Case Studies in Chemical and Environmental Engineering 10 (2024) 100923

Contents lists available at ScienceDirect

Case Studies in Chemical and Environmental Engineering

journal homepage: www.sciencedirect.com/journal/case-studies-in-chemical-and-environmental-engineering

Case Report

Health impact assessment of air pollutants in simulated temperature scenarios in the largest coal mining region of Brazil

Alicia da Silva Bonifácio [a], Rodrigo de Lima Brum [a], Ronan Adler Tavella [b], Ng Haig They [c], Willian Cézar Nadaleti [d], Mariana Vieira Coronas [e], Elizabet Saes-Silva [a], Aline Neutzling Brum [f], Romina Buffarini [a], Washington Luiz Félix Correia Filho [a], Diana Francisca Adamatti [a], Rosália Garcia Neves [a], Flavio Manoel Rodrigues da Silva Júnior [a,*]

[a] Universidade Federal do Rio Grande – FURG, Av. Itália, Km 8, Campus Carreiros, Rio Grande, RS, CEP 96203-900, Brazil
[b] Instituto de Ciências Ambientais, Químicas e Farmacêuticas, Universidade Federal de São Paulo, Rua São Nicolau 210, SP, Diadema, CEP 09913-030, Brazil
[c] Centro de Estudos Costeiros, Limnológicos e Marinhos (CECLIMAR), Departamento Interdisciplinar, Universidade Federal do Rio Grande do Sul (UFRGS), Av. Tramandaí, 976 - Imbé, RS, CEP 95625-000, Brazil
[d] Universidade Federal de Pelotas (UFPEL), Rua Benjamin Constant, 989, Porto – Pelotas, RS, CEP 96010-020, Brazil
[e] Universidade Federal de Santa Maria (UFSM), Rodovia Taufik Germano, 3013, Passo D'Areia, Campus de Cachoeira do Sul, Cachoeira do Sul, RS, CEP 96503-205, Brazil
[f] Universidade Federal do Pampa (UNIPAMPA), Rua Vinte e Um de Abril, 80, São Gregório, Campus Dom Pedrito, Dom Pedrito, RS, CEP 96450-000, Brazil

ARTICLE INFO

Keywords:
Candiota
Machine learning
Predictive models
Climate change

ABSTRACT

This study examines the impact of projected temperature increases on air pollutant levels and associated health outcomes in Candiota, Brazil, a major coal mining region. Using meteorological and air pollutant data ($PM_{2.5}$, PM_{10}, O_3) and machine learning, we simulated pollutant levels under 2 °C and 4 °C increases and assessed the consequent health impacts. Results indicate increases in O_3, PM_{10}, and $PM_{2.5}$ levels across all investigated cities, with marked seasonal differences, leading to higher mortality and hospitalizations due to cardiovascular and respiratory diseases. Underscoring the need for targeted interventions in coal mining areas as climate change exacerbates air pollution health impacts.

1. Introduction

Coal mining and its use are major contributors to the emission of greenhouse gases and atmospheric pollutants, exacerbating global climate change and posing serious health risks to both local communities and the nearby cities. Individuals residing in mining and coal-burning areas are chronically exposed to pollutants released at all stages of the extraction process. Among the primary pollutants emitted are sulfur dioxide (SO_2), nitrogen oxides (NOx), fine particulate matter ($PM_{2.5}$), and coarse particulate matter (PM_{10}) [1].

Exposure to these pollutants is associated with a wide range of health problems, including strokes, heart and lung diseases, lower respiratory infections like pneumonia, and cancer [2]. Additionally, it is estimated that this exposure contributes to approximately 20 % of neonatal deaths worldwide [3]. Although air pollution is a global problem, it disproportionately affects vulnerable groups including women, children, and the elderly, especially in developing countries or areas with high levels of emissions [4].

In Candiota, a city located in southern Brazil that holds 40 % of the nation's coal reserves, a study aimed at estimating mortality attributed to particulate matter and the health benefits associated with reducing air pollution to local regulatory standards found that over 11 % of cardiovascular deaths were attributed to $PM_{2.5}$ pollution. The study further indicated that reducing $PM_{2.5}$ and PM_{10} levels could increase life expectancy by up to 17 months and yield economic benefits surpassing US $ 24 million through reductions in hospitalizations and mortality [5]. Moreover, Candiota is scientifically recognized for environmental contamination across multiple matrices, with studies highlighting negative impacts on soil, air, and water quality [6–8], underscoring the relevance of this region in relation to pollution.

Globally, air pollutants exposure in mining regions is linked to significant health impacts. Chio et al. [9] observed that a coal-fired power

* Corresponding author.
E-mail address: f.m.r.silvajunior@gmail.com (F.M.R. da Silva Júnior).

https://doi.org/10.1016/j.cscee.2024.100923
Received 12 July 2024; Received in revised form 22 August 2024; Accepted 28 August 2024
Available online 4 September 2024

plant in Shenao, Taiwan, increased $PM_{2.5}$ levels in the region, resulting in an estimated 576 premature deaths from 2025 to 2040 across 19 cities. Additionally, multiple studies have demonstrated that proximity to coal mining activities significantly increases the likelihood of respiratory diseases and other health issues, particularly in communities living near mining sites [10,11]. These findings align with numerous studies highlighting health risks for populations living in highly polluted areas [12–14].

With the rise in global temperature and climate change, the adverse effects of air pollution exposure are intensified. Meteorological variables such as temperature, relative humidity, precipitation, wind speed, and direction, influence the dispersion, suspension, and formation of atmospheric particles [15]. Studies have shown a close relationship between air pollution levels and meteorological variables, particularly temperature [15–17]. For instance, the study by Radzka [17], which analyzed data from 2013 to 2017 in Siedlce, Poland, found that higher temperatures were associated with lower PM_{10} levels, while increased wind speeds significantly reduced $PM_{2.5}$ and PM_{10} concentrations. The study also highlighted that relative humidity had a seasonal influence on air pollutants concentrations, and wind speed notably reduced PM_{10} levels during specific months. In this sense, temperature increases, driven by climate change, could alter the dynamics of pollutant formation and dispersion, potentially leading to higher levels of pollutants in certain regions, although this effect vary depending on local conditions.

While previous studies in coal mining regions have extensively documented the health impacts of air pollutants emitted by these activities, there remains a significant gap in the literature regarding the effects of rising global temperatures—driven by climate change—on the dynamics of pollutant formation and dispersion in these areas, as well as their consequent impacts on human health. To our knowledge, no studies have yet explored how scenarios of increased temperature might alter the behavior of these pollutants or exacerbate health outcomes for populations living near coal mining sites. Given that these regions are recognized as significant hotspots for air pollution, it is essential to conduct research that investigates these interactions.

In light of the above, the present study aims to investigate the impact of temperature increase under scenarios outlined by the IPCC (RCP 4.5 and 8.5), focusing on the coal mining region of Candiota and adjacent municipalities. Employing Health Impact Assessment (HIA) methodology, this study sought to estimate the health consequences, such as mortality and hospitalizations, resulting from exposure to different levels of pollutants, including O_3, $PM_{2.5}$ and PM_{10}.

2. Material and methods

2.1. Characterization of the study area

This study encompass seven municipalities located in the coal mining region in Candiota, Brazil, in the state of Rio Grande do Sul. The municipalities included are Aceguá, Bagé, Candiota, Herval, Hulha Negra, Pedras Altas, and Pinheiro Machado. All investigated cities are adjacent to the region with active coal mining activities (Candiota), except for Herval, which was included in the study due to its geographical proximity to the region. The study area is illustrated in Fig. 1.

In Candiota, the primary sources of anthropogenic air pollutants include the Presidente Médici Thermal Power Plant (31° 33′ 01.9″ S, 53° 40′ 58.8″ W) and two coal mining sites: a one smaller coal mine (31° 26′ 49.7″ S, 53° 42′ 26.4″ W) and a larger coal mine (31° 34′ 59.7″ S, 53° 43′ 15.6″ W). Additionally, the neighboring city of Pedras Altas, and located on the border with Candiota, is the Pampa Sul Thermal Power Plant (31° 26′ 54.8″ S, 53° 46′ 43.4″ W). Both of these thermal power plants rely on coal extracted from the Candiota mines to generate energy for a significant portion of the south of Brazil territory.

Furthermore, Pinheiro Machado hosts cement industries that utilize ash from thermoelectric plants in their production processes. In the other municipalities, the primary economic activities are focused on the agricultural sector, particularly livestock farming (sheep and cattle) and crop production, including rice, wheat, corn, and sorghum. The land use distribution across the municipalities studied are detailed in Fig. 2. It is also important to note that, with the exception of Bagé, all the cities are considered small cities, with populations below 12,000 inhabitants, resulting in relatively low levels of urban emissions [18].

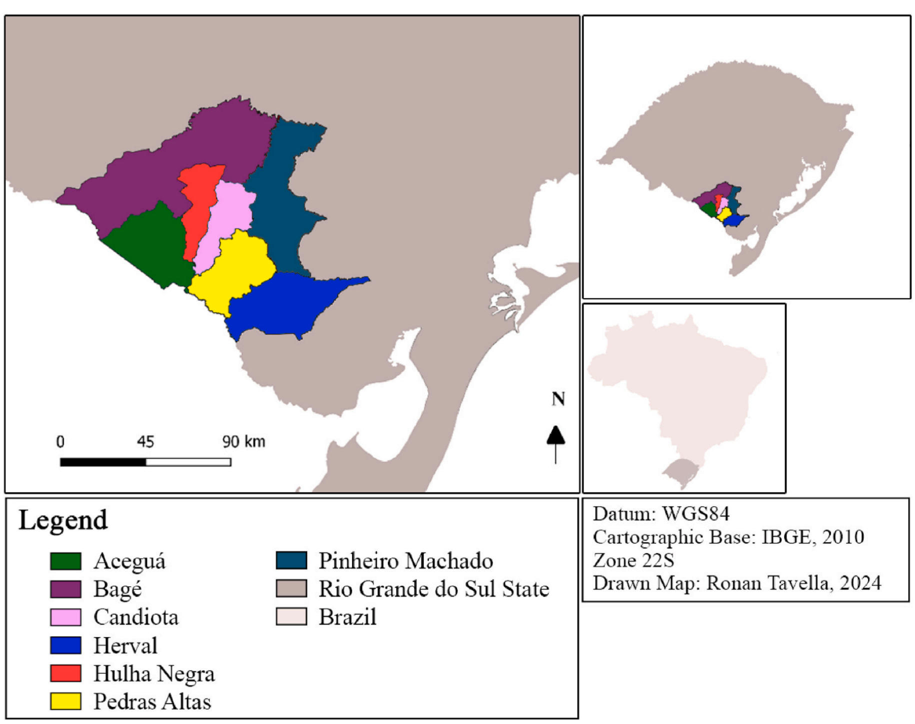

Fig. 1. Map of the study area.

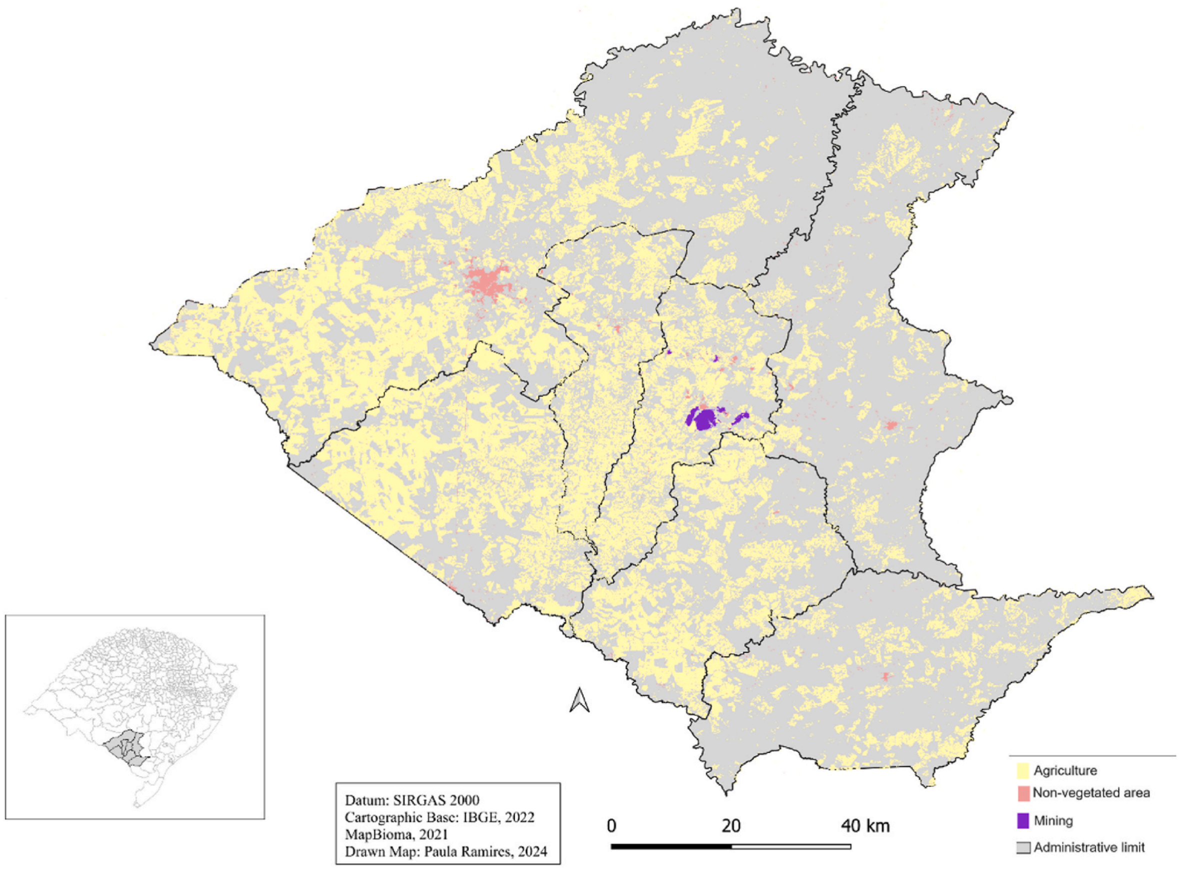

Fig. 2. Map of land use in the study area.

2.2. Data collection and study period

The levels of air pollutants (PM_{10}, $PM_{2.5}$ and O_3) for all cities were obtained from satellite data provided by the Copernicus Atmospheric Monitoring Service (CAMS) at the European Centre for Medium-Range Weather Forecasts (ECMWF). The data was manually extracted in real-time from The Weather Channel app (IBM, USA), with measurement recorded in the standard unit of $\mu g/m^3$. This methodology is further outlined in prior researches [19,20].

Pollutant data were acquired for sampling grids that represent the studied cities and locations, taking into account the spatial resolution limitations inherent in satellite-based observations. Although satellite data present certain limitations, this approach is deemed suitable for the purposes of our study due to the inadequate air quality monitoring infrastructure in Brazil, particularly in this region. As highlighted by Vormittag et al. [21], only 1.6 % of Brazilian cities have air quality monitoring stations, and approximately 41 % of these stations are privately operated, often without public data access. Notably, none of the cities in our study have monitoring stations with publicly accessible data. Moreover, different studies support this methodology for regions with sparse ground monitoring networks, using data from The Weather Channel application and other satellite-based air quality data sources [22,23].

Meteorological variables were sourced from the National Institute of Meteorology (INMET) and the Agrometeorological Monitoring System (Agritempo) databases. These variables collected included wind speed, relative humidity, atmospheric pressure, UV index, temperature and rainfall. These data were obtained either from active meteorological monitoring stations or from estimates provided by Agritempo for locations lacking active stations.

In Table S1 regarding health data, collection was conducted through the Department of Health Informatics of the Unified Health System (DATASUS), which is responsible for collecting, processing, disseminating, and providing access to essential health information for the planning, organization, and management of the Brazilian Unified Health System.

As our primary aim is to assess the impact of temperature increase scenarios on air pollutant levels in the mining region and surrounding cities, and their consequent health impacts, all cities were considered exposed. Furthermore, the investigation period covered in this study was from September 2021 to September 2022.

2.3. Simulations of temperature increase scenarios

Among the different Representative Concentration Pathways (RCPs) projected by the IPCC, scenarios predicting +2 °C and +4 °C temperature increases were utilized, represented by RCP 4.5 and RCP 8.5, respectively, reflecting a more conservative and a more alarmist scenario. Analyses for future simulations under these different scenarios were conducted using Statistica software (v.10.0), employing Machine Learning (ML) tools (support vector machine model) along with cross-validation to enhance the reliability of predicted results.

To create the "future atmosphere," various meteorological variables (humidity, pressure, wind speed, precipitation, and UV index) were considered. Simulations were performed using a multivariate approach, initially analyzing all meteorological variables individually, treating temperature as the predictor variable. This approach aimed to ensure realistic results that could be modeled alongside pollutant concentrations (PM_{10}, $PM_{2.5}$, and O_3).

Following the isolated analysis of meteorological variables, a new database was created incorporating daily average data for pollutant inclusion. Multivariate analysis was then conducted, treating pollutants as dependent variables and meteorological variables as predictors.

2.4. Health Impact Assessment (HIA)

Health Impact Assessment (HIA) is defined as a combination of procedures, analyses, methods and tools through which a policy, program or project can be assessed for its potential effects on the health of a population and the distribution of its consequences, effects and impacts [24]. For this approach we employed a methodology stemming from the APHEKOM project (Improving Knowledge and Communication for Decision Making on Air Pollution and Health in Europe) (Aphekom, 2013). The HIA Tool "short term (rev. Sept 2013)" focuses on short-term exposure. Total hospital admission data were used for non-extreme causes, as well as respiratory and circulatory system causes.

Evaluation scenarios were developed based on air pollutants levels obtained from different the temperature increase outcomes, specifically RCP4.5 (+2 °C) and 8.5 (+4 °C). This was performed to understand the number of cases that could be increased by the aggravation of pollution.

2.5. Deaths attributable to air pollution

To calculate attributable deaths we used the AirQ + software, which estimates the attributable fraction, cases attributable per 100,000 people at risk, and the proportion of cases within a range of air pollutant concentrations (based on baseline incidence of health outcomes) [25]. Demographic data from the 2022 Census, along with annual average $PM_{2.5}$ concentration data resulting from different temperature increase scenarios and actual data for the 7 cities analyzed in the study, were used for the calculation of attributable deaths. Health data used for the attributable deaths analyses are outlined in Table S2.

3. Results

Table 1 illustrates the difference between observed and predicted scenarios, considering temperature adjustments. Candiota and Pedras Altas, cities directly influenced by coal mining emissions, showed higher predicted values compared to observed ones. In the +2 °C scenario, Pedras Altas exhibited differences of 11 %, 4 %, and 6 % between observed and predicted values for O_3, PM_{10}, and $PM_{2.5}$, respectively. These differences increased to 18 %, 11 %, and 7 % in the +4 °C scenario. Similarly, Candiota showed contributions of 9 %, 7 %, and 10 % for O_3, PM_{10}, and $PM_{2.5}$ in the +2 °C scenario, with increases to 15 %, 10 %, and 14 % in the +4 °C scenario.

Comparing the investigated cities, Pinheiro Machado and Herval exhibited the highest predicted values. In the +2 °C scenario, Pinheiro Machado showed increases of 11 %, 23 %, and 13 % in O_3, PM_{10}, and $PM_{2.5}$ levels, respectively. In the +4 °C scenario, these increases rose to 18 %, 31 %, and 95 %. Similarly, Herval also demonstrated significant increases in pollutant levels, especially in the +4 °C scenario, with increases of 15 %, 17 %, and 22 % in O_3, PM_{10}, and $PM_{2.5}$ levels.

When comparing these results with those of Candiota and Pedras Altas, it is observed that although there were increases in pollutant levels, especially in the +4 °C scenario, the concentrations were not as high as those observed in the previously mentioned cities. This demonstrates that not only cities with active coal-using enterprises are the focus of emissions in these areas.

Among all cities, pollutants exhibit varying patterns, not following a standard pollutant with consistently higher levels, indicating non-linear responses in observed versus predicted scenarios and varying pollutant prominence across cities. For instance, in Candiota, $PM_{2.5}$ had the greatest influence in the +2 °C scenario, while O_3 was predominant in the +4 °C scenario. In Pedras Altas and Aceguá, O_3 dominated in both scenarios; Pinheiro Machado showed PM_{10} predominance, while Bagé, Herval, and Hulha Negra highlighted $PM_{2.5}$.

Tables 2 and 3 present the relationship between seasonal contributions for all cities and pollutants. For O_3 in all cities under the +2 °C and +4 °C scenarios, summer and autumn are the seasons contributing to the highest concentrations of this pollutant. Regarding PM_{10} and $PM_{2.5}$, spring and autumn represent the major contributions under both +2 °C and +4 °C scenarios. Unlike O_3, where no season showed a reduction in concentrations, winter showed decrease pollutant levels across all cities for PM, with the exception of Herval for $PM_{2.5}$ in the +2 °C scenario and PM_{10} in Pinheiro Machado under the +4 °C scenario.

Table 4 demonstrates the results of the HIA analyses, showing the number of increased cases related to increases in pollutant concentrations under different temperature increase scenarios (predicted values)

Table 1
Percentage difference between observed and predicted concentrations of pollutants O_3, PM_{10} and $PM_{2.5}$ in the different scenarios outlined by the IPCC (RCP 4.5 and 8.5) of temperature increase for all seven cities analyzed in the study.

City	Pollutant	+2 °C			+4 °C		
		Observed μg/m^3	Predicted μg/m^3	Difference	Observed μg/m^3	Predicted μg/m^3	Difference
Candiota	O_3	46.7	50.1	+8 %	46.7	53.9	+15 %
	PM_{10}	8.0	8.6	+7 %	8.0	8.9	+11 %
	$PM_{2.5}$	5.3	5.8	+9 %	5.3	6.1	+15 %
Pedras Altas	O_3	46.2	51.1	+11 %	46.2	54.3	+18 %
	PM_{10}	8.1	8.4	+4 %	8.1	8.7	+7 %
	$PM_{2.5}$	5.3	5.6	+6 %	5.3	5.9	+11 %
Aceguá	O_3	48.1	52.0	+8 %	48.1	54.5	+13 %
	PM_{10}	7.2	7.5	+4 %	7.2	7.8	+7 %
	$PM_{2.5}$	4.7	5.1	+8 %	4.7	5.27	+12 %
Bagé	O_3	48.3	51.2	+6 %	48.3	54.0	+12 %
	PM_{10}	7.5	8.0	+7 %	7.5	8.3	+11 %
	$PM_{2.5}$	5.0	5.4	+8 %	5.0	5.6	+12 %
Pinheiro Machado	O_3	46.5	53.5	+15 %	46.5	54.9	+19 %
	PM_{10}	7.8	9.6	+23 %	7.8	10.2	+31 %
	$PM_{2.5}$	5.2	7.04	+35 %	5.2	10.14	+95 %
Herval	O_3	48.3	53.0	+10 %	48.3	55.4	+15 %
	PM_{10}	7.7	8.7	+13 %	7.7	9.1	+18 %
	$PM_{2.5}$	5.0	6.0	+20 %	5.0	6.14	+23 %
Hulha Negra	O_3	47.9	52.2	+9 %	47.9	55.3	+15 %
	PM_{10}	7.8	8.5	+9 %	7.8	8.9	+14 %
	$PM_{2.5}$	5.2	5.8	+12 %	5.2	6.0	+15 %

Table 2
Percentage difference between the observed and predicted concentrations of the pollutants O_3, PM_{10} and $PM_{2.5}$ in the scenario outlined by the IPCC (RCP 4.5) of temperature increase for all cities, seven cities analyzed in the study, considering the seasonal variation of four seasons of the year.

RCP 4.5 (+2 °C)										
City	Seasons	O_3 μg/m^3			PM_{10} μg/m^3			$PM_{2.5}$ μg/m^3		
		Observed	Predicted	Difference	Observed	Predicted	Difference	Observed	Predicted	Difference
Candiota	Spring	51.4	52.7	+2 %	6.7	8.7	+30 %	4.5	6.0	+33 %
	Summer	55	60.2	+9 %	9.2	9.4	+2 %	6.1	6.5	+6 %
	Autumn	39.5	46.7	+18 %	7.2	8.1	+12 %	4.8	5.5	+14 %
	Winter	41.1	44.5	+8 %	9.0	8.0	−11 %	6	5.4	−10 %
Pedras Altass	Spring	50.5	52.3	+3 %	6.7	8.6	+28 %	4.4	5.8	+32 %
	Summer	53.9	61	+13 %	9.3	9.3	0 %	6.2	6.3	+2 %
	Autumn	39.4	46.9	+19 %	7.4	7.9	+7 %	4.8	5.4	+12 %
	Winter	41.3	44.7	+8 %	8.8	7.7	−12 %	5.9	5.2	−12 %
Aceguá	Spring	51.4	53.6	+4 %	6.1	7.7	+26 %	4	5.3	+32 %
	Summer	53.8	60.2	+12 %	8.3	8.3	0 %	5.5	5.6	+2 %
	Autumn	43	48.1	+12 %	6.6	7.1	+7 %	4.3	4.9	+14 %
	Winter	44.3	46.3	+4 %	7.8	6.9	−11 %	5.2	4.7	−10 %
Bagé	Spring	53.0	53.0	0 %	6.3	8.2	+30 %	4.2	5.6	+33 %
	Summer	55.6	60.4	+8 %	8.6	8.9	+3 %	5.7	6.0	+5 %
	Autumn	41.8	46.7	+12 %	6.7	7.5	+12 %	4.4	5.0	+14 %
	Winter	43.2	45.4	+5 %	8.3	7.4	−11 %	5.6	4.9	−12 %
Pinheiro Machado	Spring	50.7	53.9	+6 %	6.6	10	+51 %	4.3	6.5	+51 %
	Summer	52.9	61.9	+17 %	9.1	9.9	+9 %	6.0	9.0	+50 %
	Autumn	40.1	47.1	+17 %	6.8	6.7	-1 %	4.5	7.8	+73 %
	Winter	42.5	44.3	+4 %	9.0	8.3	−3%	5.8	8.0	−38 %
Herval	Spring	51.7	55.1	+7 %	6.6	9.0	+36 %	4.2	6.1	+45 %
	Summer	51.8	60.3	+16 %	8.9	9.8	+10 %	5.8	6.5	+12 %
	Autumn	43.4	49.5	+14 %	7.4	8.2	+11 %	4.8	5.7	+19 %
	Winter	46.3	47.6	+3 %	8.1	8.0	−1%	5.3	5.6	+6 %
Hulha Negra	Spring	52.6	54.0	+3 %	6.5	8.8	+35 %	4.3	6.0	+39 %
	Summer	56.1	62.7	+12 %	8.9	9.5	+7 %	5.9	6.4	+8 %
	Autumn	41.1	47.3	+15 %	7	8.1	+16 %	4.6	5.5	+19 %
	Winter	42.3	45.1	+7 %	8.7	7.9	−9 %	5.9	5.3	−10 %

compared to observed values. The analyzes show the results of hospital admissions for causes related to the respiratory system in different age groups exposed to O_3. The highest number of annual deaths per 100 thousand inhabitants in the +2 °C scenario was observed in Aceguá, with an increase of 9 deaths in the population over 65 years old, if there was an increase of 4.93 μg/m^3 in the average predicted annual O_3 levels. Likewise, Aceguá in the +4 °C scenario, under the same conditions, also stands out with the highest number of annual deaths per 100 thousand inhabitants, showing an increase of 11.9 deaths in the population over 65 years old with an increase of 6.46 μg/m^3 at predicted annual average O_3 levels.

Table 5 presents the results of an increase in cases for PM_{10}, where Candiota stands out with the highest number of increased cases per 100,000 inhabitants in the +2 °C scenario, considering an increase in PM_{10} levels of 0.54 μg/m^3 resulting in an increase of 6.26 cases of cardiac hospitalizations per 100,000 inhabitants. For respiratory hospitalizations, the increase of 0.54 μg/m^3 led to an increase of 10.10 cases per 100,000 inhabitants. In the +4 °C scenario, the increase in cases did not exceed 1. Pinheiro Machado in the +2 °C scenario for cardiac hospitalizations, with an increase of 1.86 μg/m^3, resulted in an increase of 0.74 cases per 100,000 inhabitants, while for respiratory hospitalizations, the same scenario of increase resulted in 0.28 increased cases per 100,000 inhabitants. In the +4 °C scenario, in the two scenarios mentioned, the increase of 2.39 μg/m^3 led to an increase of 0.96 and 0.37 cases per 100,000 inhabitants, respectively.

Table 6 displays the results of analyses on air pollution-attributable deaths for $PM_{2.5}$ across different scenarios, considering deaths from all causes, respiratory diseases, circulatory diseases, COPD, and lung cancer. Across all cities, as pollutant exposure levels increase (from scenario 1 to scenario 3), the differences in outcomes are more pronounced in higher exposure scenarios, especially for COPDand lung cancer, indicating greater sensitivity of these diseases to air pollution. Cities vary in impact, with some showing higher absolute numbers, such as Bagé and Pinheiro Machado, reflecting higher population density or other local factors influencing exposure and vulnerability.

Regarding mortality from all causes, attributable proportions vary. For instance, in Pinheiro Machado, air pollution contributes to a mortality rate of 4.22 %, translating to approximately 6.99 attributable cases per 100,000 people. These numbers are higher compared to other areas like Aceguá, where the attribution is 0.21 %: 1.14 cases per 100,000 people. Impact on respiratory and circulatory systems also shows variations. In Herval, attributable mortality for circulatory diseases is 1.18 %, reflecting 3.73 cases per 100,000 inhabitants. For respiratory diseases, Pinheiro Machado again stands out with an attribution of 2.43 % and 6.22 attributable cases per 100,000 inhabitants. In Hulha Negra, COPD shows an attribution of 3.29 %, resulting in 5.05 cases per 100,000 inhabitants, while lung cancer shows an attribution of 1.42 %, with 2.25 cases.

4. Discussion

Air pollution and climate change are two major threats to global health. The main finding of our study showed that simulated temperature increase scenarios resulted in higher annual concentrations of O_3, PM_{10}, and $PM_{2.5}$ across all the cities in the coal mining region, including both Candiota and the surrounding municipalities. However, pollutants exhibited distinct seasonal behaviors. While O_3 levels increased across all seasons in both scenarios (except for spring in Bagé in the +2 °C scenario), PM_{10} and $PM_{2.5}$ levels decreased during winter, with the exception of Herval in both simulated temperature increase scenarios. The findings do not indicate a consistent trend regarding the dynamics of air pollutants across different seasons. Additionally, the increases in

Table 3
Percentage difference between the observed and predicted concentrations of the pollutants O_3, PM_{10} and $PM_{2.5}$ in the scenario outlined by the IPCC (RCP 8.5) of temperature increase for all cities, seven cities analyzed in the study, considering the seasonal variation of four seasons of the year.

RCP 8.5 (+4 °C)										
City	Seasons	O_3 μg/m^3			PM_{10} μg/m^3			$PM_{2.5}$ μg/m^3		
		Observed	Predicted	Difference	Observed	Predicted	Difference	Observed	Predicted	Difference
Candiota	Spring	51.4	55.9	+9 %	6.7	9.0	+34 %	4.5	6.2	+38 %
	Summer	55.0	63.4	+15 %	9.2	9.8	+6 %	6.1	6.7	+10 %
	Autumn	39.5	49.5	+25 %	7.3	8.4	+15 %	4.8	5.8	+21 %
	Winter	41.1	47.1	+14 %	9	8.2	−9%	6.0	5.6	−7%
Pedras Altas	Spring	50.5	55.7	+10 %	6.7	8.8	+31 %	4.4	6.0	+36 %
	Summer	53.9	64.5	+20 %	9.4	9.5	+1 %	6.1	6.4	+5 %
	Autumn	39.4	49.9	+27 %	7.4	8.3	+12 %	4.8	5.6	+17 %
	Winter	41.3	47.4	+15 %	8.8	8.0	−9%	5.9	5.4	−9%
Aceguá	Spring	51.4	56.4	+10 %	6.0	8.0	+33 %	4.0	5.5	+37 %
	Summer	53.8	63.0	+17 %	8.3	8.5	+2 %	5.5	5.6	+2 %
	Autumn	43.0	50.5	+17 %	6.6	7.4	+12 %	4.3	5.0	+16 %
	Winter	44.3	48.5	+9 %	7.8	7.2	−8%	5.2	4.9	−6 %
Bagé	Spring	53.0	56.0	+6 %	6.3	8.5	+35 %	4.2	5.7	+36 %
	Summer	55.6	65.5	+18 %	8.6	9.2	+7 %	5.7	6.2	+9 %
	Autumn	41.8	49.2	+18 %	6.7	7.8	+16 %	4.4	5.3	+20 %
	Winter	43.2	47.6	+10 %	8.3	7.7	−7%	5.6	5.2	−7 %
Pinheiro Machado	Spring	50.7	57.3	+13 %	6.6	10.6	+61 %	4.3	7.3	+70 %
	Summer	52.9	65.2	+23 %	9.1	12.1	+33 %	6.0	10.5	+75 %
	Autumn	40.1	50.2	+25 %	6.9	9.3	+35 %	4.5	7.0	+56 %
	Winter	42.5	47.2	+11 %	8.6	8.8	+2 %	5.8	7.0	+ 21 %
Herval	Spring	51.7	57.4	+11 %	6.6	9.4	+42 %	4.2	6.3	+50 %
	Summer	51.8	63.0	+22 %	8.9	10.2	+15 %	5.8	6.6	+14 %
	Autumn	43.4	51.7	+19 %	7.4	8.5	+15 %	4.8	5.9	+23 %
	Winter	46.3	49.8	+7 %	8.0	8.2	+2 %	5.3	5.8	+9 %
Hulha Negra	Spring	52.6	57.6	+9 %	6.5	9.0	+38 %	4.3	6.2	+44 %
	Summer	56.1	66.4	+18 %	8.9	9.7	+9 %	5.9	6.6	+12 %
	Autumn	40.9	50.1	+22 %	7.0	8.4	+20 %	4.6	5.7	+24 %
	Winter	42.3	47.6	+12 %	8.7	8.2	−6%	5.9	5.6	−5%

Table 4
Number of cases attributed in relation to the increase in the predicted values in both scenarios of temperature increase (RCP 4.5 and 8.5) considering the pollutant O_3 for hospitalizations related to the respiratory system considering the age groups of 15–64 and > 64 years.

Scenario	City	Increase (μg/m^3)	Respiratory Hospitalizations 15-64	Respiratory Hospitalizations >64
			Annual number of increased cases (100 thousand inhabitants)	Annual number of increased cases (100 thousand inhabitants)
+2°C	Candiota	4.26	0.04	1.13
	Pedras Altas	7.38	0.06	6.52
	Aceguá	4.93	0.21	9.22
	Bagé	2.91	0.08	2.26
	Herval	4.79	0.09	3.27
	Hulha Negra	3.83	0.16	3.91
	Pinheiro Machado	7.07	0.06	6.24
+4°C	Candiota	7.23	0.06	1.91
	Pedras Altas	4.80	0.08	7.02
	Aceguá	6.46	0.27	11.91
	Bagé	5.65	0.0	0.09
	Herval	7.19	0.14	4.90
	Hulha Negra	6.70	0.14	3.36
	Pinheiro Machado	10.40	0.09	9.18

Table 5
Number of cases attributed in relation to the increase in the predicted values in the two scenarios of temperature increase (RCP 4.5 and 8.5) considering the pollutant PM_{10} for hospitalizations related to the respiratory system and cardiac hospitalizations.

Scenario	City	Increase (μg/m^3)	Respiratory Hospitalizations	Cardiac Hospitalizations
			Annual number of increased cases (100 thousand inhabitants)	Annual number of increased cases (100 thousand inhabitants)
+2°C	Candiota	0.54	10.10	6.26
	Pedras Altas	1.85	0.0	0.0
	Aceguá	0.3	0.12	0.02
	Bagé	0.54	0.04	0.02
	Herval	0.99	0.68	0.21
	Hulha Negra	0.03	0.00	0.0
	Pinheiro Machado	1.86	0.74	0.28
+4°C	Candiota	0.84	0.18	0.11
	Pedras Altas	0.95	0.01	0.0
	Aceguá	0.5	0.0	0.0
	Bagé	0.83	0.35	0.13
	Herval	1.32	0.51	0.16
	Hulha Negra	0.12	0.01	0.0
	Pinheiro Machado	2.39	0.96	0.37

Table 6
Deaths attributable to air pollution for $PM_{2.5}$ in the different temperature scenarios (scenario 1 = original (observed) data/scenario 2 = RCP 4.5/scenario 3 – RCP 8.5) for all seven cities analyzed in the study, considering different outcomes: deaths from all causes, diseases of the respiratory/circulatory system, COPD and lung cancer.

Outcome	City	Scenario	Estimated Attributable Proportion (%)	Estimated number of attributable cases per 100,000 Population at Risk
All causes CID 10 - A00-R99	Aceguá	1	0.0 (0.0–0.0)	0.0 (0.0–0.0)
		2	0.08 (0.06–0.09)	0.2 (0.1–0.3)
		3	0.21 (0.16–0.23)	1.14 (0.87–1.28)
	Bagé	1	0.0 (0.0–0.0)	0.0 (0.0–0.0)
		2	0.29 (0.22–0.33)	4.02 (3.8–4.62)
		3	0.45 (0.34–0.5)	5.66 (5.8–8.57)
	Candiota	1	0.26 (0.20–0.29)	2.8 (2.2–3.13)
		2	0.65 (0.49–0.73)	6.98 (5.29–7.81)
		3	0.83 (0.63–0.93)	1.95 (0.57–2.84)
	Herval	1	0.03 (0.02–0.03)	0.6 (0.45–0.67)
		2	0.76 (0.58–0.85)	14.77 (11.19–16.53)
		3	0.87 (0.66–0.98)	17 (12.88–19.02)
	Hulha Negra	1	0.0 (0.0–0.0)	0.0 (0.0–0.0)
		2	0.5 (0.06–0.9)	1.1 (0.1–0.15)
		3	0.21 (0.16–0.23)	1.14 (0.87–1.28)
	Pedras Altas	1	0.25 (0.19–0.28)	2.51 (2.06–3.93)
		2	0.50 (0.38–0.56)	2.11 (1.39–7.96)
		3	0.66 (0.5–0.74)	2.86 (2.77–8.87)
	Pinheiro Machado	1	1.5 (1.14–1.68)	3.58 (3.95–5.33)
		2	2.24 (1.7–2.51)	7.11 (5.76–8.68)
		3	4.22 (1.69–2.48)	6.99 (3.47–7.57)
Circulatory system CID 10 - I00– I99	Aceguá	1	0.0 (0.0–0.0)	0.0 (0.0–0.0)
		2	0.11 (0.09–0.14)	0.27 (0.22–0.34)
		3	0.28 (0.23–0.35)	0.67 (0.55–0.84)
	Bagé	1	0.0 (0.0–0.0)	0.0 (0.0–0.0)
		2	0.4 (0.33–0.5)	2.76 (2.28–3.46)
		3	0.6 (0.5–0.76)	4.2 (3.47–5.27)
	Candiota	1	0.35 (0.29–0.44)	1.36 (1.13–1.71)
		2	0.88 (0.73–1.11)	3.4 (2.81–4.26)
		3	1.12 (0.93–1.41)	4.31 (3.56–5.41)
	Herval	1	0.03 (0.03–0.04)	0.24 (0.20–0.30)
		2	1.03 (0.85–1.29)	2.89 (1.52–3.9)
		3	1.18 (0.98–1.48)	3.73 (1.74–5.18)
	Hulha Negra	1	0.0 (0.0–0.0)	0.0 (0.0–0.0)
		2	0.15 (0.09–0.14)	0.21 (0.12–0.30)
		3	0.28 (0.23–0.35)	0.52 (0.51–0.84)
	Pedras Altas	1	0.33 (0.28–0.42)	1.5 (1.24–1.88)
		2	0.68 (0.56–0.85)	1.8 (1.7–1.11)

Table 6 (*continued*)

Outcome	City	Scenario	Estimated Attributable Proportion (%)	Estimated number of attributable cases per 100,000 Population at Risk
		3	0.89 (0.74–1.12)	2.02 (1.32–5.04)
	Pinheiro Machado	1	2.03 (1.68–2.55)	7.04 (5.96–7.08)
		2	3.03 (2.51–3.79)	6.94 (4.86–8.44)
		3	3.69 (4.48–3.75)	7.96 (4.71–9.22)
Respiratory system CID 10 - J10-J22, P23, U04	Aceguá	1	0.0 (0.0–0.0)	0.0 (0.0–0.0)
		2	0.1 (0.03–0.18)	0.6 (0.2–1.0)
		3	0.26 (0.08–0.45)	0.6 (0.0–0.9)
	Bagé	1	0.0 (0.0–0.0)	0.0 (0.0–0.0)
		2	0.36 (0.11–0.63)	0.12 (0.04–0.2)
		3	0.55 (0.17–0.96)	1.18 (0.6–2.31)
	Candiota	1	0.32 (0.1–0.56)	0.99 (0.3–1.16)
		2	0.81 (0.25–1.4)	1.0 (0.8–1.2)
		3	1.02 (0.32–1.77)	2.4 (2.0–3.0)
	Herval	1	0.03 (0.01–0.05)	0.01 (0.0–0.03)
		2	0.94 (0.29–1.63)	1.92 (0.6–3.33)
		3	1.08 (0.34–1.87)	2.21 (0.69–3.83)
	Hulha Negra	1	0.1 (0.1–0.3)	0.0 (0.0–0.0)
		2	0.22 (0.24–0.36)	0.6 (0.1–0.7)
		3	1.01 (0.09–1.05)	2.1 (1.5–2.8)
	Pedras Altas	1	0.3 (0.09–0.53)	0.0 (0.0–0.0)
		2	0.72 (0.19–1.07)	1.85 (0.58–3.21)
		3	0.92 (0.25–1.41)	2.45 (0.76–4.24)
	Pinheiro Machado	1	1.86 (0.58–3.21)	0.0 (0.0–0.0)
		2	2.77 (0.87–4.77)	4.98 (3.93–5.13)
		3	2.74 (0.86–4.72)	3.95 (2.92–5.08)
Chronic obstructive pulmonary disease (COPD) CID 10 – J40 – J44, J47	Aceguá	1	0.0 (0.0–0.0)	0.0 (0.0–0.0)
		2	1.14 (0.14–2.35)	2.71 (0.32–5.57)
		3	1.29 (0.23–2.57)	3.05 (0.54–6.07)
	Bagé	1	0.0 (0.0–0.0)	0.0 (0.0–0.0)
		2	1.39 (0.29–2.71)	7.15 (1.49–13.92)
		3	1.57 (0.4–2.98)	7.08 (2.08–15.27)
	Candiota	1	1.36 (0.27–2.66)	2.45 (1.09–3.89)
		2	1.82 (0.56–3.33)	2.04 (0.93–5.57)
		3	2.04 (0.7–3.64)	3.41 (1.17–6.08)
	Herval	1	1.07 (0.09–2.25)	0.55 (0.05–1.15)
		2	1.95 (0.64–3.51)	3.2 (1.33–4.80)
		3	2.1 (0.74–3.72)	1.07 (0.38–1.9)
	Hulha Negra	1	0.0 (0.0–0.0)	0.0 (0.0–0.0)
		2	3.44 (2.07–4.35)	6.71 (1.32–8.57)

(*continued on next page*)

Table 6 (*continued*)

Outcome	City	Scenario	Estimated Attributable Proportion (%)	Estimated number of attributable cases per 100,000 Population at Risk
		3	3.29 (0.23–2.57)	5.05 (5.54–7.07)
	Pedras Altas	1	0.2 (0.26–1.2)	0.0 (0.0–0.0)
		2	1.64 (0.44–3.07)	2.92 (1.33–5.2)
		3	1.83 (0.56–3.34)	3.49 (1.69–10.03)
	Pinheiro Machado	1	1.92 (1.29–4.87)	2.06 (1.04–3.93)
		2	3.87 (1.94–6.15)	5.37 (4.69–7.88)
		3	3.4 (1.92–6.11)	7.3 (4.64–12.79)
Lung cancer CID 10 - C33–C34	Aceguá	1	0.0 (0.0–0.0)	0.0 (0.0–0.0)
		2	1.34 (0.07–2.77)	2.09 (0.05–2.18)
		3	1.51 (0.17–3.01)	2.19 (0.13–2.37)
	Bagé	1	0.0 (0.0–0.0)	0.0 (0.0–0.0)
		2	1.62 (0.23–3.18)	2.11 (0.3–4.12)
		3	1.83 (0.36–3.48)	2.38 (0.46–4.51)
	Candiota	1	1.58 (0.21–3.12)	2.96 (0.14–3.99)
		2	1.12 (0.52–3.88)	4.02 (2.17–5.3)
		3	2.36 (0.67–4.22)	3.5 (0.22–3.6)
	Herval	1	1.26 (0.02–2.65)	2.93 (1.3–4.07)
		2	2.26 (0.61–4.08)	5.79 (1.55–10.46)
		3	2.43 (0.72–4.31)	6.22 (1.83–11.04)
	Hulha Negra	1	0.0 (0.0–0.0)	0.0 (0.0–0.0)
		2	1.53 (0.07–2.77)	3.6 (2.7–4.19)
		3	1.42 (0.17–3.58)	2.25 (0.13–2.37)
	Pedras Altas	1	0.2 (0.2–3.09)	0.7 (0.5–0.9)
		2	1.91 (0.4–3.58)	3.2 (0.81–3.5)
		3	2.13 (0.53–3.89)	4.3 (2.93–6.5)
	Pinheiro Machado	1	2.36 (1.33–5.56)	5.42 (2.15–8.97)
		2	4.02 (2.0–6.93)	7.38 (1.1–8.73)
		3	4.58 (2.02–6.89)	7.86 (1.09–11.71)

air pollutant levels observed in the simulated scenarios were associated with negative health impacts across the region, including increases in both hospitalizations and mortality.

The impact of temperature increases on pollutant levels is a global concern, as rising temperatures are expected to exacerbate air pollution and its associated health risks. Lee et al. [26] investigated this relationship regarding O_3 with future projections of non-accidental mortality in summer across seven major cities in South Korea during the 2020s (2016–2025) and 2050s (2046–2055). Changes in temperature and ozone concentration were considered, projected using HadGEM3-RA and the Integrated Climate and Air Quality Modeling System, respectively. Four Representative Concentration Pathway (RCP) scenarios (RCP 2.6, 4.5, 6.0, and 8.5) were assessed. Results indicated that non-accidental mortality in summer will increase by 0.5 %, 0.0 %, 0.4 %, and 0.4 % in the 2020s, and by 1.9 %, 1.5 %, 1.2 %, and 4.4 % in the 2050s due to temperature change compared to baseline mortality during 2001–2010, under RCP 2.6, 4.5, 6.0, and 8.5, respectively. Meanwhile, mortality will increase by 0.0 %, 0.5 %, 0.0 %, and 0.5 % in the 2020s, and by 0.2 %, 0.2 %, 0.4 %, and 0.6 % in the 2050s due to changes in ozone concentration.

Regarding PM_{10} and $PM_{2.5}$, spring and autumn represent the highest contributions in temperature increase scenarios. Winter was able to reduce levels of these pollutants in all cities for both PM_{10} and $PM_{2.5}$, except in Herval for $PM_{2.5}$ in the +2 °C scenario and in Pinheiro Machado for PM_{10} in the +4 °C scenario. The reduction in this season can be explained by local meteorological variables. The dynamics of winter winds help disperse particulate matter, and increased humidity and precipitation favor the wet scavenging of pollutants [27]. Consequently, temperature may have a weaker relationship with air pollutant levels during this season, resulting in lower pollutant levels in predictive models. Zhang et al. [28] conducted a study designed to analyze how temperature modulated the effects of particulate matter (PM_{10}, $PM_{2.5}$) on hospital admissions in Beijing, China, from 2009 to 2011, using three models to assess health impacts of PM with temperature modifications. The results consistently showed that relatively higher temperatures (adjusted temperature ≥ cutoff temperature) significantly modified the effects of PM on pollution-related morbidity. The effects of $PM_{2.5}$ were more pronounced than those of PM_{10}. Additionally, the findings indicated that older adults and women were more vulnerable to PM under high temperature conditions [28].

In addition to environmental concerns related to the coal mining region of Candiota [29,30], various studies already associate residents' exposure with negative health outcomes [5,7,8,31,32]. Our results regarding population health indicators show that climatic factors in relation with air pollutants may influence the worsening health of residents in the region, where our worst-case temperature increase scenario (RCP 8.5) could contribute to increased deaths from all causes, circulatory/respiratory diseases, COPD, and lung cancer associated with $PM_{2.5}$ exposure. This contribution varied among cities, particularly highlighting Herval and Pinheiro Machado, demonstrating the impact of temperature increase on the dispersion of atmospheric pollutants from their main source areas (Candiota and Pedras Altas).

In this context, the land use data demonstrate that the main source of air pollutants in the region is the coal mining activity, but also allied with the use of the extracted coal to generate energy in two local thermoelectric plants. These activities significantly impact local air pollution levels. Moreover, the negative impact observed in Herval can be attributed to its proximity to Pedras Altas, where a thermoelectric plant is a major source of emissions. Similarly, Pinheiro Machado is situated in an area affected by emissions from this same plant, and the ash produced during energy generation is used in the region's cement factories, further contributing to atmospheric pollution in the city. These factors, combined with meteorological variables that intensify pollution dispersion, can exacerbate health outcomes for the local population.

In this sense, with higher concentrations of atmospheric pollutants resulting from local temperature increase, the impacts on the exposed population are expected to be more significant. A study by Cheng et al. [33] showed that significant temperature changes can cause physiological stress and alter a person's health status in response to toxic agents, potentially making them more susceptible to the effects of atmospheric pollutants. Moreover, most deaths related to air pollution occur in elderly adults [34,35], who have lower thermoregulatory capacity and higher sweat threshold compared to younger individuals. Therefore, interactions with atmospheric pollutants at higher temperatures may pose greater health risks.

Through our findings and other studies conducted in the region, we can consider air pollution in Candiota as a significant risk factor for the resident population. Marmett et al. [36] also addressed this issue by conducting an assessment focused on polycyclic aromatic hydrocarbon (PAHs) in the city. The study aimed to evaluate the carcinogenic health risk from inhalation exposure to PAHs. A total of 158 individuals were included in the study. Monitoring of PAHs and meteorological parameters was conducted, and health risk assessment was determined through the toxic equivalent quotient of benzo(*a*)pyrene (BaP-TEQ) and incremental lifetime cancer risk (ILCR) estimation. The coal activity area of Candiota showed an annual concentration of HPAs of 27.7 ng/μg/m^3, PM_{10} concentration of 26.3 μg/μg/m^3, SO_2 concentration of 9.5 μg/μg/m^3, BaP-TEQ value of 0.3 ng/m^3, and a daily inhalation of 62.4 ng/day. ILCR values of 2.8×10^{-6} and 2.6×10^{-6} were observed for estimates based on reference and actual values, respectively, and these levels were above the reference limit of 10^{-6}, indicating cancer risk and highlighting the issues associated with this region [36].

Although several studies have been conducted in this region, as well as in other coal mining areas, the majority have focused primarily on the health impacts of air pollutants emitted by coal mining activities. However, there is an evident lack of information in the literature regarding the effects of future temperature scenarios on these coal mining-affected areas. To our knowledge, no studies have yet explored how rising temperatures, driven by climate change, might influence pollutant levels and exacerbate health risks in these regions, which are recognized hotspots for air pollutants. Furthermore, the relationship between environmental and meteorological variables and their consequences on health indicators as a result of these associations is rarely addressed in the existing research, particularly for smaller cities with low population density, where such interactions might have unique dynamics and impacts. This set of information further underscores the novelty, importance, and relevance of our research.

Addressing global climate change is central to a growing field of scientific research on topics such as environmental health, disease burden, and resulting economic impacts. At the local level, cities are significant sources of air pollution due to the large quantities of pollutants they emit [37]. As the global population shifts towards urban centers, cities will increasingly concentrate exposed populations. Worldwide, there is already evidence of the relationship between temperature and pollutants such as particulate matter, demonstrating how temperature can exacerbate their health effects [37], in addition to the impacts already proven by different researchers regarding exposure to these pollutants [38–41].

Policies aimed at air pollution have focused on emission control and improving air quality, given the growing need to mitigate the effects of global climate change [42,43]. Policy makers have the responsibility to “think globally and act locally” to develop interventions aimed at reducing future climate impacts and mitigating negative health outcomes. Adapting the healthcare system is essential to address the consequences of future climate implications on the population.

The study has some limitations related to the use of air pollution data obtained from satellites, which may include non-random classification errors, saturation effects, and atmospheric effects that can lead to deviations from accurate ground-based data. However, due to the lack of adequate air quality monitoring in the area, we believe that satellite data remains the best available option for assessing air pollution in this region. Another limitation is the exclusion of factors such as land cover changes and geographic issues from the analyses, which can directly influence temperature and explain the behavior of pollutants in a specific region. Future studies should focus on prediction models that include a broader range of variables, both environmental and social, such as socioeconomic and geographic factors, as well as other atmospheric pollutants in different mining areas and mining activities. This could provide a better comprehension of the interactions between climate change and air quality in these regions.

5. Conclusion

Our findings indicate that increased temperatures scenarios (RCP 4.5 and 8.5) intensify concentrations of atmospheric pollutants (PM_{10}, $PM_{2.5}$, and O_3) in the Candiota region and all adjacent municipalities. Furthermore, in these scenarios, all seasons contribute to increased pollutant concentrations, except for winter in the case of particulate matter. Additionally, health indicators, including attributable deaths and HIA, showed that higher projected temperature increases, and its consequent impact on air pollutant levels, lead to worse health outcomes for the exposed population. This underscores the importance of addressing climate change at a regional level, particularly in areas impacted by coal mining. Investigating these regions is essential, as the compounded effects of climate change and air pollution could have profound implications for both the environment and public health.

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 307791/2023-8 (FMRSJ), and Fundação de Amparo à Pesquisa do Estado do Rio Grande do Sul (FAPERGS), Grant 21/2551-0001981-6.

Ethics approval

Not applicable.

Patient consent

Not applicable.

Permission to reproduce material from other sources

Not applicable.

CRediT authorship contribution statement

Alicia da Silva Bonifácio: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Rodrigo de Lima Brum:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Ronan Adler Tavella:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Ng Haig They:** Writing – review & editing, Writing – original draft, Conceptualization. **Willian Cézar Nadaleti:** Writing – review & editing, Writing – original draft, Conceptualization. **Mariana Vieira Coronas:** Writing – review & editing, Writing – original draft, Conceptualization. **Elizabet Saes-Silva:** Writing – review & editing, Writing – original draft, Conceptualization. **Aline Neutzling Brum:** Writing – review & editing, Writing – original draft, Conceptualization. **Romina Buffarini:** Writing – review & editing, Writing – original draft, Conceptualization. **Washington Luiz Félix Correia Filho:** Writing – review & editing, Writing – original draft, Conceptualization. **Diana Francisca Adamatti:** Writing – review & editing, Writing – original draft, Conceptualization. **Rosália Garcia Neves:** Writing – review & editing, Writing – original draft, Conceptualization. **Flavio Manoel Rodrigues da Silva Júnior:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cscee.2024.100923.

References

[1] M. Hendryx, M.S. Islam, G.H. Dong, G. Paul, Air pollution emissions 2008–2018 from Australian coal mining: implications for public and occupational health, Int. J. Environ. Res. Publ. Health 17 (5) (2020) 1570, https://doi.org/10.3390/ijerph17051570.

[2] David E. Abbey, et al., Long-term inhalable particles and other air pollutants related to mortality in nonsmokers, Am. J. Respir. Crit. Care Med. 159 (2) (1999) 373–382, https://doi.org/10.1164/ajrccm.159.2.9806020.

[3] Z. Xing, S. Zhang, Y.T. Jiang, X.X. Wang, H. Cui, Association between prenatal air pollution exposure and risk of hypospadias in offspring: a systematic review and meta-analysis of observational studies, Aging (Albany NY) 13 (6) (2021) 8865, https://doi.org/10.18632/aging.202698.

[4] A.N. Monika, R. Khatun, S. Akter, M.A. Hasnat, M.M. Rahman, M.M. Ahasan, A comparison study of the solid phantom and water phantom using 6 MV and 15 MV photon energies, depending on the depth, Bangladesh J. Nucl. Med. 27 (1) (2024) 34–38, https://doi.org/10.3329/bjnm.v27i1.71517.

[5] L.C. Honscha, F.O. Reis, P. Aikawa, M.V. Coronas, A.L. Muccillo-Baisch, P.R. M. Baisch, F.M.R. da Silva Júnior, Human health risk assessment of air pollutants in the largest coal mining area in Brazil, Environ. Sci. Pollut. Control Ser. 30 (21) (2023) 59499–59509, https://doi.org/10.1007/s11356-023-26708-9.

[6] F.M.R. da Silva Júnior, C.L.F. Fernandes, R.A. Tavella, L.C. Hoscha, P.R.M. Baisch, Genotoxic damage in coelomocytes of Eisenia andrei exposed to urban soils, Mutat. Res. Genet. Toxicol. Environ. Mutagen 842 (2019) 111–116, https://doi.org/10.1016/j.mrgentox.2019.02.007.

[7] A.P. Bigliardi, M. dos Santos, C.L.F. Fernandes, et al., Lung function among residents from the largest coal region in Brazil, Environ. Sci. Pollut. Res. 29 (2022) 46803–46812, https://doi.org/10.1007/s11356-022-19242-7.

[8] A. da Silva Bonifácio, R. de Lima Brum, R.A. Tavella, P.F. Ramires, I.M. Lessa, M. Dos Santos, F.M.R. da Silva Júnior, Human health risk assessment of metals and anions in surface water from a mineral coal region in Brazil, Environ. Monit. Assess. 193 (9) (2021) 567, https://doi.org/10.1007/s10661-021-09359-6.

[9] C.P. Chio, W.C. Lo, B.J. Tsuang, C.C. Hu, K.C. Ku, Y.J. Chen, C.C. Chan, Health impact assessment of PM2. 5 from a planned coal-fired power plant in Taiwan, J. Formos. Med. Assoc. 118 (11) (2019) 1494–1503, https://doi.org/10.1016/j.jfma.2019.08.016.

[10] S. Saha, S.K. Pattanayak, E.O. Sills, A.K. Singha, Under-mining health: environmental justice and mining in India, Health Place 17 (1) (2011 Jan 1) 140–148, https://doi.org/10.1016/j.healthplace.2010.09.007.

[11] I.R. Chowdhury, A. Paul, Respiratory health and air pollution in opencast coal mining region: a study in mahanadi coalfield, Odisha, India, Indian Econ. J. 72 (3) (2024) 460–476, https://doi.org/10.1177/00194662241235489.

[12] S.M. Ahern, B. Arnott, T. Chatterton, A. de Nazelle, I. Kellar, R.R. McEachan, Understanding parents' school travel choices: a qualitative study using the Theoretical Domains Framework, J. Transport Health 4 (2017) 278–293, https://doi.org/10.1016/j.jth.2016.11.001.

[13] J.A. Casey, D. Karasek, E.L. Ogburn, D.E. Goin, K. Dang, P.A. Braveman, R. Morello-Frosch, Retirements of coal and oil power plants in California: association with reduced preterm birth among populations nearby, Am. J. Epidemiol. 187 (8) (2018) 1586–1594, https://doi.org/10.1093/aje/kwy110.

[14] F.B. Gutierrez, S. Eslava Martins, L.C. Honscha, R. de Lima Brum, V.M.F. Vargas, N. Mirlean, F.M.R. da Silva Junior, Is there something in the air? Sources, concentrations and ionic composition of particulate matter (PM 2.5) in an industrial coastal city in Southern Brazil, Water, Air, Soil Pollut. 231 (2020) 1–10, https://doi.org/10.1007/s11270-020-04611-0.

[15] A. Wilson, B.J. Reich, C.G. Nolte, T.L. Spero, B. Hubbell, A.G. Rappold, Climate change impacts on projections of excess mortality at 2030 using spatially varying ozone–temperature risk surfaces, J. Expo. Sci. Environ. Epidemiol. 27 (1) (2017) 118–124, https://doi.org/10.1038/jes.2016.14.

[16] J. Lou, Y. Wu, P. Liu, S.H. Kota, L. Huang, Health effects of climate change through temperature and air pollution, Current Pollut. Rep. 5 (2019) 144–158, https://doi.org/10.1007/s40726-019-00112-9.

[17] E. Radzka, The effect of meteorological conditions on air pollution in Siedlce, J. Ecol. Eng. 21 (1) (2020) 97–104, https://doi.org/10.12911/22998993/113074.

[18] Instituto Brasileiro de Geografia e Estatística – IBGE, Cidades e Estados do Brasil. https://cidades.ibge.gov.br, 2022. (Accessed 19 August 2024).

[19] F.M. Júnior, L.C. Honscha, R.D. Brum, P.F. Ramires, R.A. Tavella, C.L. Fernandes, J.O. Pentado, A.D. Bonifácio, L.M. Volcão, M. Dos Santos, M.V. Coronas, Air quality in cities of the extreme south of Brazil, Ecotoxicol. Environ. Contam. 15 (1) (2020 Nov 10) 61–67, https://doi.org/10.5132/eec.2020.01.08.

[20] R.A. Tavella, N.G. da Rosa Moraes, C.D. Aick, P.F. Ramires, N. Pereira, A.G. Soares, F.M. da Silva Júnior, Weekend effect of air pollutants in small and medium-sized cities: the role of policies stringency to COVID-19 containment, Atmos. Pollut. Res. 14 (2) (2023 Feb 1) 101662, https://doi.org/10.1016/j.apr.2023.101662.

[21] E.D.M.P.D.A. Vormittag, S.S.R. Cirqueira, H. Wicher, P.H.N. Saldiva, Análise do monitoramento da qualidade do ar no Brasil, Estud. Avançados 35 (102) (2021) 7–30, https://doi.org/10.1590/s0103-4014.2021.35102.002.

[22] M.J. Alvarado, A.E. McVey, J.D. Hegarty, E.S. Cross, C.A. Hasenkopf, R. Lynch, G. Kleiman, Evaluating the use of satellite observations to supplement ground-level air quality data in selected cities in low-and middle-income countries, Atmos. Environ. 218 (2019) 117016, https://doi.org/10.1016/j.atmosenv.2019.117016.

[23] D. Mejía, G. Faican, R. Zalakeviciute, C. Matovelle, S. Bonilla, J.A. Sobrino, Spatio-temporal evaluation of air pollution using ground-based and satellite data during COVID-19 in Ecuador, Heliyon 10 (7) (2024) e05684, https://doi.org/10.1016/j.heliyon.2024.e28152.

[24] H.L. Macintyre, C. Mitsakou, M. Vieno, M.R. Heal, C. Heaviside, K.S. Exley, Impacts of emissions policies on future UK mortality burdens associated with air pollution, Environ. Int. 174 (2023) 107862, https://doi.org/10.1016/j.envint.2023.107862.

[25] D.J. Naghan, A. Neisi, G. Goudarzi, M. Dastoorpoor, A. Fadaei, K.A. Angali, Estimation of the effects PM2. 5, NO2, O3 pollutants on the health of Shahrekord residents based on AirQ+ software during (2012–2018), Toxicol Rep 9 (2022) 842–847, https://doi.org/10.1016/j.toxrep.2022.03.045.

[26] J.Y. Lee, S.H. Lee, S.C. Hong, H. Kim, Projecting future summer mortality due to ambient ozone concentration and temperature changes, Atmos. Environ. 156 (2017) 88–94, https://doi.org/10.1016/j.atmosenv.2017.02.034.

[27] D. Sirithian, P. Thanatrakolsri, Relationships between meteorological and particulate matter concentrations (PM2. 5 and PM10) during the haze period in urban and rural areas, northern Thailand, Air Soil. Water Res. 15 (2022) 11786221221117264, https://doi.org/10.1177/11786221221117264.

[28] Y. Zhang, S. Wang, X. Fan, X. Ye, Temperature modulation of the health effects of particulate matter in Beijing, China, Environ. Sci. Pollut. Control Ser. 25 (2018) 10857–10866, https://doi.org/10.1007/s11356-018-1256-3.

[29] P.J.S. Filho, V.R.P. Nogueira, L.C. Krause, M.R.A. Rodrigues, M.D.C.R. Peralba, E. B. Caramao, Polycyclic aromatic hydrocarbons from Candiota (South Brazilian) coal extracts, Polycycl. Aromat. Comp. 22 (1) (2002) 13–22, https://doi.org/10.1080/10406630210374.

[30] P. de Souza Junior, L.M.R.P.D. Santos, W. Viotto-Souza, N.D.C. de Carvalho, E. C. Souza, C.B. Kasper, A.L.Q. Santos, Functional myology of the thoracic limb in Pampas fox (Lycalopex gymnocercus): a descriptive and comparative analysis, J. Anat. 233 (6) (2018) 783–806, https://doi.org/10.1111/joa.12892.

[31] M. Dos Santos, J.O. Penteado, M.C.F. Soares, A.L. Muccillo-Baisch, F.M.R. Da Silva-Júnior, Association between DNA damage, dietary patterns, nutritional status, and non-communicable diseases in coal miners, Environ. Sci. Pollut. Control Ser. 26 (2019) 15600–15607, https://doi.org/10.1007/s11356-019-04922-8.

[32] R. de Lima Brum, M. Dos Santos, U.J. da Silva Junior, A.L. Muccillo-Baisch, F.M. R. da Silva Júnior, Urinary Pb levels in schoolchildren from the largest coal mining area in Brazil and its associated factors: a cross-sectional study, Environ. Sci. Pollut. Control Ser. 29 (49) (2022) 74407–74415, https://doi.org/10.1007/s11356-022-21058-4.

[33] Y. Cheng, H. Kan, Effect of the interaction between outdoor air pollution and extreme temperature on daily mortality in Shanghai, China, J. Epidemiol. 22 (1) (2012) 28–36, https://doi.org/10.2188/jea.JE20110049.

[34] M. Gordon, R.M. Staebler, J. Liggio, S.M. Li, J. Wentzell, G. Lu, J.R. Brook, Measured and modeled variation in pollutant concentration near roadways, Atmos. Environ. 57 (2012) 138–145, https://doi.org/10.1016/j.atmosenv.2012.04.022.

[35] T.F. Bateson, J. Schwartz, Children's response to air pollutants, J. Toxicol. Environ. Health, Part A 71 (3) (2007) 238–243, https://doi.org/10.1080/15287390701598234.

[36] B. Marmett, R.B. Carvalho, A.L. Muccillo-Baisch, P.R.M. Baisch, M. Dos Santos, E. M. Garcia, F.M.R. da Silva Júnior, Emissions monitoring and carcinogenic risk assessment of PM 10-bounded PAHs in the air from Candiota's coal activity area, Brazil, Environ. Geochem. Health 45 (3) (2023) 899–911, https://doi.org/10.1007/s10653-022-01253-5.

[37] A.D. Slovic, M.A. de Oliveira, J. Biehl, H. Ribeiro, How can urban policies improve air quality and help mitigate global climate change: a systematic mapping review, J. Urban Health 93 (2016) 73–95. https://10.1007/s11524-015-0007-8.

[38] Y. Zhang, S. Wang, X. Fan, X. Ye, Temperature modulation of the health effects of particulate matter in Beijing, China, Environ. Sci. Pollut. Control Ser. 25 (2018) 10857–10866, https://doi.org/10.1007/s11356-018-1256-3.

[39] J.J. Kim, T. Hann, S.J. Lee, Effect of flow and humidity on indoor deposition of particulate matter, Environ. Pollut. 255 (2019) 113263, https://doi.org/10.1016/j.envpol.2019.113263.

[40] F. Chen, Z. Fan, Z. Qiao, Y. Cui, M. Zhang, X. Zhao, X. Li, Does temperature modify the effect of PM10 on mortality? A systematic review and meta-analysis, Environ. Pollut. 224 (2017) 326–335, https://doi.org/10.1016/j.envpol.2017.02.012.

[41] A. Wilson, B.J. Reich, C.G. Nolte, T.L. Spero, B. Hubbell, A.G. Rappold, Climate change impacts on projections of excess mortality at 2030 using spatially varying

ozone–temperature risk surfaces, J. Expo. Sci. Environ. Epidemiol. 27 (1) (2017) 118–124, https://doi.org/10.1038/jes.2016.14.
[42] F.R. de Moura, P.D.W. Machado, P.F. Ramires, R.A. Tavella, H. Carvalho, F.M.R. da Silva Júnior, In the line of fire: analyzing burning impacts on air pollution and air quality in an Amazonian city, Brazil, Atmos. Pollut. Res. 15 (4) (2024) 102033, https://doi.org/10.1016/j.apr.2023.102033.
[43] C. Kousky, Informing climate adaptation: a review of the economic costs of natural disasters, Energy Econ. 46 (2014) 576–592, https://doi.org/10.1016/j.eneco.2013.09.029.

Health Impact Assessment of Air Pollutants in Simulated Temperature Scenarios in the Largest Coal Mining Region of Brazil

Alicia da Silva Bonifácio[1], Rodrigo de Lima Brum[1], Ronan Adler Tavella[2], Ng Haig They[3], Willian Cézar Nadaleti[4], Mariana Vieira Coronas[5], Elizabet Saes-Silva[1], Aline Neutzling Brum[6], Romina Buffarini[1], Washington Luiz Félix Correia Filho[1], Diana Francisca Adamatti[1], Rosália Garcia Neves[1], Flavio Manoel Rodrigues da Silva Júnior[1]*

[1] Universidade Federal do Rio Grande – FURG, Av. Itália, km 8, Campus Carreiros, Rio Grande, RS 96203-900, Brazil

[2] Instituto de Ciências Ambientais, Químicas e Farmacêuticas, Universidade Federal de São Paulo, R São Nicolau 210, CEP 09913-030, SP, Diadema, Brazil.

[3] Centro de Estudos Costeiros, Limnológicos e Marinhos (CECLIMAR), Departamento Interdisciplinar, Universidade Federal do Rio Grande do Sul (UFRGS) – Imbé, RS, Brazil

[4] Universidade Federal de Pelotas (UFPEL), Rua Benjamin Constant, 989, Porto – Pelotas, RS, Brazil, 96010-020

[5] Universidade Federal de Santa Maria (UFSM), Rodovia Taufik Germano, 3013, Passo D'Areia, Campus de Cachoeira do Sul – Cachoeira do Sul, RS, Brazil, 96503-205

[6] Universidade Federal do Pampa (UNIPAMPA), Rua Vinte e Um de Abril, 80, São Gregório, Campus Dom Pedrito – Dom Pedrito, RS, Brazil, 96450-000

* Corresponding author email: f.m.r.silvajunior@gmail.com +55 53 32935249

SUPPLEMENTAL MATERIAL

Table S1. Mortality and hospitalization data collected from Datasus.

Mortality data	Hospitalization data	CID 10
Total (not external)	Total (not external)	A00-R99
Respiratory system	Respiratory system	J00-J99
Circulatory system	Circulatory system	I00- I99
Lung disease		I26-I28
chronic obstructive disease (DPOC)		J40 – J44, J47
Lung cancer		C33-C34

Table S2. Data used to calculate attributable deaths in the AirQ+ software

CID 10	Condition	Condition
A00-R99	Mortality from natural causes	>30 years
J40 – J44, J47	DPOC	>30 years
C33-C34	Lung cancer	>30 years
J10-J22, P23, U04	Respiratory infection	>30 years
I00- I99	Circulatory system	>30 years