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Ozone and $PM_{2.5}$ behavior in small cities in southern Brazil

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ABSTRACT
Air pollution is one of the greatest challenges facing humanity today. The number of studies has grown annually, but most of the time they have been conducted in megacities or heavily industrialized regions. In this study, we aimed to evaluate the behavior of O_3 and $PM_{2.5}$ in 5 small cities (< 1500 inhabitants) in southern Brazil, comparing them with reference cities in their micro-regions and with the metropolis Porto Alegre, capital of the state of Rio Grande do Sul. During the short period evaluated, the levels of pollutants in small cities would not differ from those found in the reference cities and were equivalent to the levels in the studied metropolis. Also, during 2 periods (18 to 20 September 2021 and 30 September to 2 October 2021) there were episodes of high levels of $PM_{2.5}$, superior to the national air quality criteria in 4 of the 5 small cities. The likely origin of the pollutants is the long-distance transport of pollutants from biomass burning in the Amazon. Multiple regression analysis showed little or no influence of local meteorological parameters for O_3 and $PM_{2.5}$ levels, but showed a strong association with pollutant levels in the respective reference cities. Understanding the dynamics of air pollutants in small cities is essential to understand some health outcomes in these populations and has been recently recommended by the World Health Organization.

Comportamento do ozônio e $PM_{2,5}$ em pequenas cidades do sul do Brasil

Palavras-chave:
poluição do ar; ozônio; material particulado; Rio Grande do Sul

RESUMO
A poluição do ar é um dos maiores desafios que a humanidade enfrenta na atualidade. O número de estudos cresce anualmente, mas na maioria das vezes eles são conduzidos em megacidades ou regiões fortemente industrializadas. Neste estudo, objetivamos avaliar o comportamento de O_3 e $PM_{2.5}$ em 5 pequenas cidades (< 1500 habitantes) no sul do Brasil, comparando-as com cidades de referência em suas microrregiões e com a metrópole Porto Alegre, capital do estado do Rio Grande do Sul. No curto período avaliado, os níveis de poluentes nas cidades pequenas não diferiram dos encontrados nas cidades de referência e foram equivalentes aos níveis da metrópole estudada. Além disso, durante 2 períodos (18 a 20 de setembro de 2021 e 30 de setembro a 2 de outubro de 2021) ocorreram episódios de níveis elevados de $PM_{2.5}$, superiores aos critérios nacionais de qualidade do ar em 4 das 5 pequenas cidades. A provável origem dos poluentes é o transporte de longa distância de poluentes da queima de biomassa na Amazônia. A análise de regressão múltipla mostrou pouca ou nenhuma influência dos parâmetros meteorológicos locais para os níveis de O_3 e $PM_{2.5}$, mas mostrou forte associação com os níveis de poluentes nas respectivas cidades de referência. Compreender a dinâmica dos poluentes atmosféricos em pequenas cidades é essencial para compreender alguns desfechos de saúde dessas populações e foi recentemente recomendado pela Organização Mundial da Saúde.

1. Introduction

Air pollution has been identified as an important triggering factor for numerous diseases around the world and it is estimated that 7 million deaths annually are related to the

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inhalation of these pollutants (1). Studies show that air pollution can reduce the life expectancy of the general population by up to 3 years in some regions of the world (2) and that the global reduction in the levels of particulate matter with a diameter smaller than 2.5 µm ($PM_{2.5}$) at 10 µg.m^{-3} would have an impact on reducing mortality equivalent to the eradication of lung cancer (3).

Conservative data indicate that half of the world population has been exposed to high levels of $PM_{2.5}$, when comparing the period between 2010 and 2016 (4), while the WHO (1) estimates that 9 out of 10 individuals are exposed at unsafe levels of air pollutants. Living in polluted sites increases the risk of developing respiratory, cardiovascular, cerebrovascular diseases, adverse neonatal outcomes and cancer (5,6). Most of these studies have been conducted in industrialized areas or in large urban agglomerations, where industries and motor vehicles are the main sources of contamination, respectively (1).

However, it is known that the dispersion of air pollutants can influence locations very far from the source of pollution and, therefore, cause damage to populations living far from these large industrial and urban centers (7). In this sense, meteorological variables play an important role in the displacement, concentration or dissipation of pollutants (8). In addition, there are other less studied sources of air pollution, such as forest fires, agricultural activities and natural sources that can compromise, even seasonally, the air quality and health of populations (9).

Studies on the dynamics of air pollutants in small and medium-sized cities are still a little discussed subject (10,11). However, some research has shown average annual concentrations of $PM_{2.5}$ in small towns exceed air quality standards (12,13). Meteorological variables are important factors associated with pollution events in small towns and among the potential sources of pollution there is the burning of biomass for heating and for agriculture and crustal dust (14,15).

In Brazil, this topic is even scarcer, where less than 2 % of the more than 5,000 municipalities have some continuous monitoring of air pollution (16). Most studies have been concentrated in large metropolises, and the rare studies in small towns have pointed to the contribution of long-distance transport of pollutants and from non-urban/industrial sources (7).

In this study, we evaluated the concentration of air pollutants in 5 small cities (< 1.5 thousand inhabitants) in the state of Rio Grande do Sul, southern Brazil and compared their levels with reference cities in each micro-region (with populations between 16 and 107 thousand inhabitants) and with the state capital, Porto Alegre, which has 1.5 million inhabitants.

2. Material and methods

2.1 Cities

The study was carried out with five small cities (< 1,500 inhabitants) from different microregions of the state of Rio Grande do Sul, southern Brazil: Engenho Velho (Frederico Westphalen microregion), União da Serra (Guaporé microregion), Porto Vera Cruz (microregion Santa Rosa), Carlos Gomes (Erechim microregion), Tupanci do Sul (Sananduva microregion). According to the Instituto Brasileiro de Geografia e Estatística (IBGE), each small city in the state is associated with a microregion and has a reference city. In addition to data from small cities and reference cities in each microregion, data were collected from the state capital, Porto Alegre, which has more than 1.5 million inhabitants. Soy, corn and wheat and fruit farming and livestock are the main economic activities of small cities (17). Among the reference cities of each microregion, Frederico

Westphalen's economy is directed towards trade and, to a lesser extent, agricultural activities and small industries, in Guaporé agriculture and agribusiness activities stand out, Santa Rosa has its economy dedicated to agriculture, Erechim has the services and commerce sectors as the base of the economy and in Sananduva agriculture and cattle raising stand out. Porto Alegre, an important metropolis in southern Brazil, has its economy based on services, trade and, to a lesser extent, industrial activity (17). The geographic location of the studied municipalities is shown in Figure 1, while the population data and distances between municipalities are shown in Table 1.

2.2 Data collection and analysis

The O_3 and $PM_{2.5}$ concentration (in $\mu g.m^{-3}$) and meteorological data were manually extracted from the Copernicus Atmospheric Monitoring Service (CAMS) for the period between September 18, 2021 and October 17, 2021. This period signifies the commencement of our monitoring activities. Additionally, September and October are recognized for their elevated frequency of wildfire occurrences in the country. Daily pollutant data were presented as mean, IC95 and minimum and maximum limits. Based on daily data, the percentage of episodes in which the concentrations of O_3 and $PM_{2.5}$ in the small cities evaluated exceeded the values of the concentrations in the reference city of the respective microregion and the state capital (Porto Alegre) was calculated. For comparison with Brazilian legal limits, we used the most restrictive value in order to protect health. Finally, a multiple linear regression analysis was performed, considering as independent variables the meteorological parameters (humidity, atmospheric pressure, wind speed, UV radiation index, and temperature) and the daily concentrations of pollutants in the respective reference city and in Porto Alegre. The values of β were presented, considering a critical p value of 0.05.

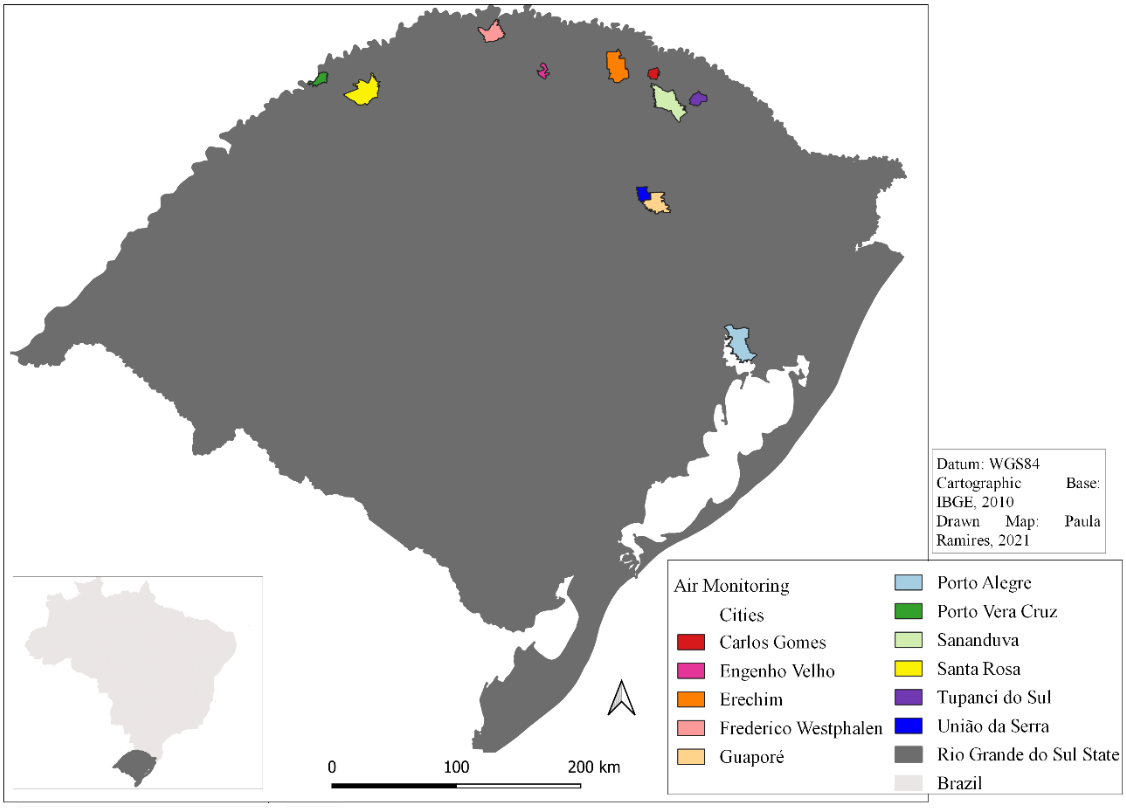

Figure 1 – Map highlighting the small cities studied

Table 1 – Information on the small cities studied

Small city	Population	Reference city	Population	Distance to reference city (km)	Distance to the state capital (km)
Engenho Velho	932	Frederico Westphalen	31,675	101	371
União da Serra	1,084	Guaporé	26,199	23.3	223
Porto Vera Cruz	1,258	Santa Rosa	73,882	50.2	540
Carlos Gomes	1,327	Erechim	107,368	50.9	345
Tupanci do Sul	1,447	Sananduva	16,382	37.9	316

3. Results

Daily measurements of O_3 and $PM_{2.5}$ in the cities studied (small cities, reference cities and state capital) are shown in Figure 2, while the averages for the investigated period are shown in Figure 3. Regarding O_3, only Porto Alegre city presented 4 daily episodes above the limit of the current national legislation (100 µg.m^{-3}), while all the other cities studied did not exceed the legal limit. On the other hand, in the case of $PM_{2.5}$, Porto Alegre did not exceed the legal daily limit in any episode during the period evaluated, while 4 of the 5 small cities exceeded the limit of 25 µg.m^{-3} in one (Engenho Velho, Carlos Gomes and Tupanci do Sul) or two episodes (Porto Vera Cruz). Regarding the reference cities, 4 of the 5 cities also exceeded the legal limits in one (Sananduva) or two (Frederico Westphalen, Santa Rosa and Erechim) episodes. The small city União da Serra and its reference city Guaporé did not exceed the legal limits for O_3 and $PM_{2.5}$ in any episode during the study period (Figure 2). União da Serra and Guaporé are also the cities with the lowest average concentrations of O_3 and $PM_{2.5}$ in the period studied (Figure 3).

Figure 4 shows the percentage of episodes in which small cities exceeded the daily values of their respective reference city or state capital. In the case of O_3, in 23 to 80 % of the episodes (23 % - Engenho Velho; 30 % - Porto Vera Cruz; 43 % - União da Serra; 80 % - Carlos Gomes and Tupanci do Sul) the small cities had a concentration higher than the reference city and in 13 to 27 % of the episodes (13 % - União da Serra; 20 % - Porto Vera Cruz and Tupanci do Sul and 27 % Engenho Velho and Carlos Gomes) the concentration of O_3 in small cities was higher than in the state capital, Porto Alegre. In relation to $PM_{2.5}$, in 17 to 67 % of the episodes (17 % - Carlos Gomes; 20 % Tupanci do Sul; 23 % - Engenho Velho; 53 % - União da Serra and 67 % - Porto Vera Cruz), the small cities had pollutant levels above the reference city and in 27 to 43 % of the episodes (27 % - União da Serra; 33 % Tupanci do Sul; 37 % - Engenho Velho and Carlos Gomes and 43 % - Porto Vera Cruz) the concentration of this pollutant was above the concentration measured in the state capital.

Table 2 shows the results of the multiple linear regression analysis considering the meteorological variables and the concentration of O_3 in the reference cities and in Porto Alegre. For the small cities Engenho Velho and Carlos Gomes, the only significant predictive variable in the model was the concentration of O_3 in the respective reference town. In União da Serra, in addition to the O_3 concentration in the reference city, humidity was a significant positive predictive variable, but with a low β value (β = 0.08). In Porto Vera Cruz and Tupanci do Sul, in addition to the significant positive association with the concentration of O_3 of the reference city, other variables were significant in the model, however with a negative association. Humidity, wind speed and O_3 concentration in Porto Alegre were variables associated with O_3 concentration in Porto Vera Cruz and humidity and UV radiation were variables negatively associated with O_3 concentration in Tupanci do Sul.

The multiple linear regression model for $PM_{2.5}$ concentrations in small cities is shown in Table 3. In all five small cities, the $PM_{2.5}$ concentration in the respective reference city was positively associated, while in Porto Vera Cruz city, temperature was also a significant predictive variable for $PM_{2.5}$ levels, while $PM_{2.5}$ concentration in Porto Alegre was negatively associated with the concentration of this pollutant in Tupanci do Sul.

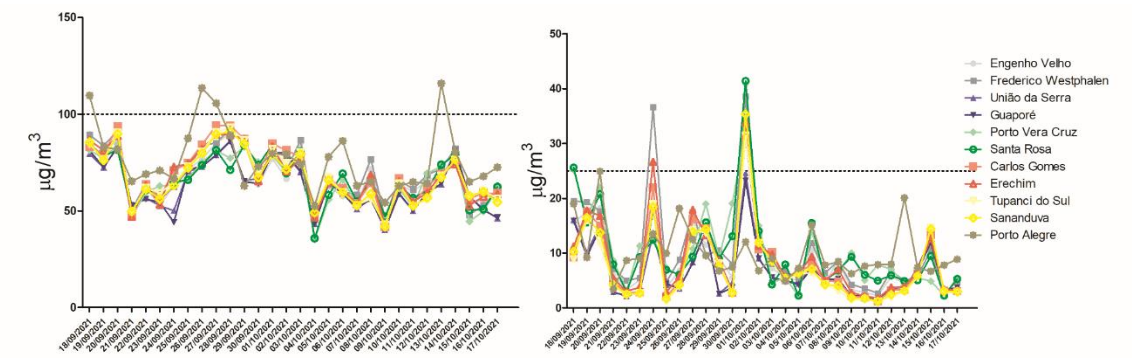

Figure 2 – Daily temporal behavior of O_3 (left) and $PM_{2.5}$ (right) in the cities studied. The dashed line represents the limit provided for in Brazilian legislation – 100 µg/m^3 (O_3) and 25 µg/m^3 ($PM_{2.5}$)

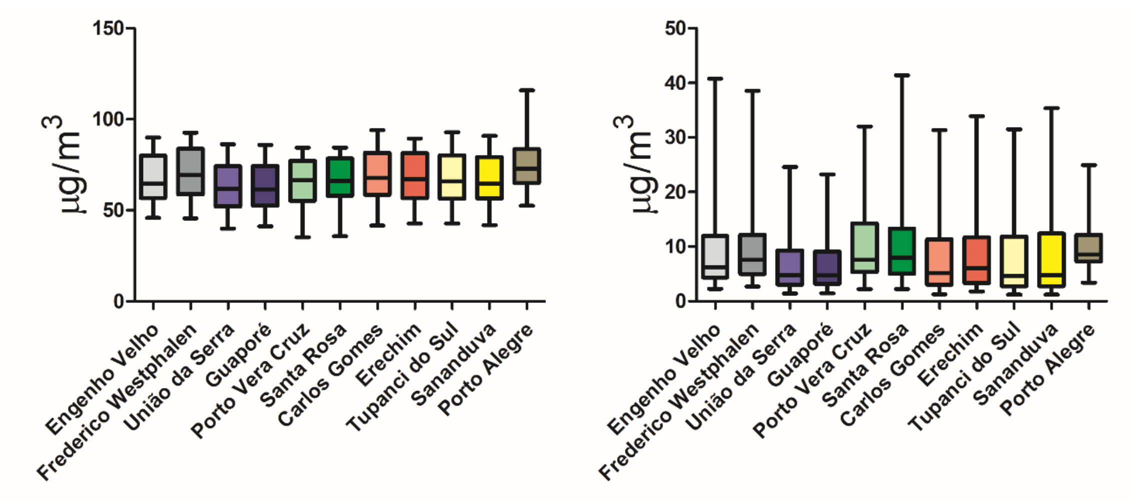

Figure 3 – Average concentration of O_3 (left) and $PM_{2.5}$ (right) in the cities studied

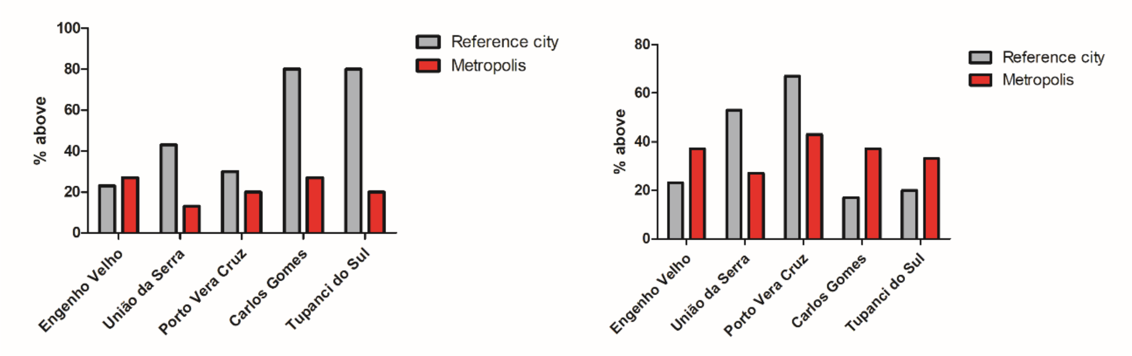

Figure 4 – Percentage of measures of O_3 (left) and $PM_{2.5}$ (right) in small cities above the concentration of its reference city and of state capital

Table 2 – Multiple regression analysis to O_3. β-value and p-value (in parentheses)

	Engenho Velho	União da Serra	Porto Vera Cruz	Carlos Gomes	Tupanci do Sul
Humidity	0.11 (p>0.05)	**0.08 (p=0.05)**	**-0.23 (p=0.003)**	-0.12 (p>0.05)	**-0.10 (p=0.01)**
Air pressure	0.05 (p>0.05)	0.04 (p>0.05)	-0.08 (p>0.05)	-0.08 (p>0.05)	-0.01 (p>0.05)
Wind	-0.03 (p>0.05)	0.02 (p>0.05)	**-0.14 (p=0.002)**	-0.04 (p>0.05)	-0.03 (p>0.05)
UV	0.04 (p>0.05)	0.06 (p>0.05)	-0.10 (p>0.05)	-0.04 (p>0.05)	**-0.09 (p=0.007)**
Temperature	0.05 (p>0.05)	0.09 (p>0.05)	0.10 (p>0.05)	0.03 (p>0.05)	-0.04 (p>0.05)
O_3 reference city	**0.99 (p<0.0001)**	**0.97 (p<0.0001)**	**0.84 (p<0.0001)**	**0.90 (p<0.0001)**	**1.02 (p<0.0001)**
O_3 metropolis	0.004 (p>0.05)	-0.04 (p>0.05)	**-0.12 (p=0.02)**	-0.02 (p>0.05)	-0.01 (p>0.05)

significant values (p<0.05) are highlighted in bold

Table 3 – Multiple regression analysis to $PM_{2.5}$. β-value and p-value (in parentheses)

	Engenho Velho	União da Serra	Porto Vera Cruz	Carlos Gomes	Tupanci do Sul
Humidity	-0.04 (p>0.05)	0.05 (p>0.05)	0.01 (p>0.05)	-0.01 (p>0.05)	-0.02 (p>0.05)
Air pressure	-0.14 (p>0.05)	-0.08 (p>0.05)	0.12 (p>0.05)	-0.04 (p>0.05)	0.01 (p>0.05)
Wind	0.06 (p>0.05)	0.01 (p>0.05)	-0.01 (p>0.05)	-0.01 (p>0.05)	-0.04 (p>0.05)
UV	-0.15 (p>0.05)	0.04 (p>0.05)	-0.04 (p>0.05)	0.001 (p>0.05)	-0.02 (p>0.05)
Temperature	0.18 (p>0.05)	0.03 (p>0.05)	**0.35 (p=0.003)**	0.06 (p>0.05)	0.02 (p>0.05)
$PM_{2.5}$ reference city	**0.85 (p<0.0001)**	**0.95 (p<0.0001)**	**0.90 (p<0.0001)**	**0.98 (p<0.0001)**	**0.98 (p<0.0001)**
$PM_{2.5}$ metropolis	-0.07 (p>0.05)	-0.02 (p>0.05)	-0.11 (p>0.05)	**-0.09 (p=0.004)**	-0.04 (p>0.05)

significant values (p<0.05) are highlighted in bold

4. Discussion

The findings of the current study show that the levels of O_3 and $PM_{2.5}$ in small cities are equivalent to the levels detected in the reference cities of each microregion and close to those measured in the capital of the state of Rio Grande do Sul, a metropolis with more than 1.5 million inhabitants. The latest WHO guidance points to two main gaps in the coverage of global air quality monitoring: the first is the lack of monitoring in many countries around the world and the second is inadequate monitoring in rural areas and in areas far from large cities (1). In this sense, the results of this study help to understand these two gaps, since Brazil is still a country in which less than 2 % of its municipalities have some monitoring of air quality (16) and the largest part of these studies are concentrated in large metropolises (18-20) or industrial regions (21,22).

South American countries have not been identified as worrying about air pollution compared to countries in Africa or Asia, for example (25), but the lack of in-depth information and availability of discontinued data for most municipalities may be helping to underestimate the potential health risks associated with air pollution in the region. Allied to this, more recent sources of air pollution, such as the intensification of forest fires in the Amazon (23) and Pantanal (24) and dust storms in southeastern Brazil may contribute to more critical scenarios in the region from now on.

In the case of small cities and other regions with low anthropogenic emissions, it is important to identify the sources of air pollutants. A study conducted in a medium-sized city in southeastern Brazil pointed out two important sources of air pollutants: the burning of biomass (sugar cane) in the region and the transport of pollutants from the city of São Paulo, which is further away 200 km from the study area (7). Another study conducted in a rural region with small cities in southern Brazil identified soil, agricultural activities and local vehicular emissions as the main local sources of air pollutants, but also pointed out the influence from aerosols related to biomass burning and industrial activity transported over long distances (9).

Although a more detailed investigation is needed, as there are no important sources of air pollutants in the region, the two episodes that registered a significant increase in $PM_{2.5}$ levels in most of the cities investigated (September 18th to 20th and September 30th to October 2nd) are probably related to the transport of pollutants over long distances. This region of Brazil is often influenced by the South American Low Level Jet (SALLJ), a wind that occurs east of the Andes and is an important agent of transport and mixing of atmospheric components (25). A spatial distribution pattern of $PM_{2.5}$ for these two episodes and another period with reduced $PM_{2.5}$ levels (10-12 October 2021) is presented in the Figure 5, with images taken from the website https://windy.org. This information helps to corroborate the influence of long-distance transport and SALLJ for these two episodes. In addition, other studies have reinforced the role of long-distance transport of pollutants from Amazon biomass burning to southeastern and southern Brazil (26,27) and to Argentina (28).

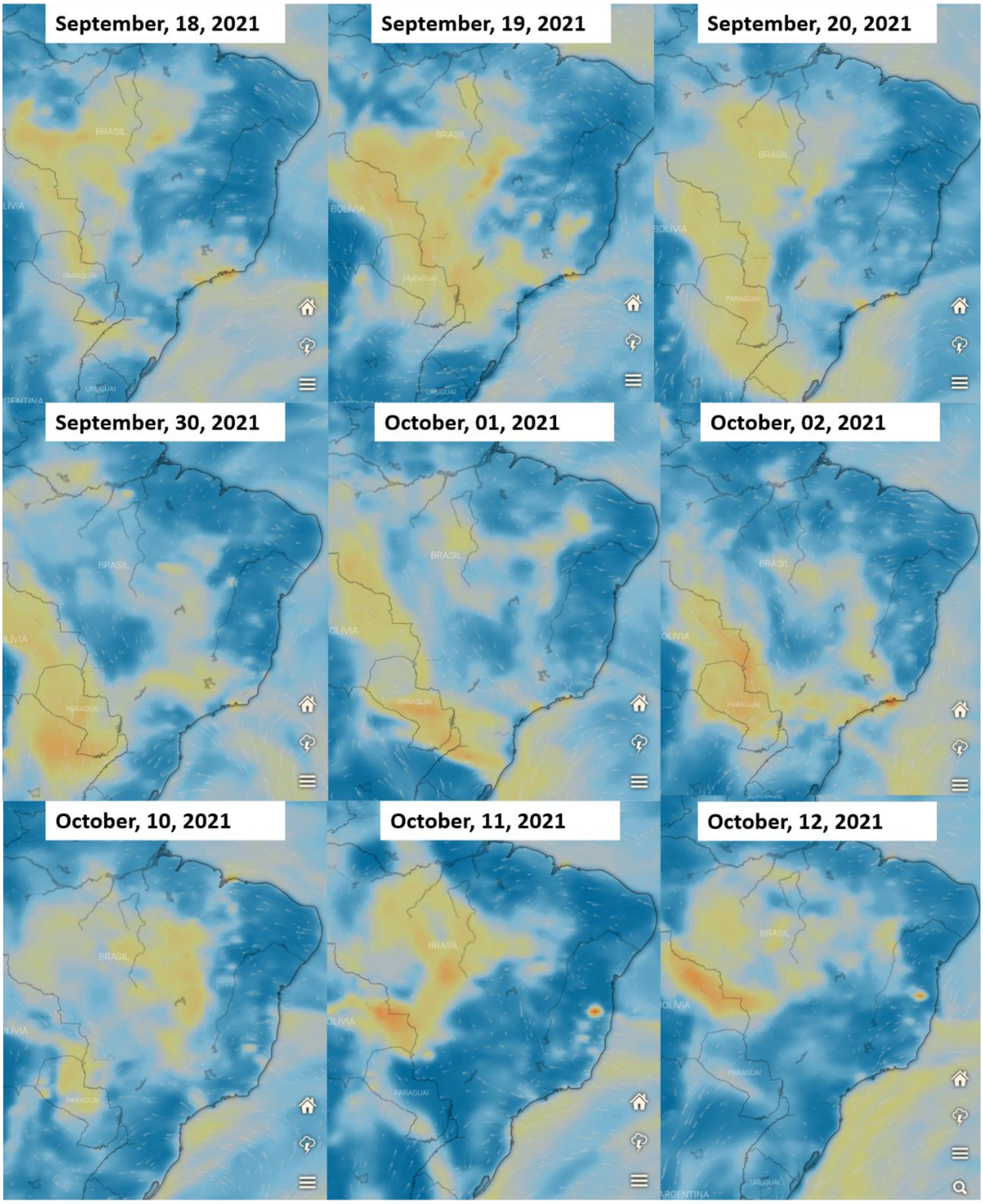

Figure 5 – Maps extracted from the website https://windy.org with the two episodes of elevated $PM_{2.5}$ levels in the study region (18 to 20 September, 2021 and 30 September to 2 October, 2021) and a third period without elevated levels for comparison purposes (10 to 12 September October ,2021).

Although the basal concentrations of $PM_{2.5}$ in the region are below the national quality criteria, during the monitored period these two episodes contributed to a significant increase in the concentration of this pollutant, surpassing the air quality criteria for most of the cities studied. Episodes of significant increase in levels of air pollutants have already been reported in small cities in various parts of the world, such as in China (29), South Korea (14,15), India (30), Greece (12), Poland (13), among others. However, we emphasize that in all these studies, with the exception of the study by Loupa et al (12), the so-called "small cities" had a population size above 50 thousand inhabitants and the current study evaluated cities with very low population size (< 1,500 inhabitants).

Despite the limited time period of our study, our results indicate that even cities far from the state's metropolitan area may present O_3 and $PM_{2.5}$ levels equivalent to those found in the capital. We emphasize the need for long-term temporal/seasonal monitoring in the region to establish standards for pollutants, as well as studies that elucidate the sources of pollution in episodes of high levels of air pollution. Finally, we encourage studies in small towns to be conducted in other parts of Brazil, even with satellite data, since most municipalities do not have air quality monitoring stations. This is also a strategy encouraged in the new WHO guidance (1).

5. Conclusion

This study showed that small cities (<1,500 inhabitants) had an average concentration of O_3 and $PM_{2.5}$ similar to the reference cities in their region and also comparable to the state capital, Porto Alegre, a city with more than 1.5 million inhabitants. During the analyzed period, there were two episodes of increase in $PM_{2.5}$ levels, probably associated with long-distance transport of pollutants from biomass burning.

6. Conflicts of interest/Competing interests:

The authors declare that they have no competing interests

7. Funding

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