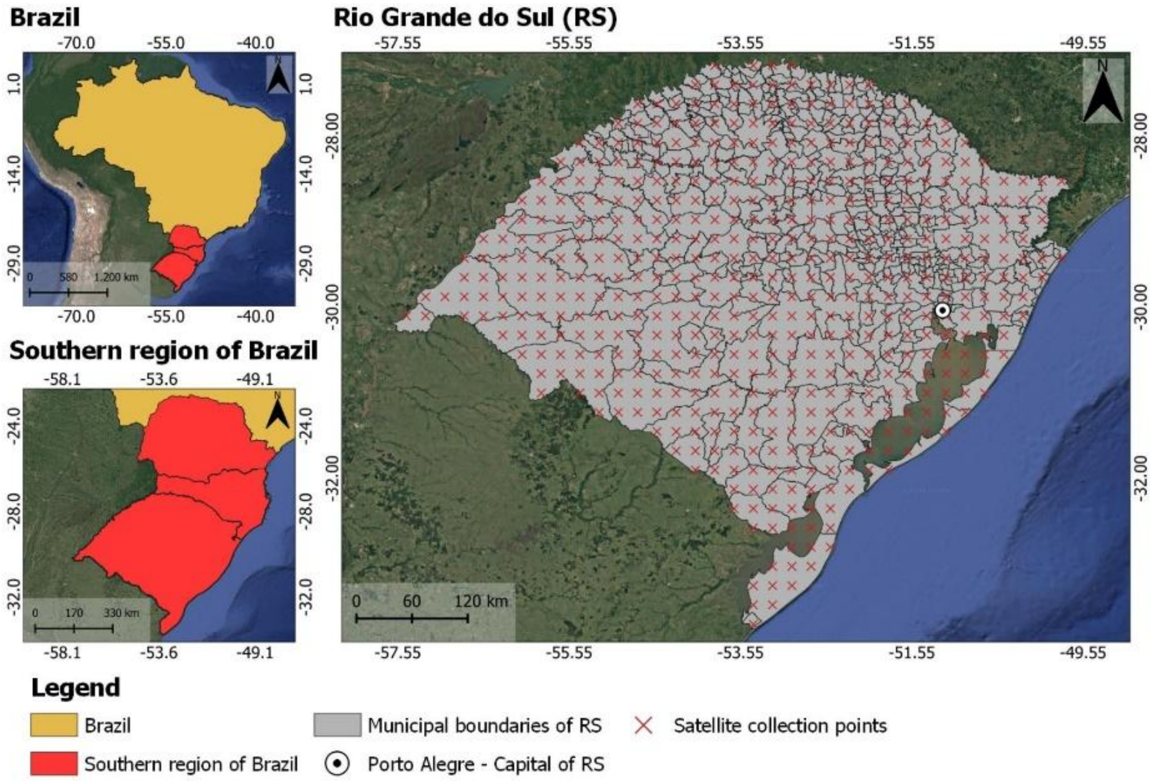

Figure 1: Location of the state of Rio Grande do Sul in Brazil, in relation to the grid of detection points via TROPOMI.

Source: Prepared from the IBGE database (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, 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 performed using QGIS (Quantum GIS), which enabled geospatial visualization, analysis, and map preparation for this study. The methodology was designed to provide a comprehensive analysis of air pollution in Rio Grande do Sul, using Sentinel-5P satellite data, essential for understanding air quality in large regions (Chen *et al*., 2024). The integration of remote sensing with geospatial analysis techniques and validation using terrestrial data provides a solid basis for understanding CO and NO_2 concentrations over time (Bodah *et al*., 2022; Maheshwarkar *et al*., 2024). Despite limitations related to cloud cover and spatial resolution in urban areas, the method allows the identification of emission patterns and their potential impacts on public health (Bodah *et al*., 2022). The collected data were modeled using the K-means clustering methodology (Hajihosseinlou *et al*., 2024), improving the understanding of the results. This approach contributes significantly to air quality management and environmental monitoring in large regions, with potential for future expansion through 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)).

Satellite images	Valid	Lost	Average	Standard Deviation	Variance	Minimum	Maximum
CO | SUM - 01/01/2021	522	0	0.020	0.005	2.51E-05	0	0.111
CO | SUM - 01/11/2021	522	0	0.025	0.004	1.29E-05	0	0.053
CO | SUM - 01/22/2021	522	0	0.017	0.003	7.78E-06	0	0.027
CO | SUM - 01/29/2021	522	0	0.019	0.005	2.19E-05	0	0.044

CO | WIN - 09/03/2021	522	0	0.028	0.004	1.33E-05	0.01	0.047
CO | WIN - 09/10/2021	522	0	0.023	0.003	9.21E-06	0.002	0.031
CO | WIN - 09/18/2021	522	0	0.029	0.004	1.77E-05	0.011	0.046
CO | WIN - 09/29/2021	522	0	0.027	0.004	1.59E-05	0.014	0.043
CO | SUM - 01/03/2024	522	0	0.020	0.002	4.65E-06	0.01	0.027
CO | SUM - 01/12/2024	522	0	0.020	0.003	8.83E-06	0	0.031
CO | SUM - 01/20/2024	522	0	0.019	0.002	5.46E-06	0.005	0.025
CO | SUM - 01/30/2024	522	0	0.017	0.002	5.19E-06	0.003	0.028
CO | WIN - 09/02/2024	522	0	0.024	0.003	1.10E-05	0.005	0.035
CO | WIN - 09/11/2024	522	0	0.144	0.044	0.002	0.064	0.255
CO | WIN - 09/22/2024	522	0	0.077	0.022	4.82E-04	0.032	0.126
CO | WIN - 09/29/2024	522	0	0.035	0.006	3.88E-05	0.007	0.056
NO_2 | SUM - 01/01/2021	522	0	5.87E-05	5.59E-06	3.12E-11	4.09E-05	8.13E-05
NO_2 | SUM - 01/11/2021	522	0	6.26E-05	5.24E-06	2.75E-11	3.56E-05	8.11E-05
NO_2 | SUM - 01/22/2021	522	0	5.60E-05	6.03E-06	3.63E-11	3.28E-05	8.30E-05
NO_2 | SUM - 01/29/2021	522	0	5.70E-05	4.55E-06	2.07E-11	4.49E-05	7.10E-05
NO_2 | WIN - 09/03/2021	522	0	5.46E-05	5.21E-06	2.71E-11	4.26E-05	7.78E-05
NO_2 | WIN - 09/10/2021	522	0	5.25E-05	4.31E-06	1.86E-11	3.80E-05	7.03E-05
NO_2 | WIN - 09/18/2021	522	0	6.03E-05	5.33E-06	2.84E-11	4.58E-05	7.80E-05
NO_2 | WIN - 09/29/2021	522	0	5.69E-05	4.75E-06	2.25E-11	4.36E-05	7.26E-05
NO_2 | SUM - 01/03/2024	522	0	6.79E-05	5.31E-06	2.82E-11	5.24E-05	8.26E-05
NO_2 | SUM - 01/12/2024	522	0	6.20E-05	5.10E-06	2.61E-11	4.57E-05	7.44E-05
NO_2 | SUM - 01/20/2024	522	0	6.19E-05	5.06E-06	2.56E-11	4.57E-05	7.38E-05
NO_2 | SUM - 01/30/2024	522	0	6.08E-05	3.97E-06	1.58E-11	4.95E-05	7.42E-05
NO_2 | WIN - 09/02/2024	522	0	5.61E-05	7.07E-06	5.00E-11	3.85E-05	9.58E-05
NO_2 | WIN - 09/11/2024	522	0	7.39E-05	6.35E-06	4.03E-11	5.23E-05	9.37E-05
NO_2 | WIN - 09/22/2024	522	0	6.95E-05	6.77E-06	4.58E-11	5.10E-05	9.29E-05
NO_2 | WIN - 09/29/2024	522	0	6.55E-05	6.15E-06	3.79E-11	4.54E-05	1.05E-04

Table 1 - Descriptive statistics of the data collected in the summer (SUM) and winter (WIN) from the 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.

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).

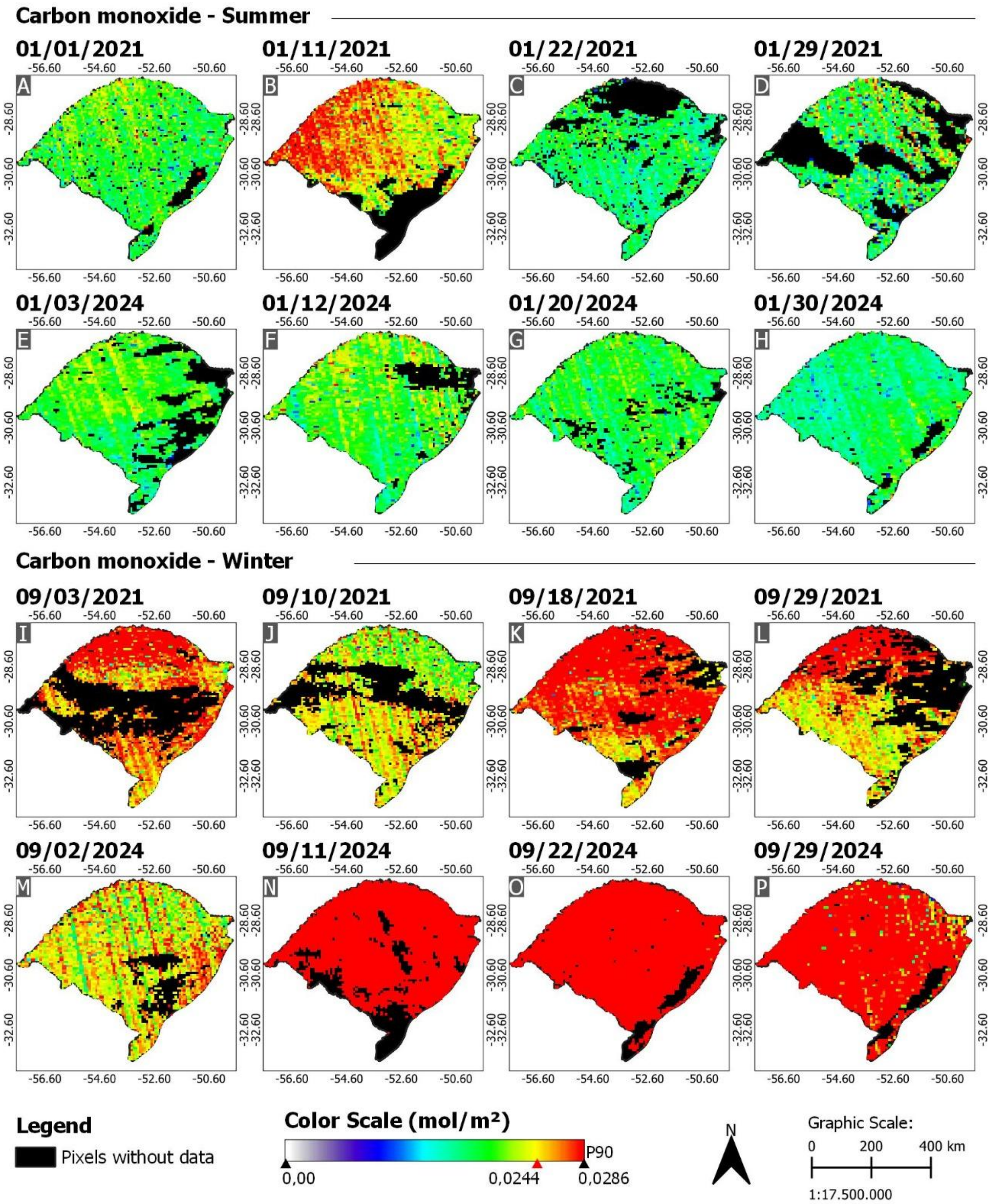

Figure 2 – Representation of carbon monoxide (CO) levels collected in this study via TROPOMI.

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 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 NO_2 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).

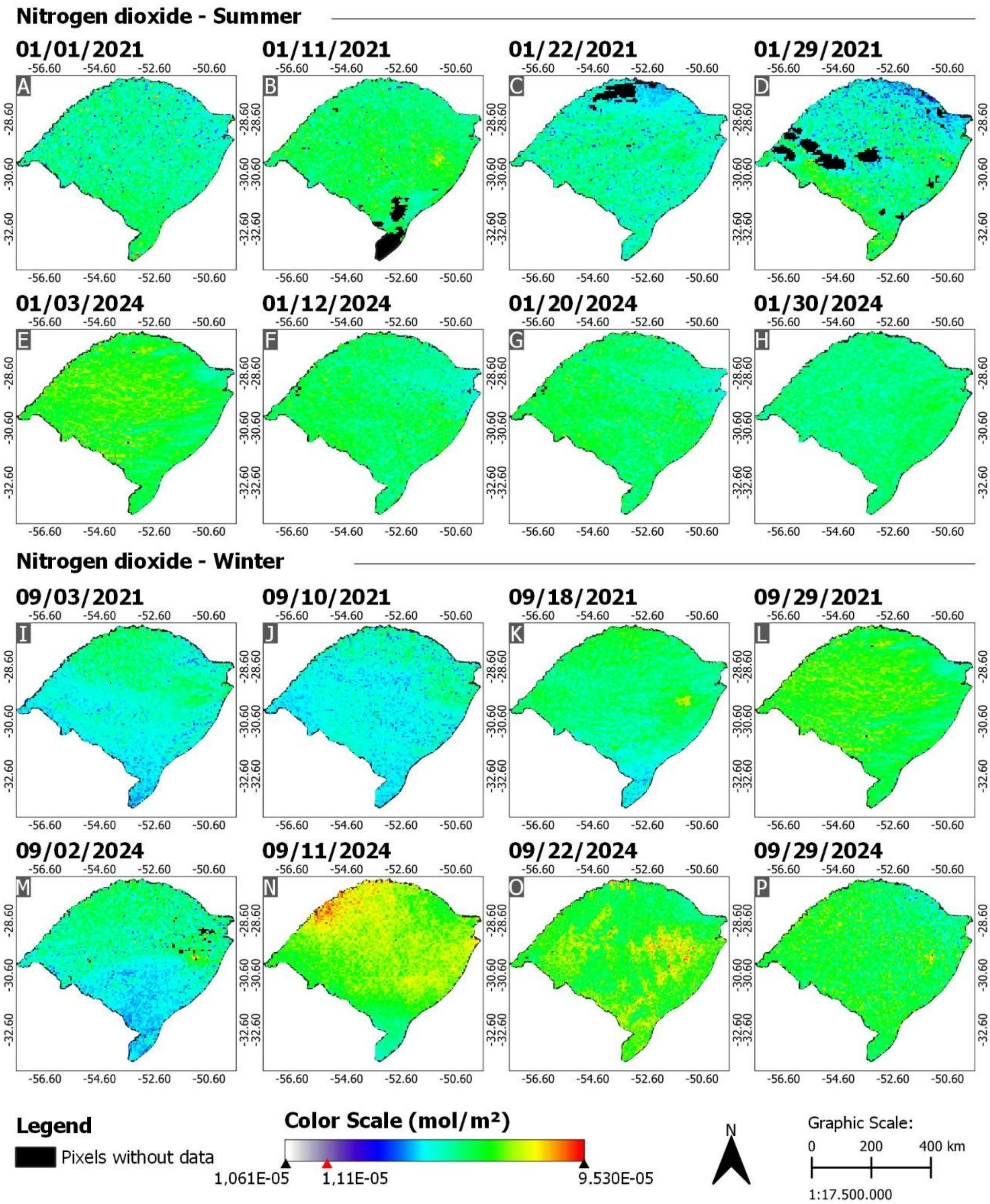

Figure 3 – Representation of the nitrogen dioxide (NO_2) levels collected in this study via TROPOMI.

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.

Regarding the performance of the statistical model (Hajihosseinlou *et al*., 2024), Table 2 presents the characteristics of each cluster. Cluster 1 (67 points) shows an explained proportion of 0.142, a sum of squares of 1.936, and a Silhouette index of 0.054, indicating reasonable separation. Cluster 4 (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. Cluster 2 (104 points) presents 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 (126 points) shows an explained proportion of 0.200, a sum of squares of 2.730, and the highest Silhouette index (0.084), indicating clearer definition. Finally, Cluster 3 (136 points) has the highest explained proportion (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.

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	0.200
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

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

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 NO_2'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 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)).

Satellite images	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
CO | SUM - 01/01/2021	0.378	-0.522	-0.018	-0.053	-0.145
CO | SUM - 01/11/2021	0.168	0.203	-0.062	-0.045	-0.159
CO | SUM - 01/22/2021	0.239	0.112	-0.053	-0.071	-0.112
CO | SUM - 01/29/2021	0.009	0.051	0.254	-0.032	-0.299
CO | WIN - 09/03/2021	0.566	0.096	0.016	-0.213	-0.247
CO | WIN - 09/10/2021	0.178	-0.614	0.291	-0.276	0.294
CO | WIN - 09/18/2021	-0.751	-0.223	-0.155	1.430	-0.258
CO | WIN - 09/29/2021	1.014	0.200	-0.232	0.096	-0.522
CO | SUM - 01/03/2024	0.176	0.392	0.081	0.351	-0.753
CO | SUM - 01/12/2024	0.321	0.159	-0.032	0.180	-0.395
CO | SUM - 01/20/2024	0.110	0.135	-0.067	-0.075	-0.045
CO | SUM - 01/30/2024	0.204	-0.048	-0.422	-0.098	0.456
CO | WIN - 09/02/2024	-0.048	0.078	-0.086	-0.209	0.202
CO | WIN - 09/11/2024	-0.078	0.214	-0.128	0.092	-0.062
CO | WIN - 09/22/2024	-0.330	-1.052	0.599	0.911	-0.246
CO | WIN - 09/29/2024	-0.419	-0.721	0.823	0.164	-0.186
NO_2 | SUM - 01/01/2021	0.673	-0.508	-0.001	0.277	-0.133
NO_2 | SUM - 01/11/2021	-0.375	-0.343	0.120	-0.178	0.479
NO_2 | SUM - 01/22/2021	0.133	-0.558	0.396	-0.271	0.153
NO_2 | SUM - 01/29/2021	-0.326	-0.198	0.326	0.891	-0.645
NO_2 | WIN - 09/03/2021	-0.748	0.189	-0.377	1.188	-0.190
NO_2 | WIN - 09/10/2021	-0.243	0.561	-0.299	0.227	-0.171
NO_2 | WIN - 09/18/2021	-1.268	0.106	0.072	0.760	-0.028
NO_2 | WIN - 09/29/2021	-0.331	-0.186	0.269	0.907	-0.602
NO_2 | SUM - 01/03/2024	-0.557	-0.560	0.498	0.378	-0.046
NO_2 | SUM - 01/12/2024	-0.149	-1.050	0.277	0.126	0.558
NO_2 | SUM - 01/20/2024	-0.171	-1.061	0.306	0.171	0.515
NO_2 | SUM - 01/30/2024	0.227	0.021	-0.223	-0.090	0.167
NO_2 | WIN - 09/02/2024	-0.976	0.644	-0.197	0.802	-0.366
NO_2 | WIN - 09/11/2024	-1.387	-0.031	-0.086	1.161	0.036
NO_2 | WIN - 09/22/2024	0.306	-0.385	0.059	-0.210	0.239
NO_2 | WIN - 09/29/2024	0.098	-0.568	0.325	0.233	-0.099

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

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

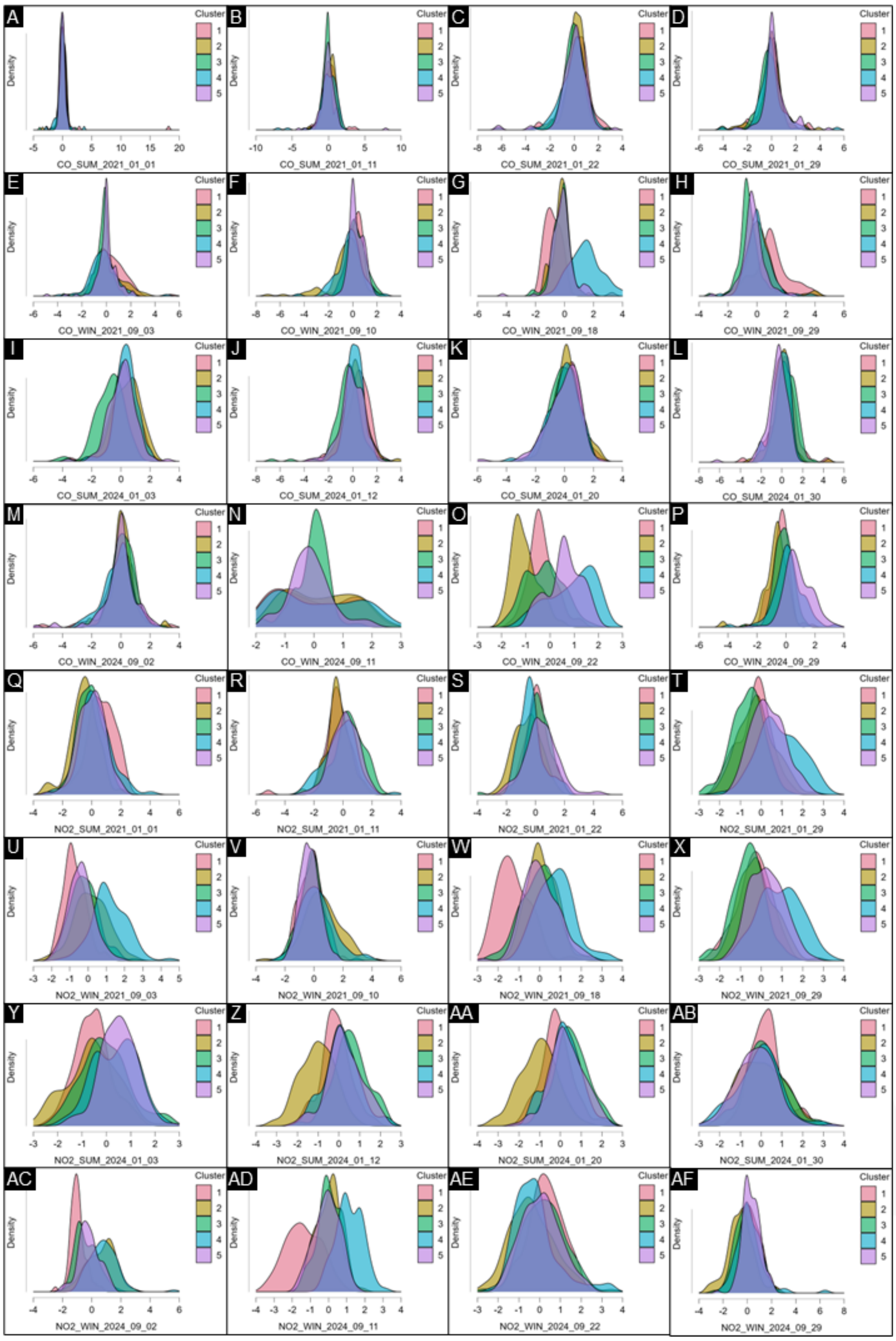

Figure 4 – Representation of the clusters related to CO and NO_2 levels modeled via TROPOMI.

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.

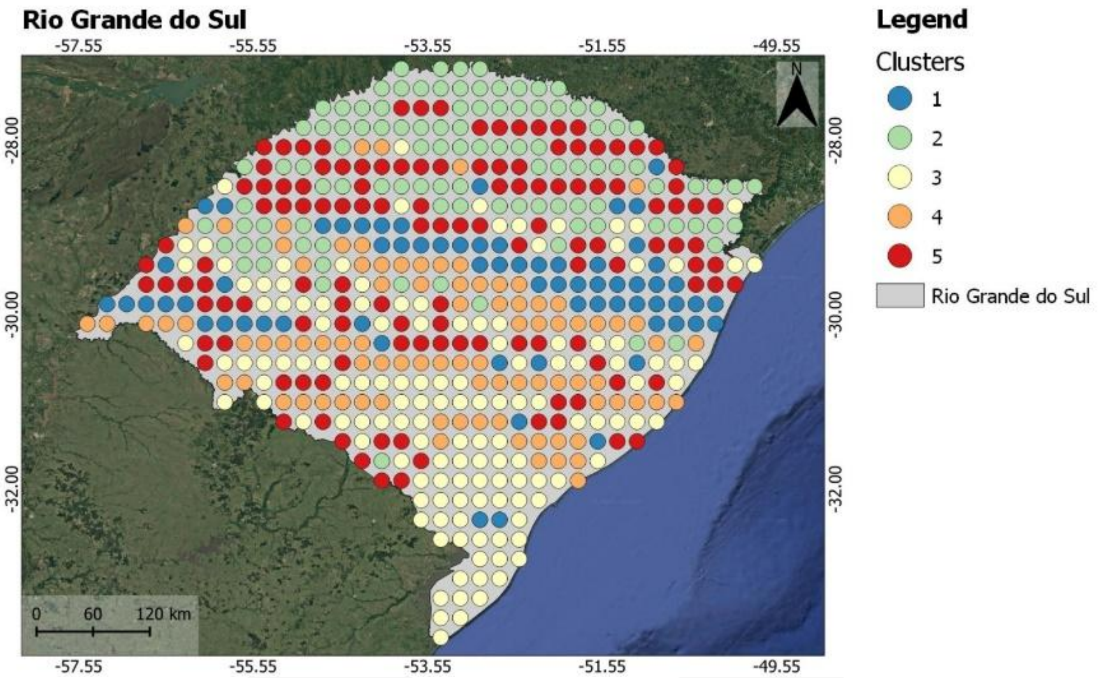

Figure 5 – Overlapping clusters in the state of Rio Grande do Sul in relation to CO and NO_2 levels detected via TROPOMI.

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

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.

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