Weekend effect on air pollutant levels in southernmost cities of Brazil with different economic activities

Leonardo de Vasconcellos Ceglinski · Ronan Adler Tavella · Alicia da Silva Bonifácio · Jéssica El Koury Santos · Flavio Manoel Rodrigues da Silva Júnior

Received: 19 July 2022 / Accepted: 19 September 2022 / Published online: 27 September 2022 © The Author(s), under exclusive licence to Springer Nature Switzerland AG 2022

Abstract In view of the current premises of the need to investigate air pollution in small- and medium-sized cities, combined with concerns regarding the weekly behavior of air pollutants, this study aimed to investigate the weekly pattern of air pollution (\(O_3\), \(NO_2\), \(SO_2\), \(PM_{2.5}\)) and the weekend effect in 4 Brazilian cities with different main economic activities. Our main findings include (1) positive weekend effect for all the assessed air pollutants in the four cities; therefore, in the southernmost region of Brazil, there was an increase in the concentration of air pollutants during weekends when compared to weekdays; (2) the highest levels of \(NO_2\) and \(SO_2\) were observed in the city characterized by the economic activity revolving around coal mining and generation of electricity through the burning of this mineraloid in a coal-fired power plant, while the highest levels of \(PM_{2.5}\) were in the city with economic activity linked to industries, due to its recognized industrial complex; and (3) the seasonal evaluation of the weekend effect showed different behaviors for the air pollutants in each location, which is related to the set of meteorological conditions, economic activities, and population mobility in each location. In conclusion, our results demonstrate the aspects of pollution between cities and highlight that the comprehensive understanding of the weekend effect and its intricacies allows the responsible personal and government authorities to gain deep insights into the true effectiveness of future control strategies and the development of possible action plans.

Keywords Air pollution · Brazil · Small cities · Medium-sized cities · Air quality

Introduction

The continuous monitoring of air pollutant levels in different regions of the globe has already demonstrated the characteristic existence of weekly patterns. This weekly cycle of the urban air quality is a feature of almost all large urban centers associated with vehicular traffic, industrial operations, and urban mobility (Mohtar et al., 2018; Li et al., 2019; Elansky et al., 2020; Yousefian et al., 2020). As a rule, the largest amounts of pollutants are emitted on working days and their smallest amounts are emitted on weekends. This impacts on higher levels of pollutants during the
might be expected if air pollution levels were reduced and based on this, this effect is recurrently referred to as the weekend effect.

The relation of variations between air pollutants and the weekly cycle of cities with relevant operation of industrial enterprises and traffic intensity was first illustrated by the example of large cities in the USA (Cleveland et al., 1974; Lebrón, 1975). Later studies with a more in-depth approach revealed the influence of climatic conditions, urban-infrastructure features, relief, and other factors on weekend effect (Brönnimann & Neu, 1997; Paschalidou & Kassomenos, 2004; Stephens et al., 2008; Yoo et al., 2015), and observed that this effect is manifested in both atmospheric photochemical and transport processes that are characteristic of all large urban centers (Yoo et al., 2015; Elansky et al., 2020). Usually, the weekend effect is investigated with ozone as the focus and little attention is given to other air pollutants (Atkinson-Palombo et al., 2006; Huryn & Gough, 2014; Sicard et al., 2020; Tang et al., 2008; Zhao et al., 2019). The probable reason for this is that scientists are concerned with studying scenarios that exacerbate a condition (in this case, elevated ozone levels at the weekends) and because, due to its physico-chemical transformations, ozone is not commonly a critical pollutant in metropolises and large cities, therefore studying its rise on weekends can transform it in a temporary air quality villain. Thus, despite the weekend effect being an efficient tool for evaluating different emission scenarios, its focus should comprise the majority of the criteria air pollutants, and serve as a guide in forecasting the air quality and extreme ecological situations (Elansky et al., 2020; Koo et al., 2012).

In 2021 a concern was raised by the World Health Organization (WHO) regarding the appellant of monitoring air pollutants in large urban centers (WHO, 2021). Since the beginning of the monitoring of world air quality, efforts have always been directed to locations recognized for having high concentrations of pollutants, which generated great interest from the scientific community and of the media, that is, large urban centers and metropolises. However, currently, equally important are the studies in areas considered to have low levels of pollution, mainly because these studies answer important questions regarding the effects of low-level exposures and the evaluation of thresholds, providing critical information on the benefits that might be expected if air pollution levels were reduced worldwide. Thus, despite the fact that the weekly patterns of air pollutants are recognized in the context of large urban centers (Mohtar et al., 2018; Li et al., 2019; Elansky et al., 2020; Yousefian et al., 2020) and there is evidence that points to the existence of changes in these patterns in rural contexts (Debaje & Kakade, 2006; Schipa et al., 2009), the knowledge about the behavior presented by the criteria air pollutants in small urban areas is still notably inferior and limited to few studies.

In Brazil, the evaluation of the weekly pattern and the weekend effects of air pollutants was only directly studied in the main metropolis and within regions with high levels of urbanization, therefore impacted by the population density (Martins et al., 2015; Silva Júnior et al., 2009). Silva Júnior et al. (2009) investigated the differences between the levels of ozone and nitrogen oxides during weekdays and weekends in the city of São Paulo, and observed the existence of a weekend effect for both pollutants, with an increase in ozone levels on weekends for the monitoring station closer to the site with intense vehicular traffic and reductions for nitrogen oxides (NO and NO₂). The same trend was also observed in the city of Rio de Janeiro by Martins et al. (2015), where all monitored stations showed an increase in ozone concentration on weekends and a reduction in nitrogen oxide levels demonstrating how these cities, considered world metropolises, present similar results for the weekly behavior of pollutants. From this information, it is evident the need for studies that investigate small and medium cities far from these large urban centers and that possibly present different behaviors for air pollutants over the weeks and different seasons of the year. Therefore, our study aimed to investigate the weekly pattern and the weekend effect in 4 Brazilian cities with different main economic activities (industries, commerce, coal activities, and agriculture and livestock).

Material and methods

Study site and monitoring period

This study included the cities of Rio Grande, Pelotas, Candiota, and Herval, located in the south of the state of Rio Grande do Sul (Fig. 1). These cities were chosen for their different population densities and for their main economic activities. The information...
regarding cities and their economic activities was obtained from the Brazilian Institute of Geography and Statistics (IBGE) (2021) and are presented in Table 1.

As it involves different information about Brazilian cities, definitions about the terms used to express the sizes of cities are important (IBGE, 2002). Small cities are urban agglomerations with a population of up to 100,000 inhabitants, medium-sized (mid-sized) cities are those between 100,000 and 500,000 inhabitants, while large cities are those with a population above 500,000 inhabitants. Large urban centers are a large and densely populated urban area; in this study it is used to describe both these locations and large cities. Metropole is very large and densely populated city, or conurbation, which is a significant economic, political, and cultural center for a country or region.

In addition to these observations, we present an approach to the economy of each city: Rio Grande has

| City (coordinates)                  | Population (2021) | Territorial area (km²) | Population density (inhab. km⁻²) | Economy                                                                 |
|------------------------------------|-------------------|------------------------|----------------------------------|-------------------------------------------------------------------------|
| Rio Grande (32°01’40”S; 52°05’40”W) | 212,881           | 2,709,391              | 72.79                            | Its gross domestic product (GDP) is represented at 38% by industrial and port activity |
| Pelotas (31°46’34”S; 52°21’34”W)   | 343,826           | 1,609,708              | 203.89                           | Its GDP is represented at 65% by trade and logistics                    |
| Candiota (31°28’36”S; 53°40’45”W)  | 9707              | 933,628                | 9.39                             | Its GDP is represented at 46% by the exploitation of mineral wealth, such as coal and limestone, and by the generation of thermoelectric energy using coal |
| Herval (32°04’46”S; 53°24’11”W)    | 6807              | 1,759,717              | 3.84                             | Its GDP is represented at 50% by agricultural activities                |
an economy that relies mainly on a large industrial complex that is composed of fertilizer, oil, food, fish, and metallurgical industries, being also characterized by its high port activity, with one of the main ports in Brazil; Pelotas has an economy that revolves around the region’s trade, with the secondary sector having the presence of industries linked to the agribusiness sector. In addition, it is considered a key city for the distribution of goods and products to the rest of the state; Candiota has an economy that relies mainly on the largest coal mine in Brazil, from which it extracts the mineraloid both for trade and for generating thermoelectric energy in a power plant located in the same city; and Herval has an economy that relies mainly on livestock with high bovine production and also on soybeans.

The monitoring period was conducted monthly from June 2020 to May 2021 for a period of 12 months and including a complete seasonal cycle in the south hemisphere: autumn—from March 21 to June 21; winter—from June 21 to September 23; spring—from September 23 to December 21; and summer—from December 21 to March 21.

Sampling procedure

The levels of atmospheric pollutants ozone (O₃), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and particulate matter with diameter less than 2.5 μm (PM₂.₅) were collected from satellite data of the Copernicus Atmospheric Monitoring Service (CAMS) from the European Centre for Medium-Range Weather Forecasts (ECMWF), manually extracted in real time from The Weather Channel application (IBM, USA). The procedure was performed in accordance with Da Silva Júnior et al. (2020), Carvalho et al. (2021), Leão et al. (2021), and Tavella and da Silva Júnior (2021). A daily average was obtained at a standardized time for all data collected. The unit of measurement adopted for all pollutants was μg.m⁻³. The data were organized by day of the week, week of the year, and season of the year for further analysis. Meteorological data for each of the regions were obtained through the Instituto Nacional de Meteorologia (INMET, 2021).

Weekend effect calculation and data analysis

The calculations used to investigate the weekend effect were performed in accordance with the equation used by Fang et al. (2022). This is the classical method and has been adopted by many studies since the first years of assessing weekend effect (Lebron, 1975) until recent years (Fang et al., 2022).

\[
WE = \left( \frac{C_{\text{weekend}} - C_{\text{weekday}}}{C_{\text{weekday}}} \right) \times 100 \%
\]

where \( C \) is the concentration of any of the pollutants studied (O₃, NO₂, SO₂, and PM₂.₅); WE is the weekend effect for pollutant \( C \); \( C_{\text{weekend}} \) is the daily mean concentration of the pollutant on weekend days (i.e., Saturday and Sunday); \( C_{\text{weekday}} \) is the daily mean concentration of the pollutant on weekdays (i.e., Monday to Friday). The data was presented as the percentage of increase or decrease of the pollutant during the weekend (weekend effect) annually and between seasons.

Results

Weekly pattern of air pollution

The mean concentration and behavior of air pollutants observed during the different days of the week for the four pollutants evaluated are shown in Fig. 2. The highest weekly mean for O₃ levels was observed in the city of Rio Grande (53.61 μg.m⁻³), while the lowest was in Candiota (48.78 μg.m⁻³); in addition, it can be observed how this pollutant presented a homogeneous weekly behavior in each of the cities evaluated. For NO₂ and SO₂ the highest weekly concentrations were observed in the Candiota region, with a weekly average of 3.44 and 5.52 μg.m⁻³, respectively. PM₂.₅ was higher in the city of Rio Grande and Pelotas, with weekly mean of 6.74 and 5.41 μg.m⁻³, respectively. Moreover, the results regarding the meteorological variables are presented in Table S1.

Annual weekend effect

The annual data for the weekend effect behavior for the different air pollutants were computed and presented in Fig. 3. It is possible to observe that there was an increase in the concentration of all air pollutants during the weekends in all the assessed cities. Thus, our study verified the presence of a positive
weekend effect for air pollutants in the four cities. Among the observed increases, we found that O₃ presented the lowest percentages of increase and a greater weekend effect in the cities of Rio Grande (2.85%) and Pelotas (2.81%). This effect was more pronounced for NO₂ and SO₂, in which their most expressive increases were observed in Candiota, with increases of 22.18% and 16.46%, respectively. In Herval, the city closest to Candiota in our study, the weekend effects observed for NO₂ and SO₂ were the second highest. In turn, PM₂.₅ levels showed a strong positive weekend effect in all cities, of which the highest were found in Candiota (15.39%) and Pelotas (12.71%).

Weekend effect between seasons

An in-depth analysis of the weekend effect in the seasons demonstrates the different behaviors of pollutants in the face of seasonal changes (Fig. 4). For O₃, it is observed that there is an increase in the levels of this pollutant during the autumn weekends in all cities, with a less expressive increase in the winter of Rio Grande and Pelotas. A reduction of this pollutant is observed in the other seasons of the year. In turn, NO₂ concentrations show an increase on the weekends of the hottest seasons (summer
spring), while in the coldest seasons (autumn and winter) the decrease on weekends in the observed cities is remarkable. SO$_2$ levels show a strong downward trend on weekends of all seasons, but in the city of Rio Grande and Candiota, there is an increase in summer. Finally, PM$_{2.5}$ levels show reductions on weekends during winter, spring, and autumn, but higher concentrations are observed in the summer in the four cities.

Discussion

Main findings and importance of the study

The approach used in our study of evaluating the weekend effect in small and medium size cities and considering their distinct economic activities proved to be a unique undertaking. Through it, it was possible to investigate not only the different behaviors of pollutants in these locations but also to observe how the economic activities linked to each of the cities influence the results. In summary, our main findings can be divided into three: (1) we observed a positive weekend effect for all the assessed air pollutants in the four cities, therefore, in this region there was an increase in the concentration of air pollutants during weekends when compared to weekdays; (2) the highest levels of NO$_2$ and SO$_2$ were in the city characterized by the economic activity revolving around coal mining and generation of electricity through the burning of this mineraloid in a coal-fired power plant, while the highest levels of PM$_{2.5}$ were in the city characterized by economic activity linked to multiple industries, due to its recognized industrial complex; and, (3) the seasonal evaluation of the weekend effect showed different behaviors for the air pollutants in each location, which is possibly related to the set of meteorological conditions, economic activities, and population mobility in each location.
Numerous anthropogenic activities are responsible for the great burden of air pollution, of which the burning of fossil fuels, industrial and vehicular emissions, stand out (Popescu & Ionel, 2010). This wide range of polluting factors is usually found in high proportions in large urban centers and metropolises. Thus, eventually, these locations are responsible for detaining the majority of monitoring and studies about the presence of these pollutants, as well as their behavior within this “ecosystem” (Chan & Yao, 2008; Krzyzanowski et al., 2014). However, due to this scientific and global tendency to study these locations, the WHO highlighted, in its last air quality guideline (2021), that there is a growing and evident need for studies that investigate the behavior of these pollutants in places far from large urban centers and also with different scenarios. With this, our study gains strength by carrying out this investigation not only in locations far from those locations but also by shining light into cities that have different characteristics in relation to their economic activities and population density, thus observing at the same time how the main sources of emissions from these locations can affect these factors. In addition, we focused on the study of the differences found in the behavior and emissions of these pollutants during weekdays and weekends, also observing these differences during the different seasons of the year, thus investigating how the main anthropogenic activities affect the overall picture of pollutants.

Human action contributes massively to the increase in pollutant levels in any region (Popescu & Ionel, 2010). In this context, and almost as a rule spreading across the globe, the largest amounts of pollutants are majorly emitted on working days and their smallest amounts are emitted on weekends (Elansky et al., 2020). Multiple studies have already proven this pattern in different locations (Atkinson-Palombo et al., 2006; Tang et al., 2008; Huryn & Gough, 2014; Yoo et al., 2015; Zhao et al., 2019; Elansky et al., 2020; Sicard et al., 2020) and have also shown how strikes (Chiquetto et al., 2021; Sujatha, 2017), holidays (Tan et al., 2009, 2013), and even the COVID-19 pandemic (Tavella & da Silva Júnior, 2020) cause a significant change in the composition of these pollutants in the local atmosphere. This difference between the concentration of air pollution on weekdays and weekends is called weekend effect.

This term emerged and is almost exclusively used to describe the behavior of ozone during the weekend (Atkinson-Palombo et al., 2006; Cleveland et al., 1974; Huryn & Gough, 2014; Lebron, 1975; Sicard et al., 2020; Tang et al., 2008; Zhao et al., 2019). In urban centers and metropolises, this situation occurs because ozone has a different behavior from the other criteria air pollutants during the weekend. Despite having lower emissions of air pollutants during this period, ozone usually shows an increase in its levels during weekends (Sicard et al., 2020; Zhao et al., 2019). This fact directly linked to the mechanism of ozone formation (Stillman, 1999; Tavella & da Silva Júnior, 2021). However, the probable reason for the focus on ozone is that scientists present concerns regarding scenarios that exacerbate a condition (in this case, elevated ozone levels at the weekends) and because, due to its physicochemical transformations, ozone is not commonly a critical pollutant in metropolises and large cities. Therefore, studying its rise on weekends, together with the fact that high levels of this pollutant have adverse health effects, can transform it into a temporary air quality villain. Allied to this, the investigation of the weekend effect for other air pollutants still receives little attention (Mohtar et al., 2018; Li et al., 2019; Elansky et al., 2020; Yousefian et al., 2020), and even less attention can be said about regions far from large urban centers. In this context, our study gains even more strength, as our research goes beyond studying the weekend effect on ozone and expands it to assess the weekend effect on multiple other criteria air pollutants (NO\textsubscript{2}, SO\textsubscript{2}, and PM\textsubscript{2.5}).

Weekend effect in the assessed cities

Our research expressed the existence of a positive weekend effect for all the pollutants assessed in the cities of Rio Grande, Pelotas, Candiota, and Herval, with more expressive increases for PM\textsubscript{2.5}. This result is unexpected for the proposed air pollution investigation. This is because usually, as mentioned earlier, it is expected that the emission of pollutants during the weekend periods is lower than during the week, for reasons that permeate mostly the decrease in vehicular flow and the reduction of other emission activities. However, our results indicate two possible scenarios for these findings: the first being a possible increase in the vehicular flow of these cities during the weekend,
which, due to cultural aspects in the region, actually happens; and the second being the increase in other polluting activities involving these regions, since, with the exception of Pelotas, all other regions have main economic activities that do not suffer reductions or stops during the weekend.

The cultural aspects mentioned above are mostly related to inter/intra-municipal mobility for the practice of cultural and leisure activities. This is a reality in this region, as the places considered most attractive to perform these activities are far from the downtown and urban neighborhoods. For example, in Pelotas and Rio Grande, which despite having attractive beaches full of leisure options, the downtown area is located more than 20 km away, leading to an increase in the vehicular flow to enjoy these places. This information has further support through our results, as we can verify that the intensity of the weekend effect in this region is greater in the summer (characteristic season for beach and outdoor activities), possibly related to this increase in social mobility toward these regions. Allied to the aforementioned scenarios, it is important to emphasize that our study comprised the COVID-19 pandemic, so our data and the increase in air pollution during the weekend may have been impacted due to the social structure created by COVID-19. Global studies performed during the COVID-19 pandemic have demonstrated a clear and defined relationship between the restriction measures adopted by governments and the levels of air pollutants in different cities around the world (Sharifi & Khavarian-Garmsir, 2020; Tavella & da Silva Júnior, 2021). Thus, there is a possibility that, in the face of containment measures, the population movement increased during the weekends for leisure activities while many of the work activities were being performed as home office and, consequently, the emission of air pollutants during the week was reduced.

Despite the set of observed results expressing a different behavior than expected, the increase in O₃ levels during the weekend is something usually observed in studies in large cities. Similar findings were already pointed out even in Brazil through studies performed in the cities of São Paulo (Silva Júnior et al., 2009) and Rio de Janeiro (Martins et al., 2015), which showed an increase of approximately 20% and 9%, respectively, in the levels of ozone in these locations. In turn, our highest increase was approximately 4 and 5% in the city of Pelotas and Rio Grande, both cities characterized by the highest population density in our study, and with all the subsequent pollutant emission that comes with it. This information is important because the cities included in our study are located far from metropolises and large cities, consequently having a different behavior for O₃ than these locations; therefore, it is possible to notice that even in these regions, O₃ shows an increase behavior during the weekend, which increases the spectrum of concern about this pollutant and also serves as a warning to local competent authorities.

Impacts of economic activities and seasons on air pollutants and the weekend effect

The constitution of the assessed cities affected the findings regarding the mean weekly concentration of air pollutants. Initially we can notice how levels of ozone were higher in the investigated cities than what is usually observed in metropolises (Elansky et al., 2020; Sicard et al., 2020; Yousefian et al., 2020). However, the opposite is observed for NO₂, where the levels of this compound were remarkably low in our study, and in metropolises, the mean concentrations are 10 to 15 times higher (Silva Júnior et al., 2009; Zhao et al., 2019; Elansky et al., 2020). On one hand, the highest levels of NO₂ and SO₂ were in the city of Candiota, which is characterized by the economic activity of coal mining and generation of electricity through the burning of this mineraloid in a coal-fired power plant. On the other hand, the highest levels of PM₂.₅ were observed in the city of Rio Grande, which is a city with economic activity linked to various industrial activities, being even recognized on a national scale for its industrial complex. These results are in agreement with what is observed in the literature, since the activity of mining and power generation with coal is recognized by the emission of high levels of SO₂ and nitrogen oxides (Li et al., 2021), while the presence of large industrial complexes is directly related to high levels of PM₂.₅ in local air (Hsu et al., 2017; Jeon et al., 2010). In fact, the study by Gutierrez et al. (2020) carried out in the city of Rio Grande highlighted the presence of high levels of PM₂.₅ in the air in this region, with 50% of the samples collected exceeding quality criteria established by the WHO (2006) and CONAMA (2018). These data reinforce the need and importance of studying smaller and non-metropolitan regions, taking into consideration the
region’s economic activity. Furthermore, Ulguim et al. (2021) and Da Silva Júnior et al. (2020), in their study analyzing the main atmospheric pollutants (O₃, NO₂, SO₂, PM₂.₅, PM₁₀, and CO) in nine cities in the southern region of Rio Grande do Sul, including the four cities studied in the present manuscript, identified and highlighted how the economic activity of each region strongly influences the concentration levels of atmospheric pollutants.

It is a fact that adjacent cities are likely to form air pollution clusters due to the mixing and diluting nature of air pollutants; consequently, cities may have similar pollution levels as their neighbors (Jiang & Bai, 2018; Liang & Gong, 2020; Sharma et al., 2022). Despite this, the environmental influence of a city on its neighbors is directly related to the levels of air pollutants emitted and also meteorological parameters, i.e., wind direction and speed (Liang & Gong, 2020; Sharma et al., 2022). This impact is highly expressive when it comes from a city with high emission of air pollutants and can be extremely low, practically null, in cities with low emissions. In this context, it is important to emphasize that the investigated cities are located close to each other, mainly Rio Grande to Pelotas and Candiota to Herval, and, in this scenario, there is the possibility that air pollution in a city is affecting the air quality of its neighbors (not only those studied). This is possibly observed in the SO₂ levels in Herval, which is a city characterized by rural activities and without significant sources of emission of this pollutant, but close to the region of Candiota, which, as mentioned before, is a city with significant SO₂ emissions. Thus, we emphasize how this impact can happen even in small cities, but as long as they have high emissions of some criteria air pollutant, usually related to the city’s economic activity, as in the case of Candiota.

Despite having punctual differences between locations, in general, the pollutants showed similar variations between seasons, demonstrating how the meteorological conditions faced by cities were somewhat homogeneous and representative in the entire study. However, the seasonal evaluation of the weekend effect showed different intensities for the air pollutants in each location, which is possibly related to the set of meteorological conditions, economic activities, and population density and mobility in each location. Among the observed changes, the one that most draws attention is the increase in O₃ concentration on weekends in summer being more expressive than in the rest of the year; this attention is mainly due to the knowledge that in the warmer seasons the levels of ozone are usually higher (Wells et al., 2021), since the formation reaction involves solar irradiation. Almost concomitantly with this, the increase observed in NO₂ levels on spring and summer weekends (hot months) is somewhat strange, since, contrary to the behavior of O₃, the levels of this pollutant tend to be higher in the cooler seasons (Roberts-Semple et al., 2012). In addition, the different intensities of weekend effect among the air pollutants appear to be related to the economic activities of each region, closely following the alterations previously described. However, we note that further studies are important to fully understand the relationship between the behavior of these pollutants in the seasons of this region.

Through our research it was possible to evidence the presence of positive weekend effect in the four cities of the southernmost region of Brazil, as well as to demonstrate the importance of considering the main economic activities of a city when studying the relationship between air pollutants and human activities within the complex atmospheric mixture. Despite this, our study has some limitations, among which we highlight the monitoring period of 1 year, as we may suppose that longer monitoring periods would provide data to develop a more complete and conclusive profile on the behaviors presented, the use of satellite data for the acquisition of air pollutant levels, and the possible impact of the COVID-19 pandemic on our results since the study period included the application of governmental distancing measures to contain COVID-19.

The study of air pollution, its behavior and health effects, is a current topic of recognized importance and that has a growing interest in the scientific community. Our results, although limited to some cities included in the study, further improve the knowledge about the effects of pollution in small and medium cities far from large urban centers, as well as highlighting how the main economic activities practiced in some cities impact air pollution as strongly, or even stronger, than large population clusters. We identified that a positive weekend effect occurred for all air pollutants in all assessed locations, varying basically in its intensity, emphasizing that the highest levels of individual air pollutants were observed in cities with economic activities directly related to
the emission of the compounds, and that the weekend effect in the different seasons of the year were homogeneously impacted in all cities but with different intensities, related to their economic activity and population mobility. In this sense, the comprehensive understanding of the weekly patterns of air pollution and the weekend effect and its intricacies allows the responsible personal and government authorities to gain deep insights into the true effectiveness of future control strategies and the development of possible action plans. This strategy should be investigated in other locations with different sources of pollution, environmental policies, and behavioral patterns of the population for a better understanding of the relationship between air pollutants and the weekly cycle.

Conclusion

Our findings indicate the presence of a positive weekend effect for \(\text{O}_2\), \(\text{NO}_2\), \(\text{SO}_2\), and \(\text{PM}_{2.5}\) in all assessed cities. The highest levels of \(\text{NO}_2\) and \(\text{SO}_2\) were observed in the city characterized by the economic activity of coal mining and generation of electricity through the burning of this mineraloid in a coal-fired power plant, while the highest levels of \(\text{PM}_{2.5}\) were in the city characterized by economic activity linked to a diverse set of industries, due to its national recognized industrial complex. Moreover, the weekend effect in the different seasons of the year was homogeneously impacted in all cities but with different intensities for each air pollutant, possibly related to their economic activity and population mobility. Overall, these results promote the understanding of the weekly patterns of air pollution and the weekend effect and its intricacies in the four cities investigated, thus, serving as a guide for the responsible authorities about future strategies and policies for air quality control.

Acknowledgements

The authors thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), and Universidade Federal do Rio Grande – FURG.

Author contribution

LVC and RAT were responsible for preparing the first version of the manuscript text; ASB and JEKS were responsible for reviewing the database and to discuss the findings. FMRSJ was the study supervisor. All authors read and approved the final version of the manuscript.

Funding

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001, Conselho Nacional de Desenvolvimento Científico e Tecnológico—Research Productivity Fellowship, Grant 310856/2020-5 (FMRSJ) and Fundação de Amparo à Pesquisa do Estado do Rio Grande do Sul (FAPERGS), Grant 21/2551-0001981-6.

Availability of data and materials

The datasets used and/or analyzed during the current discussion are available and from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Conflicts of interest

The authors declare no competing interests.

References

Atkinson-Palombo, C. M., Miller, J. A., & Balling, R. C., Jr. (2006). Quantifying the ozone “weekend effect” at various locations in Phoenix. Arizona. Atmospheric Environment, 40(39), 7644–7658.

Brönnimann, S., & Neu, U. (1997). Weekend-weekday differences of near-surface ozone concentrations in Switzerland for different meteorological conditions. Atmospheric Environment, 31(8), 1127–1135.

Carvalho, R. B., Marmett, B., Dorneles, G. P., da Silva, I. M., Romão, P. R. T., da Silva Júnior, F. M. R., & Rhoden, C. R. (2021). O3 concentration and duration of exposure are factors influencing the environmental health risk of exercising in Rio Grande, Brazil. Environmental Geochemistry and Health, 1–10.

CONAMA. Resolução nº 491. (2018). Dispõe sobre padrões de qualidade do ar. Brasília: Diário oficial da República Federal do Brasil.

Chan, C. K., & Yao, X. (2008). Air pollution in mega cities in China. Atmospheric Environment, 42(1), 1–42.

Chiquetto, J. B., Alvim, D. S., Rozante, J. R., Faria, M., Rozante, V., & Gobo, J. P. A. (2021). Impact of a truck driver’s strike on air pollution levels in São Paulo. Atmospheric Environment, 246, 118072.

Cleveland, W. S., Graedel, T. E., Kleiner, B., & Warner, J. L. (1974). Sunday and weekday variations in photochemical air pollutants in New Jersey and New York. Science, 186(4168), 1037–1038.

Da Silva Júnior, F. M. R., Honscha, L. C., Brum, R. D. L., Ramires, P. F., Tavella, R. A., Fernandes, C. L. F., & Coronas, M. V. (2020). Air quality in cities of the extreme south of Brazil. Ecotoxicology and Environmental Contamination, 15(1), 61–67.

Debaje, S. B., & Kakade, A. D. (2006). Weekend ozone effect over rural and urban site in India. Aerosol and Air Quality Research, 6(3), 322–333.
Elansky, N. F., Shilkin, A. V., Ponomarev, N. A., Semutnikova, E. G., & Zakharova, P. V. (2020). Weekly patterns and weekend effects of air pollution in the Moscow megacity. *Atmospheric Environment*, 224, 117303.

Fang, C., Xue, K., Li, J., & Wang, J. (2022). Characteristics and weekend effect of air pollution in Eastern Jilin Province. *Atmosphere*, 13(5), 681.

Gutierrez, F. B., Eslava Martins, S., Honscha, L. C., de Lima Brumm, R., Vargas, V. M. F., Mirlean, N., ... & da Silva Junior, F. M. R. (2020). Is there something in the air? Sources, concentrations and ionic composition of particulate matter (PM2.5) in an industrial coastal city in Southern Brazil. *Water, Air, & Soil Pollution*, 231(5), 1–10. https://doi.org/10.1007/s11270-020-04611-0

Hsu, C. Y., Chiang, H. C., Chen, M. J., Chuang, C. Y., Tsen, C. M., Fang, G. C., & Chen, Y. C. (2017). Ambient PM2.5 in the residential area near industrial complexes: Spatiotemporal variation, source apportionment, and health impact. *Science of the Total Environment*, 590, 204–214.

Huryn, S. M., & Gough, W. A. (2014). Impact of urbanization on the ozone weekday/weekend effect in Southern Ontario, Canada. *Urban Climate*, 8, 11–20.

IBGE. Instituto Brasileiro de Geografia e Estatística. (2002). *Caracterização e tendências da rede urbana do Brasil: Configurações atuais e tendências da rede urbana* (p. 2001). IBGE.

IBGE. Instituto Brasileiro de Geografia e Estatística. (2021). *IBGE – Cidades* (p. 2013). IBGE.

INMET. Instituto Nacional de Meteorologia. (2021). BDMEP – Banco de dados meteorológicos do Brasil. Brasília, Distrito Federal: INMET.

Jeon, J. M., Kang, B. W., Lee, H. S., & Lee, C. M. (2010). Health risk assessment of heavy metals in PM 2.5 in industrial areas. *Journal of Environmental Health Sciences*, 36(4), 294–305.

Jiang, L., & Bai, L. (2018). Spatio-temporal characteristics of urban air pollution and their causal relationships: Evidence from Beijing and its neighboring cities. *Scientific Reports*, 8(1), 1–12.

Koo, B., Jung, J., Pollack, A. K., Lindhjem, C., Jimenez, M., & Yarwood, G. (2012). Impact of meteorology and anthropogenic emissions on the local and regional ozone weekend effect in Midwestern US. *Atmospheric Environment*, 57, 13–21.

Krzyzanowski, M., Apte, J. S., Bonjour, S. P., Brauer, M., Cohen, A. J., & Prüss-Ustun, A. M. (2014). Air pollution in the mega-cities. *Current Environmental Health Reports*, 1(3), 185–191.

Leão, M. L. P., Penteado, J. O., Ulguim, S. M., Gabriel, R. R., Dos Santos, M., Brum, A. N., ... & da Silva Júnior, F. M. R. (2021). Health impact assessment of air pollutants during the COVID-19 pandemic in a Brazilian metropolis. *Environmental Science and Pollution Research*, 28(31), 41843–41850. https://doi.org/10.1007/s11356-021-13650-x

Lebron, F. (1975). A comparison of weekend-weekday ozone and hydrocarbon concentrations in the Baltimore-Washington metropolitan area. *Atmospheric Environment* (1967), 9(9), 861–863.

Li, A., Chen, C., Chen, J., & Lei, P. (2021). Environmental investigation of pollutants in coal mine operation and waste dump area monitored in Ordos Region. *China. RSC Advances, 11*(17), 10340–10352.

Li, R., Wang, Z., Cui, L., Fu, H., Zhang, L., Kong, L., & Chen, J. (2019). Air pollution characteristics in China during 2015–2016: Spatiotemporal variations and key meteorological factors. *Science of the Total Environment*, 648, 902–915.

Liang, L., & Gong, P. (2020). Urban and air pollution: A multi-city study of long-term effects of urban landscape patterns on air quality trends. *Scientific Reports*, 10(1), 1–13.

Martins, E. M., Nunes, A. C., & Corrêa, S. (2015). Understanding ozone concentrations during weekdays and weekends in the urban area of the city of Rio de Janeiro. *Journal of the Brazilian Chemical Society*, 26, 1967–1975.

Mohtar, A. A. A., Latif, M. T., Baharudin, N. H., Ahamad, F., Chung, J. X., Othman, M., & Juneng, L. (2018). Variation of major air pollutants in different seasonal conditions in an urban environment in Malaysia. *Geoscience Letters*, 5(1), 1–13.

Paschalidou, A. K., & Kassomenos, P. A. (2004). Comparison of air pollutant concentrations between weekdays and weekends in Athens, Greece for various meteorological conditions. *Environmental Technology*, 25(11), 1241–1255.

Papescu, F., & Ionel, I. (2010). Anthropogenic air pollution sources. *Air quality*, 1–22.

Roberts-Semple, D., Song, F., & Gao, Y. (2012). Seasonal characteristics of ambient nitrogen oxides and ground-level ozone in metropolitan northeastern New Jersey. *Atmospheric Pollution Research*, 3(2), 247–257.

Schipa, I., Tanzarella, A., & Mangia, C. (2009). Differences between weekend and weekday ozone levels over rural and urban sites in Southern Italy. *Environmental Monitoring and Assessment*, 156(1), 59–523.

Sharifi, A., & Khavari-Garmsir, A. R. (2020). The COVID-19 pandemic: Impacts on cities and major lessons for urban planning, design, and management. *Science of the Total Environment*, 749, 142391.

Sharma, D., Soni, V. K., & Pradhan, S. (2022). Assessment of variation in air quality over Delhi and neighbouring cities of Noida and Greater Noida. *Journal of Earth System Science*, 131(3), 1–16.

Sidar, P., Paioletti, E., Agathokleous, E., Arnimienne, V., Proietti, C., Coulilably, F., & De Marco, A. (2020). Ozone weekend effect in cities: Deep insights for urban air pollution control. *Environmental Research, 191*, 110193.

Stillman, S. (1999). The relation between ozone, NOx and hydrocarbons in urban and polluted rural environments. *Atmospheric Environment*, 33(12), 1821–1845.

Silva Júnior, R. S. D., Oliveira, M. G. L. D., & Andrade, M. D. F. (2009). Weekend/weekday differences in concentrations of ozone, nox, and non-methane hydrocarbon in the metropolitan area of São Paulo. *Revista Brasileira De Meteorologia*, 24(1), 100–110.

Stephens, S., Madronich, S., Wu, F., Olson, J. B., Ramos, R., Retama, A., & Munoz, R. (2008). Weekly patterns of Méxiko City’s surface concentrations of CO, NO x, PM 10 and O 3 during 1986–2007. *Atmospheric Chemistry and Physics*, 8(17), 5313–5325.

Sujatha, P. (2017). Contribution of vehicular emissions on urban air quality: Results from public strike in Hyderabad.
Tan, P. H., Chou, C., & Chou, C. C. K. (2013). Impact of urbanization on the air pollution “holiday effect” in Taiwan. *Atmospheric Environment*, 70, 361–375.

Tan, P. H., Chou, C., Liang, J. Y., Chou, C. C. K., & Shiu, C. J. (2009). Air pollution “holiday effect” resulting from the Chinese New Year. *Atmospheric Environment*, 43(13), 2114–2124.

Tang, W., Zhao, C., Geng, F., Peng, L., Zhou, G., Gao, W., & Tie, X. (2008). Study of ozone “weekend effect” in Shanghai. *Science in China Series d: Earth Sciences*, 51(9), 1354–1360.

Tavella, R. A., & da Silva Júnior, F. M. R. (2020). COVID-19 and air pollution: What do we know so far? *ViTATLE-Revista De Ciências Da Saúde*, 32(1), 22–31.

Tavella, R. A., & da Silva Júnior, F. M. R. (2021). Watch out for trends: Did ozone increased or decreased during the COVID-19 pandemic? *Environmental Science and Pollution Research*, 28(47), 67880–67885.

Ulugim, S. M., Tavella, R. A., Dias, D., & Rodrigues, F. M. (2021). Dinâmica dos Poluentes Atmosféricos e o Modelo de Distanciamento Controlado do Rio Grande do Sul para Controle da Pandemia da Covid-19.

Wells, B., Dolwick, P., Eder, B., Evangelista, M., Foley, K., Mannshardt, E., & Weishampel, A. (2021). Improved estimation of trends in US ozone concentrations adjusted for interannual variability in meteorological conditions. *Atmospheric Environment*, 248, 118234.

WHO. World Health Organization. (2006). *Air quality guidelines: Global update 2005: Particulate matter, ozone, nitrogen dioxide and sulfur dioxide*. Geneva: World Health Organization.

WHO. World Health Organization. (2021). WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: World Health Organization.

Yoo, J. M., Jeong, M. J., Kim, D., Stockwell, W. R., Yang, J. H., Shin, H. W., & Lee, S. D. (2015). Spatiotemporal variations of air pollutants (O3, NO2, SO2, CO, PM10, and VOCs) with land-use types. *Atmospheric Chemistry and Physics*, 15(18), 10857–10885.

Yousefian, F., Faridi, S., Azimi, F., Aghaei, M., Shamsipour, M., Yaghmaeian, K., & Hassanvand, M. S. (2020). Temporal variations of ambient air pollutants and meteorological influences on their concentrations in Tehran during 2012–2017. *Scientific Reports*, 10(1), 1–11.

Zhao, X., Zhou, W., & Han, L. (2019). Human activities and urban air pollution in Chinese mega city: An insight of ozone weekend effect in Beijing. *Physics and Chemistry of the Earth, Parts A/B/C*, 110, 109–116.

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.