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Impact of monthly air pollution and weather conditions on cardiorespiratory mortality in Portuguese Metropolitan Areas

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This study analyses cardiorespiratory mortality rates (CARDIO) and their association with air pollutants - particulate matter with aerodynamic diameters lower of equal to 10 or 2.5 (µm) (PM_{10}, $PM_{2.5}$), carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3) - and meteorological variables (temperature, humidity, wind speed, direction) in the Lisbon (LMA) and Porto (PMA) metropolitan areas from 2011 to 2020. Monthly analyses reveal regional patterns and seasonal variations. The results show that PMA had a higher average CARDIO rate (202.94 [Deaths per 100 000]) compared to LMA (169.70 [Deaths per 100 000]). Linear and Poisson regression, contingency tables, correspondence analysis and Pearson's chi-squared tests confirmed significant associations between low temperature and wind speeds, high pollutant concentrations, and increased mortality. Lower temperature (≤ 13 [°C]) and wind speed (≤ 2.5 [m/s]) were consistently associated with increased CARDIO in both regions. High pollutant levels, particularly PM_{10} (≥ 24 [µg/m³]) and NO_2 (≥ 24 [µg/m³]), were also associated with higher CARDIO rates. Additionally, high $PM_{2.5}$ and CO levels were linked to increased CARDIO in LMA. The seasonal Mann-Kendall test showed no significant trend in CARDIO for LMA, but a statically significant increasing trend of 2.14 [Deaths per 100 000]) per month for PMA. This study shows the importance of mid-term exposure standards and emphasises the need for multifactorial assessments of air quality and meteorological impacts on health, as regional differences in pollutant dynamics and meteorological conditions may significantly impact cardiorespiratory mortality in urban areas.

Keywords Atmospheric pollutants, Meteorological factors, Cardiorespiratory diseases, Environmental pollution, Multivariate statistical analysis, Air quality

According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC_AR6)[1], global climate change is intensifying both the frequency and severity of extreme weather events, such as heat waves, cold spells, storms, and intense precipitation[1]. The IPCC_AR6 report emphasises the important connection between climate change and air pollution emitted from anthropogenic sources and wildfires[1]. A systematic review by Weilnhammer et al.[2] showed that heat waves, cold spells, droughts, wildfires, and floods in Europe can be associated with negative effects on human health, including all-cause mortality, cardiovascular mortality and morbidity, respiratory mortality, and mental health[2]. Nevertheless, some of these associations require further validation, indicating the need for more research, particularly on the role of air pollution under extreme temperatures[2].

Environmental epidemiological studies have shown a notable association between exposure to air pollution and extreme weather events and the prevalence of cardiorespiratory diseases in humans[3–14]. Furthermore, this exposure is associated with an increased risk of premature death related to these diseases[2–14]. The stability of the relationship between weather and mortality varies over time and is influenced by seasonal factors[3,14–20]. These

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studies showed that seasonality in morbidity and mortality varies both geographically and temporally and may be influenced by environmental factors such as weather and air pollution[3,14–20].

Studies show that although cold-related mortality is expected to decrease slightly due to fewer cold spells[17], cold weather remains a significant health risk, particularly in regions with milder winters or specific climatic vulnerabilities[17,22,23]. In European countries, mortality is typically higher in winter than in summer[3,6,15–20]. Winter mortality in western countries of the Northern Hemisphere due to colder temperatures represents a paradox, with warmer climates (e.g., Portugal, Spain, and Italy) experiencing greater excess deaths than colder climates such as Finland and Norway[18,27]. This phenomenon may be related to anthropogenic factors, primarily air pollution, which affects respiratory and cardiovascular health[18,27]. This partly relates also with household conditions, which in general lack thermal comfort and where domestic heating is mainly assured by wood biomass, the cheapest fuel available, with consequent pollutant emissions[28]. Cold stress may increase myocardial oxygen demand, elevating the risk of cardiac complications, particularly in the elderly[29]. However, other environmental factors such as relative humidity, and air pollution concentrations also contribute to cold-related cardiovascular stress[6,8,9,20]. The relationship between seasonal mortality, meteorological factors, and air pollution is complex and multifaceted. Seasonal variations influenced by factors such as temperature, relative humidity, and air pollution, may affect mortality and morbidity[20]. Marti-Soler et al.[22] analysed over 54 million deaths from 19 countries (including 14 European countries among them Portugal) and found a consistent seasonal pattern in overall, cardiovascular (CVD), and non-CVD/non-cancer mortality, with higher death rates in winter across both hemispheres.

Studies have found associations between heat waves and cold spells and increased health risks[2,3,12–14,18–27]. In Europe, urban populations, especially the elderly, face increased mortality risks from exposure to higher temperature[26,29–32]. On the other hand, PM_{10}, $PM_{2.5}$, sulphur dioxide (SO_2), NO_2, CO, and O_3, may significantly contribute to spatial-temporal effects on cardiorespiratory mortality and morbidity rates in urban areas[4–11,31,33–40]. In Cyprus, extreme weather, specifically warm rainy days and cold cloudy days, were linked to increased hospital admissions for cardiovascular and respiratory conditions, particularly among the elderly[8]. Additionally, PM_{10} air pollution was associated with higher morbidity, with a more pronounced effect on cardiovascular diseases[8]. The effects of air pollution on mortality in Portugal from 2010 to 2019 were estimated to result in more than 5 000 annual deaths associated with NO_2 and $PM_{2.5}$, with higher mortality rates observed in urban municipalities along the Atlantic coast[36]. Additionally, more than 140 annual deaths were attributed to O_3 exposure[36]. The spatial-temporal analysis point up the need for quantitative assessments, showing the importance of implementing air pollution control strategies[36].

In this context, the World Health Organization (WHO)[41] sets air quality guidelines focusing on daily and annual standards for PM_{10} (annual average: 15 µg/m³; 24-hour average: 45 µg/m³), $PM_{2.5}$ (annual average: 5 µg/m³; 24-hour average: 15 µg/m³), NO_2 (annual average: 10 µg/m³; 24-hour average: 25 µg/m³), O_3 (concentrations of 100 µg/m³ 8-hour average) and CO (4 mg/m3 24-hour average)[41]. These guidelines prioritize short-term (daily) and long-term (annual) exposure metrics, reflecting the established understanding of their health impacts. However, WHO does not have specific monthly standards for air pollution because of the emphasis on short-term and long-term averages and the challenges of establishing universally applicable values. Also, air pollutant concentration varies widely between regions, influenced by complex factors such as local emissions, meteorological conditions, and geographical features[36–39,45]. Meteorological variables such as air temperature, relative humidity and wind speed have no specific standards but are considered for their influence on human health and pollutant dispersion.

While linear regression analyses are valuable and widely used techniques for investigating associations between environmental factors and mortality, these approaches often assume linearity and may not fully account for the complex, non-linear interactions and interdependencies among multiple environmental variables and health outcomes. In this regard, this study aims to complement these approaches by employing methods designed to capture these multidimensional relationships. To address this limitation, this study introduces an integrative methodology applied to the Lisbon (LMA) and Porto (PMA) metropolitan areas. It investigates complex relationships between monthly atmospheric variables—including air pollutants and meteorological factors—and cardiorespiratory mortality. The methodology combines linear and Poisson regression analysis with advanced statistical techniques such as contingency tables, correspondence analysis, Pearson's chi-squared tests, and seasonal Mann-Kendall tests. This approach enables an examination of complex interdependencies by integrating both categorical and quantitative variations in monthly meteorological variables, pollutant concentrations, and cardiorespiratory mortality rates. By employing this multifaceted framework, the study provides an approach to enhancing the analysis and advancing our understanding of the complex, dynamic, and region-specific interactions between environmental factors and public health outcomes.

In urban areas, daily and annual standards play a critical role in monitoring air pollutants and meteorological factors. However, the use of a monthly approach—referred here as medium-term assessment—to set monthly air quality and meteorological standards for specific urban areas could be important for formulating effective mitigation policies. The term medium-term assessment refers to the evaluation of air quality and meteorological parameters on a monthly basis. The concept of "medium-term assessment" is an original idea developed in this work to bridge the gap between daily and annual assessments. Its application provides a complementary understanding of the temporal dynamics and impact of air pollutants and meteorological variables on public health and could be extended to other research contexts and regions.

The mid-term assessment framework offers important relevance across diverse contexts. In developed regions, it complements daily and annual standards by identifying subtle seasonal or monthly trends, such as heightened vulnerability during winter temperature inversions, even in areas with well-regulated emissions. In developing regions, where pollution levels are highly variable due to factors like biomass burning and unregulated traffic, it provides a practical solution for monitoring and guiding interventions, particularly in settings with limited

infrastructure. Globally, this methodology bridges an important gap in air quality evaluation by addressing medium-term temporal scales, making it adaptable to various geographic and socio-economic contexts and enhancing understanding of the complex interplay between air pollution, meteorology, and public health.

Also, this study demonstrates the importance of systematically categorising quantitative variables and examining the monthly contribution of air pollutants and meteorological variables to the burden of disease. In addition, an in-depth analysis of the dynamics of pollutants and meteorological variables was conducted for LMA and PMA, providing important information into their behaviour within the studied metropolitan areas. This method allows for an understanding of the temporal dynamics of atmospheric variables, particularly in relation to seasonal variations, trends, and patterns. Focusing on large metropolitan areas, specifically Portuguese LMA and PMA, this study aligns with efforts to achieve the Sustainable Development Goals (SDGs) outlined in the United Nations (UN) 2030 Agenda, particularly those related to a healthy environment[42]. In addition to supporting the development of environmental policies, scientifically based mid-term standards can provide tangible benefits in creating healthier and more resilient urban spaces.

Results
Evaluation of health outcome and environmental data
The results show the annual variation of age-standardised cardiorespiratory mortality rates (CARDIO), air pollutants, and meteorological variables in the Lisbon (LMA) and Porto (PMA) metropolitan areas (Fig. 1(**a**)-(**p**)). For 2020, only non-COVID-19 deaths were considered, focusing specifically on cardiorespiratory mortality unrelated to the virus. CARDIO_PMA (Fig. 1(**a**)) exhibited a higher mean mortality rate (202.94 [Deaths per 100 000 population]) compared to CARDIO_LMA (169.70 [Deaths per 100 000 population]). The wider interquartile range and higher maximum values in the PMA, particularly in 2012 and 2016, indicated greater variability in mortality compared to the LMA. The medians (CARDIO_LMA: 155.56 [Deaths per 100 000 population]; CARDIO_PMA: 183.93 [Deaths per 100 000 population]) also reflect this difference. Regarding meteorological variables (Fig. 1(**c**)-(**h**)), Lisbon exhibited higher mean temperatures (16.67 [°C] vs. 15.29 [°C] in Porto), while Porto had higher relative humidity (74.70 [%] vs. 73.77 [%] in Lisbon). Wind speeds were similar (2.68 [m/s] in Porto, 2.55 [m/s] in Lisbon), although Porto recorded higher maximum wind speeds over the decade.

No multicollinearity between meteorological and pollutant variables was observed, as indicated by Spearman correlation matrices and Tolerance Index (TI) values, with all pairs exceeding the threshold of 0.20 (details in **Fig. S2**(**a**)-(**b**) and Supplementary Information).

For PM_{10} (Fig. 1(**i**)-(**j**)), the annual average concentrations in Lisbon and Porto were 20.83 [μg/m^3] and 20.77 [μg/m^3], respectively, both exceeding the 2021 WHO guideline of 15 [μg/m^3]. Porto exhibited a larger annual interquartile range, indicating greater variability in PM_{10} levels. Annual maximum PM_{10} concentrations peaked in 2011, reaching 39.44 [μg/m^3] in Porto and 37.35 [μg/m^3] in Lisbon. Annual minimum concentrations were similar in both regions, with Lisbon showing slightly lower variability. For O_3 (Fig. 1(**k**)-(**l**)), the annual average concentrations were 58.57 [μg/m^3] in Lisbon and 40.96 [μg/m^3] in Porto. Lisbon had a wider interquartile range, reflecting greater variability in O_3 levels. Both regions saw peak O_3 concentrations in 2013, with 83.12 [μg/m^3] in Lisbon and 68.72 [μg/m^3] in Porto. Annual NO_2 concentrations (Fig. 1(**m**)-(**n**)) averaged 19.72 [μg/m^3] in Lisbon and 20.31 [μg/m^3] in Porto, both exceeding the WHO guideline of 10 [μg/m^3]. Porto had a greater annual variability, as indicated by a larger interquartile range (4.37 [μg/m^3]) compared to Lisbon (2.42 [μg/m^3]). Maximum NO_2 levels reached 39.56 [μg/m^3] in Lisbon and 37.70 [μg/m^3] in Porto, with Porto showing slightly higher variability in concentrations.

Annual average $PM_{2.5}$ (Fig. 1(**o**)) concentration was 10.33 [μg/m^3] and a low interquartile range of 0.67 [μg/m^3], indicating stable annual averages. The highest concentration, recorded in 2015, was 20.24 [μg/m^3], while the lowest was 4.79 [μg/m^3] in 2019, just below the WHO guideline of 5 [μg/m^3]. Annual CO concentrations in LMA (Fig. 1(**p**)) averaged 0.26 [mg/m^3], with a consistent trend across years. The highest recorded value was 0.47 [mg/m^3] in 2013, and the lowest was 0.13 [mg/m^3] in 2020. Data for $PM_{2.5}$ and CO were only available for LMA.

Figure 2 presents the monthly values of cardiorespiratory mortality rates (CARDIO), meteorological and air pollutants variables for LMA and PMA. In CARDIO_LMA (Fig. 2(**a**)), January had the highest mean (247.39 [Deaths per 100 000 population]) and median (234.92 [Deaths per 100 000 population]) mortality rates. September recorded the lowest mean (133.23 [Deaths per 100 000 population]). Similarly, in CARDIO_PMA (Fig. 2(**b**)), January showed the highest mean (307.44 [Deaths per 100 000 population]) and median (292.03 [Deaths per 100 000 population]), while September had the lowest mean (155.07 [Deaths per 100 000 population]). For temperature, monthly TEMP_LMA (Fig. 2(**c**)) varied from 10.81 [°C] in January to 22.81 [°C] in August, with an overall average of 16.67 [°C], while the median ranged from 10.88 °C to 22.71 [°C]. In TEMP_PMA (Fig. 2(**d**)), monthly temperatures ranged from 10.14 [°C] in January to 21.78 [°C] in August, with an overall monthly average of 15.29 [°C], and monthly medians from 10.01 [°C] to 19.79 [°C]. Monthly RH_LMA (Fig. 2(**e**)) ranged from 64.20 [%] in August to 84.94 [%] in December, with an average of 73.77 [%], while RH_PMA (Fig. 2(**f**)) ranged from 73.25 [%] in April to 79.34 [%] in January, with an average of 74.70 [%]. Median RH values followed similar seasonal patterns in both regions. For monthly wind speed, WS_LMA (Fig. 2(**g**)) ranged from 2.19 [m/s] in October to 2.83 [m/s] in March, with an average of 2.55 [m/s]. WS_PMA (Fig. 2(**h**)) showed more variability, with wind speeds ranging from 1.94 [m/s] in August to 3.48 [m/s] in June, with an overall average of 2.68 [m/s].

Figure 2 also presents monthly variations in air pollutant concentrations for LMA and PMA. Monthly PM_{10} (Fig. 2(**i**)-(**j**)) shows that Lisbon had similar average concentration (20.83 [μg/m^3]) compared to Porto (20.77 [μg/m^3]), though variations occurred throughout the year. Monthly median PM_{10} values were similar, with 20.16 [μg/m^3] in Lisbon and 20.52 [μg/m^3] in Porto. Porto consistently recorded higher monthly maximum PM_{10} concentrations, peaking at 39.44 [μg/m^3] in October compared to Lisbon's 37.35 [μg/m^3]. Monthly O_3
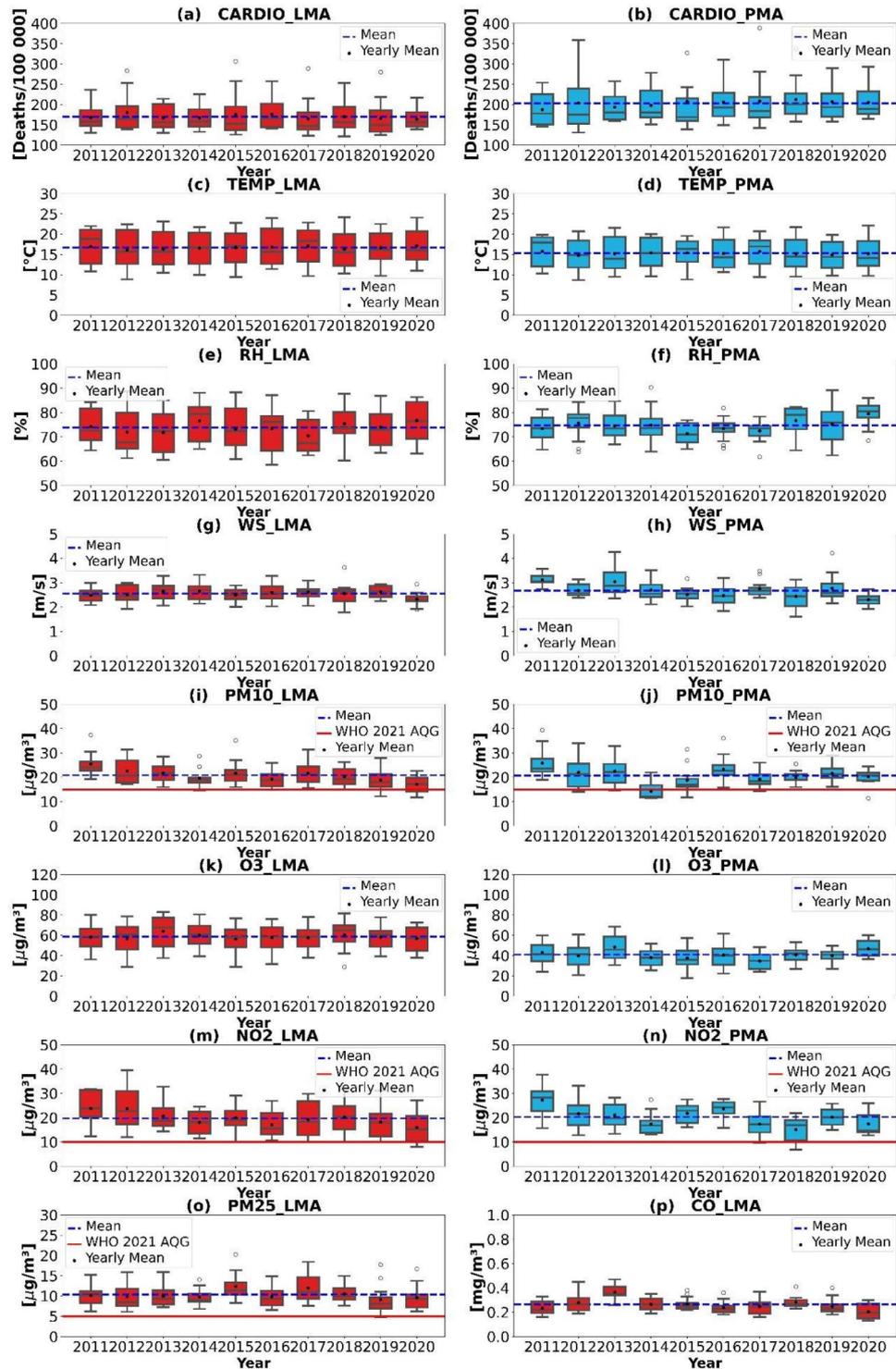
Fig. 1. Yearly boxplots of Lisbon (LMA - red boxplot) and Porto (PMA - blue boxplot), respectively, 2011–2020: (**a**)-(**b**) Cardiorespiratory mortality [Deaths per 100 000 population]; (**c**)-(**d**) Average temperature [°C]; (**e**)-(**f**) Relative humidity [%]; (**g**)-(**h**) Wind Speed [m/s]; (**i**)-(**j**) PM_{10} [μg/m³]; (**k**)-(**l**) O_3 [μg/m³]; (**m**)-(**n**) NO_2 [μg/m³]; (o) $PM_{2.5}$ [μg/m³]; and (**p**) CO [mg/m³]. The red line in (**i**), (**j**), (**m**), (**n**) and (**o**) represent the annual WHO 2021 Air Quality Guidelines (WHO 2021 AQG) for PM_{10} (15 μg/m³), NO_2 (10 μg/m³) and $PM_{2.5}$ (5 μg/m³), respectively.
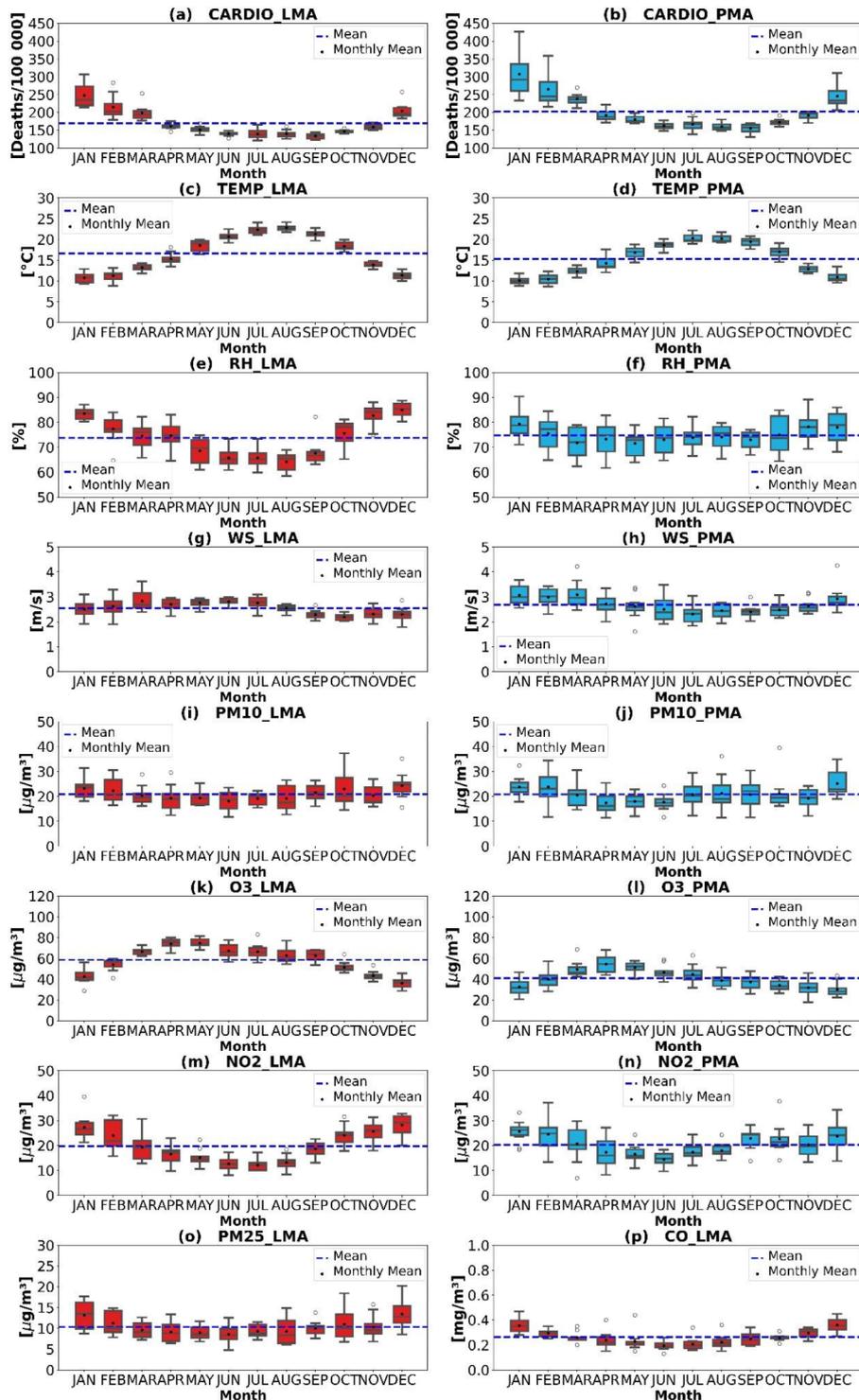
Fig. 2. Monthly boxplots of Lisbon (LMA - red boxplot) and Porto (PMA - blue boxplot) metropolitan area, respectively, 2011–2020: (**a**)-(**b**) Cardiorespiratory mortality [Deaths per 100 000 population]; (**c**)-(**d**) Average temperature [°C]; (**e**)-(**f**) Relative humidity [%]; (**g**)-(**h**) Wind Speed [m/s]; (**i**)-(**j**) PM_{10} [μg/m³]; (**k**)-(**l**) O_3 [μg/m³]; (**m**)-(**n**) NO_2 [μg/m³]; (**o**) $PM_{2.5}$ [μg/m³]; and (**p**) CO [mg/m³].

concentrations (Fig. 2(**k**)-(**l**)) were higher in Lisbon, with an overall average of 58.57 [μg/m³] compared to 40.96 [μg/m³] in Porto. Monthly median O_3 levels followed the same pattern. Maximum O_3 concentrations were also higher in Lisbon, peaking at 80.04 [μg/m³] in April, compared to 68.38 [μg/m³] in Porto. Porto consistently had lower minimum O_3 levels, resulting in a narrower variation range. Monthly NO_2 (Fig. 2(**m**)-(**n**)) showed

similar average concentrations in Porto (20.31 [μg/m³]) compared to Lisbon (19.72 [μg/m³]), although Lisbon had higher peaks. Median NO_2 levels were similar between the regions. Monthly minimum NO_2 concentrations were lower in Lisbon, indicating less variation compared to Porto. For $PM_{2.5}$ at LMA (Fig. 2(o)), the monthly mean concentration was 10.33 [μg/m³], ranging from 4.79 [μg/m³] in June to 20.24 [μg/m³] in December, with moderate variability. Monthly CO levels (Fig. 2(p)) showed consistent patterns in Lisbon, with a mean concentration of 0.26 [mg/m³]. The lowest CO level was 0.13 [mg/m³] in June, while the highest was 0.47 [mg/m³] in December.

Figure 3 shows the monthly temporal dynamics and seasonal Mann-Kendall trends of cardiorespiratory mortality (CARDIO), air pollutants concentrations, and meteorological variables in LMA and PMA from 2011 to 2020. In LMA (Fig. 3(a)), a peak occurred in 2015, reaching 306.61 [Deaths per 100 000 population], primarily in the winter months, with fluctuations in subsequent years. In PMA (Fig. 3(b)), January 2015 saw a peak of 426.48 [Deaths per 100 000 population]. The seasonal Mann-Kendall test detected no statistically significant long-term trend in CARDIO mortality for LMA, but a statistically significant increasing trend was observed for PMA, with an average rate of 2.14 [Deaths per 100 000 population] per month.

Temperature patterns (Fig. 3(c)-(d)) show lower values in the winter months corresponding to high CARDIO rates. These results suggest seasonal susceptibility, likely due to colder weather. In LMA, the coldest months were January and February 2012 (9.39 and 8.87 [°C]), December 2014 (9.96 [°C]), and January 2019 (9.72 [°C]). In PMA, the coldest months followed a similar pattern, with January and February 2012 being the coldest (9.39 [°C] and 8.68 [°C]). Warmer summer temperatures consistently exceeded 20 °C in both regions, aligning with lower mortality rates. The shared seasonal temperature patterns likely contribute to the observed cardiorespiratory mortality trends.

Relative humidity (Fig. 3(e)-(f)) in LMA shows a seasonal pattern, with higher humidity in winter and lower in summer. In contrast, PMA has higher variability but low seasonality. Regarding wind speed (Fig. 3(g)-(h)) pattern, in LMA wind speeds were higher in summer (2.80 to 2.99 [m/s]) than in winter (2.08 to 2.57 [m/s]), indicating a 13% increase in summer, which likely enhances pollution dispersion. In PMA, the opposite pattern occurred, with lower summer winds (2.02 to 2.11 [m/s]) and higher winter winds (2.37 to 4.26 [m/s]), potentially affecting pollution dispersion. Among meteorological variables, only wind speed in PMA (WS_PMA) showed a statistically significant decreasing trend, possibly due to urban development.

Figure 3(i)-(j) shows PM_{10} concentrations in LMA and PMA. In LMA, concentrations varied without seasonal pattern, with higher values in summer (19.26 to 37.35 μg/m³) for 2011, 2012, 2013, and 2016, and in winter (14.70 to 35.16 μg/m³) for 2014–2020. PMA showed similar behaviour, with higher summer levels in 2011, 2012, 2013, and 2015 (19.00 to 39.44 μg/m³) and winter peaks in 2014–2020 (11.53 to 36.08 μg/m³). For both regions, no statistically significant seasonal trend was observed in PM_{10} concentrations. Figure 3(k)-(l) shows O_3 concentrations, with higher levels in spring (March-May) in both regions. However, no statistically significant long-term seasonal trend was observed for O_3 in either region. Figure 3(m)-(n) depicts NO_2 concentrations, showing seasonal variation with winter months, particularly December, having the highest levels (13.77 to 34.28 [μg/m³] in LMA and 31.29 to 32.77 [μg/m³] in PMA). Summer months showed lower NO_2 concentrations. Both LMA and PMA exhibited statistically significant decreasing trends in NO_2 levels, with reductions of 0.64 [μg/m³] per month in LMA and [μg/m³] per month in PMA.

The calendar plot of $PM_{2.5}$ in LMA (Fig. 3(o)) shows higher concentrations in winter, especially in December and January (6.21 to 17.72 [μg/m³]), with peaks in January 2012, 2015, 2017, and 2019. Summer months (July and August) generally had lower concentrations (6.12 to 14.89 [μg/m³]). No statistically significant seasonal trend was detected in $PM_{2.5}$ concentration in LMA. CO concentrations (Fig. 3(p)) presented a statistically significant decreasing seasonal trend with reductions of 0.005 [mg/m³] per month in LMA. The highest CO levels occurred in January (peaking at 0.47 [mg/m³] in 2013) and lower values in summer (0.16 to 0.26 [mg/m³]).

Figure S3(a)-(f) and Fig. S4(a)-(d) shows the seasonal wind patterns and their influence on seasonal atmospheric pollutant dispersion in the LMA and PMA. In winter, southeast-southwest (SE-S-SW) winds dominate in both regions, with LMA recording wind speeds up to 3.29 [m/s], associated with PM_{10} concentrations ranging from 22.96 to 31.43 [μg/m³], O_3 from 28.88 to 59.75 [μg/m³], NO_2 from 23.44 to 39.56 [μg/m³], $PM_{2.5}$ from 9.39 to 17.72 [μg/m³], and CO from 0.27 to 0.47 [mg/m³]. In PMA, similar wind patterns show PM_{10} concentrations from 22.04 to 43.25 [μg/m³] and NO_2 from 22.04 to 39.56 [μg/m³]. In spring, SE winds prevail in both regions, with PM_{10}, O_3, NO_2, and CO concentrations peaking in April. In LMA, O_3 levels range from 65.15 to 81.64 [μg/m³]. Summer in both areas is dominated by east-northeast-southeast (E-NE-SE) winds, with LMA showing pollutant concentrations of PM_{10} (11.78 to 26.54 [μg/m³]), O_3 (54.54 to 83.12 [μg/m³]), and CO (0.13 to 0.36 [mg/m³]), generally contributing to lower concentrations of PM_{10} and NO_2 but elevated O_3 levels due to higher solar radiation and photochemical reactions. In PMA, O_3 concentrations during summer vary from 40.89 to 83.12 [μg/m³]. In autumn, south-southwest (S-SW) winds return in both regions, bringing moderate pollutant levels in LMA, with PM_{10} concentrations ranging from 15.03 to 37.35 [μg/m³], O_3 from 56.22 to 68.84 [μg/m³], and CO from 0.19 to 0.34 [mg/m³]. PMA similarly shows autumn PM_{10} concentrations ranging from 14.29 to 37.35 [μg/m³], with winds maintaining higher speeds which may contribute to pollutant dispersion.

Statistical analysis for environmental risk assessment

A quantile-based categorization (Table S3)—where low (L_) represents values below the first quartile (Q1), medium (M_) indicates values between the first (Q1) and third quartiles (Q3), and high (H_) denotes values above the third quartile (Q3)—was used to assess associations between categorised variables, pollutants-meteorological and CARDIO variables. This approach allows for the evaluation of relationships between categorised variables and facilitates the establishment of monthly standards. These monthly standards, referred to as medium-term assessment, are used to establish pollutants-meteorological-CARDIO benchmarks for each variable based on the quantitative values corresponding to the low, medium and high categories.
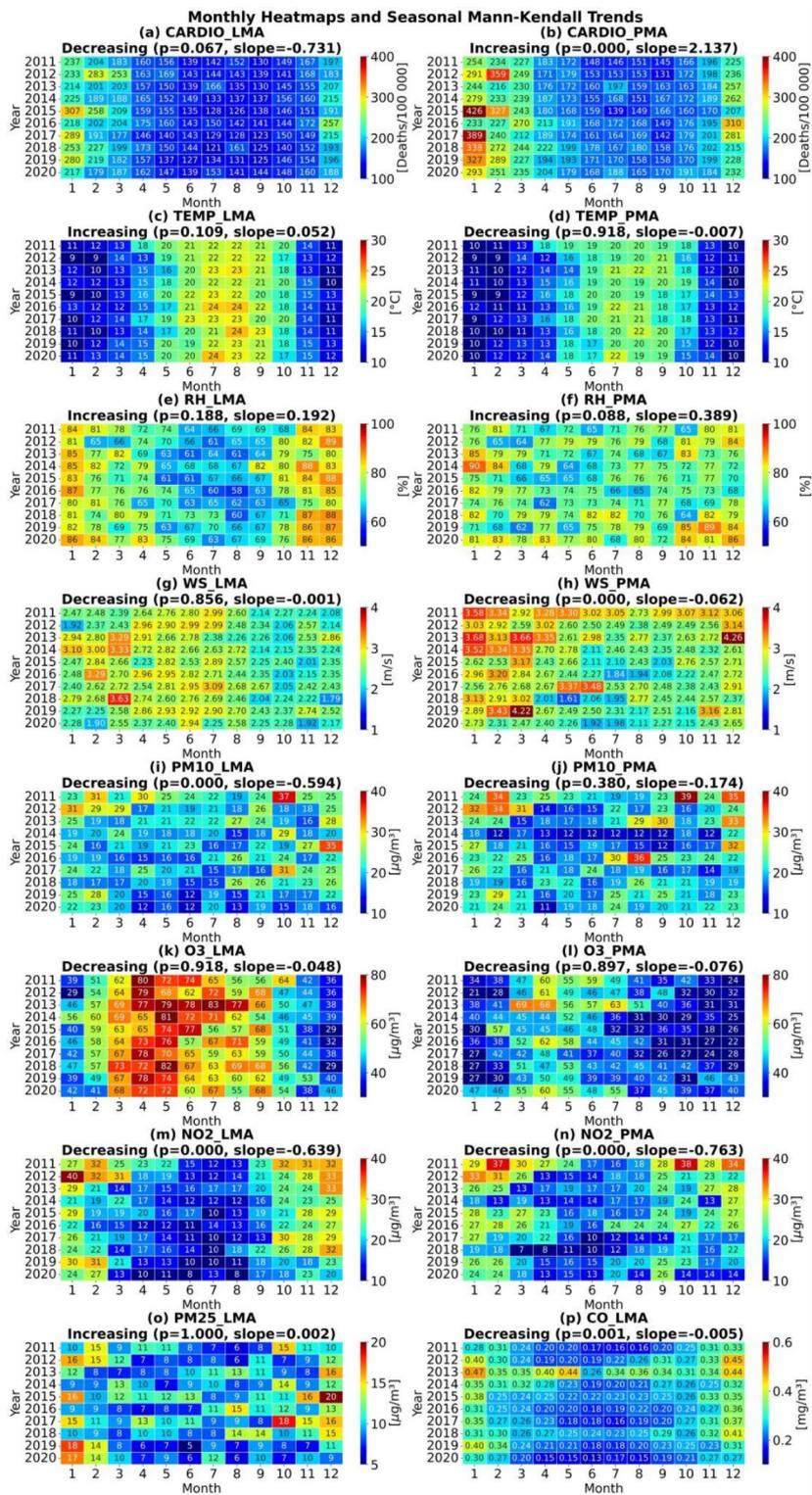
Fig. 3. Monthly calendar plot with seasonal Mann-Kendall test for Lisbon (LMA) and Porto (PMA) metropolitan area, respectively, 2011–2020 of: (**a**)-(**b**) Cardiorespiratory mortality [Deaths per 100 000 population]; (**c**)-(**d**) Average temperature [°C]; (**e**)-(**f**) Relative humidity [%]; (**g**)-(**h**) Wind Speed [m/s]; (**i**)-(**j**) PM_{10} [μg/m³]; (**k**)-(**l**) O_3 [μg/m³]; (m)-(n) NO_2 [μg/m³]; (**o**) $PM_{2.5}$ [μg/m³]; and (**p**) CO [mg/m³].

Figure 4(**a**)-(**n**) presents stacked bar plots of contingency tables showing monthly patterns in categorised levels of air pollutants and meteorological variables (independent variables) alongside age-standardised CARDIO mortality rates (dependent variable) in LMA and PMA. Analysis of the contingency tables for both regions (Fig. 4(**a**)-(**b**)) shows that H_CARDIO (190.76 [Deaths per 100 000 population]) in LMA and (230.15 [Deaths
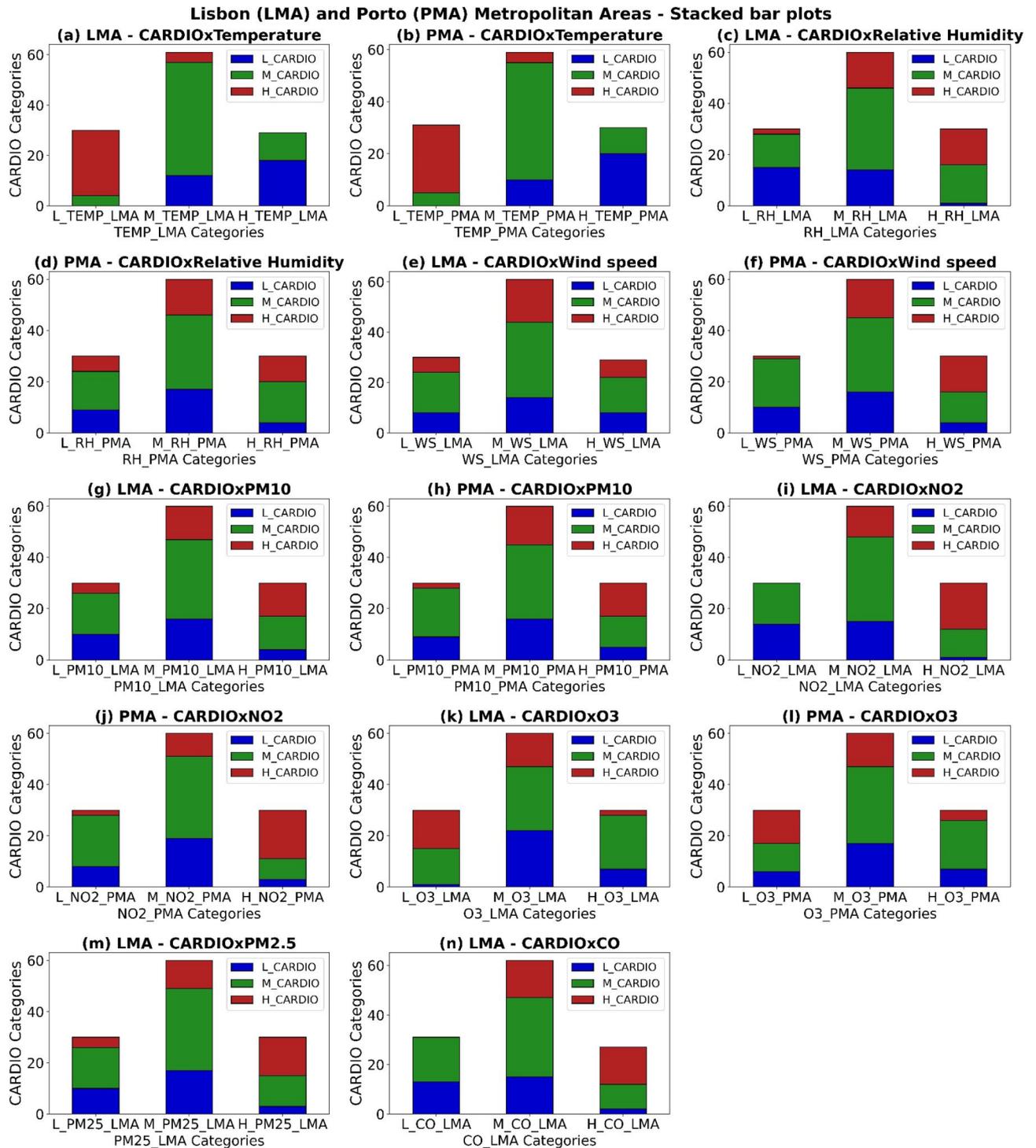
Fig. 4. Stacked bar plots for Lisbon (LMA) and Porto (PMA) metropolitan areas, respectively, 2011–2020 of Cardiorespiratory mortality (CARDIO) quartile categories and quartile categories for: (**a**)-(**b**) Temperature; (**c**)-(**d**) Relative humidity; (**e**)-(**f**) Wind speed; (**g**)-(**h**) PM_{10}; (**i**)-(**j**) NO_2; (**k**)-(**l**) O_3; (**m**) $PM_{2.5}$; and (**n**) CO.

per 100 000 population]) in PMA is associated with L_TEMP (12.78 [°C] in LMA and (11.90 [°C]) in PMA. Pearson's chi-squared test (X^2) (Table 1) supports these findings, showing statistically significant associations between categorised CARDIO mortality and temperature in both LMA and PMA.

In the LMA (Fig. 4(**c**)), there is an association between H_CARDIO_LMA and H_RH_LMA (81.07 [%], and between L_CARDIO and L_RH (66.26 [%]). In contrast, in the PMA (Fig. 4(**d**)), the relationship between CARDIO and RH categories is not significant. The Pearson's chi-squared test (Table 1) confirms a statistically significant association between CARDIO and RH in the LMA. In the PMA, however, the association is not statistically significant. Associations between H_CARDIO and L_WS (2.28 [m/s] in LMA and 2.40 [m/s] in

Pearson's Chi-squared test			
LMA	X²	df	p-value
CARDIOxTEMP	97.07	4	0.000
CARDIOxRH	17.90	4	0.001
CARDIOxWS	62.70	4	0.000
CARDIOxPM10	13.47	4	0.009
CARDIOxPM25	18.17	4	0.001
CARDIOxO3	34.00	4	0.000
CARDIOxNO2	24.83	4	0.000
CARDIOxCO	31.03	4	0.000
PMA			
CARDIOxTEMP	104.03	4	0.000
CARDIOxRH	0.67	4	0.955
CARDIOxWS	33.90	4	0.000
CARDIOxPM10	13.63	4	0.009
CARDIOxO3	13.73	4	0.008
CARDIOxNO2	16.00	4	0.003

Table 1. Pearson's Chi-squared test for Lisbon (LMA) and Porto (PMA) Metropolitan Area.

PMA) and L_CARDIO and H_WS (2.80 [m/s] in LMA and 2.99 [m/s] in PMA) categories were found in both regions as showed in Fig. 4(**e**)-(**f**). Pearson's chi-squared test in Table 1 confirms this, with statistically significant association between the categorised values of WS.

Associations between PM_{10} and CARDIO categories in LMA and PMA are presented in Fig. 4(**g**)-(**h**). Pearson's chi-squared test results indicate a statistically significant association between H_CARDIO and H_PM10 in both regions (24.15 [μg/m³] in LMA and 23.36 [μg/m³] in PMA). Similarly, NO2 (Fig. 4(**i**)-(**j**)) show an association between H_NO2 (24.42 [μg/m³] in LMA and 24.50 [μg/m³]) and H_CARDIO in both LMA and PMA. Pearson's chi-squared test results further confirm statistically significant associations. The contingency table for O_3 in LMA (Fig. 4(**k**)) shows an association between L_O3_LMA (46.98 [μg/m³]) and H_CARDIO_LMA, confirmed by Pearson's chi-squared test (Table 1), indicating a statistically significant relationship. In contrast, PMA (Fig. 4(**l**)) presented a non-significant association between L_O3_PMA (32.13 [μg/m³]) and H_CARDIO_PMA, with Pearson's chi-squared test showing no significant association (Table 1). These patterns may be influenced by the photochemical relationship between O_3 and nitrogen oxides (NO_x), where low O_3 concentration may reflect higher NO_2 levels. O_3 forms in the troposphere when NO_x and volatile organic compounds (VOCs) react in the presence of sunlight. In polluted urban areas, NO_x emissions can deplete ozone near the ground but increase it in downwind regions.

In addition to contingency tables and Pearson's chi-squared test, Correspondence Analysis (CA) was used to further investigate the relationships between categorised levels of air pollutants, meteorological variables, and CARDIO mortality rates. A two-dimensional space was used in this study because Components 1 and 2 explained the largest proportion of the total variance. Figure 5(**a**)-(**b**) presents the CA results for CARDIO and TEMP categories in LMA and PMA, where Components 1 and 2 together explained 80% of the variance. The proximity between L_TEMP and H_CARDIO, as well as H_TEMP and L_CARDIO, in both regions suggests a strong association between these categories. For RH (Fig. 5(**c**)-(**d**)), Components 1 and 2 explained 60% of the variance in LMA and 52% in PMA. The biplot shows an association between H_RH and H_CARDIO, and L_RH and L_CARDIO in LMA, while this association was weaker in PMA. For wind speed (WS) (Fig. 5(**e**)-(**f**)), Components 1 and 2 explained 73% of the variance in LMA and 65% in PMA, with a strong association between L_WS and H_CARDIO, and H_WS and L_CARDIO in both regions.

The PM_{10} biplot in Fig. 5(**g**)-(**h**) shows that Components 1 and 2 explained 60% of the variance in both LMA and PMA, with H_PM10 associated with H_CARDIO in both regions. For NO_2 (Fig. 5(**i**)-(**j**)), the first two components explained over 60% of the variance, with associations between L_NO2 and L_CARDIO, and H_NO2 and H_CARDIO. In the O_3 biplot (Fig. 5(**k**)-(**l**)), Components 1 and 2 explained 60% of the variance in both regions, with an association between L_CARDIO and H_O3 in Component 1, explaining approximately 34%. The $PM_{2.5}$ biplot (Fig. 5(**m**)) explained 60% of the variance in LMA, showing associations between L_PM25_LMA and L_CARDIO_LMA, and H_PM25_LMA and H_CARDIO_LMA. A similar pattern was observed for CO (Fig. 5(**n**)), where Components 1 and 2 explained 65% of the variance, linking L_CO_LMA to L_CARDIO_LMA, and H_CO_LMA to H_CARDIO_LMA. The correspondence analysis between pollutant-meteorological and CARDIO variables aligns with the contingency tables and Pearson's Chi-squared test for LMA and PMA, are statistically significant and unlikely to occur by chance. CA also provides additional information about the strength of the association between categories and the proportion of total variance explained by the first two components.

Linear and Poisson regression analyses (Table 2) were conducted to assess the relationships between cardiorespiratory mortality (CARDIO) and environmental variables in the Lisbon Metropolitan Area (LMA) and Porto Metropolitan Area (PMA), using monthly data from 2011 to 2020. Linear regression identified significant ($p < 0.05$) negative associations between temperature and mortality in both regions (β =−2.927 in
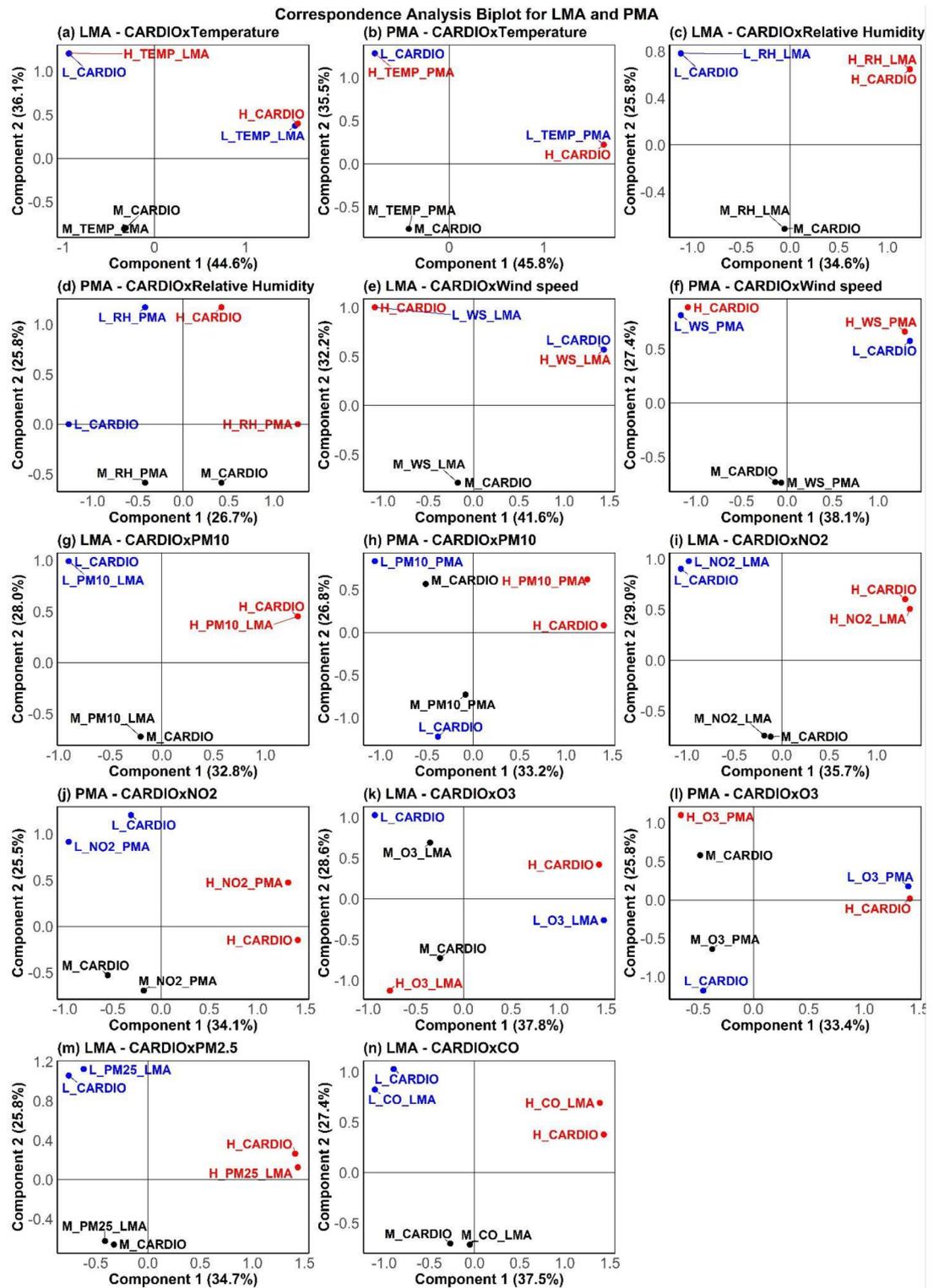
Fig. 5. Correspondence analysis biplot for Lisbon (LMA) and Porto (PMA) metropolitan areas, respectively, 2011–2020 of Cardiorespiratory mortality (CARDIO) quartile categories and quartile categories for: (**a**)-(**b**) Temperature; (**c**)-(**d**) Relative humidity; (**e**)-(**f**) Wind speed; (**g**)-(**h**) PM_{10}; (**i**)-(**j**) NO_2; (**k**)-(**l**) O_3; (**m**) $PM_{2.5}$; and (**n**) CO.

	Linear Regression			Poisson Regression		
LMA	β	R-Squared	p-value	β	Pseudo R-Squared	p-value
CARDIOxTEMP	−2.927	0.666	0.000	−0.043	0.262	0.000
CARDIOxRH	1.000	0.269	0.000	0.014	0.105	0.000
CARDIOxWS	−0.980	0.000	0.823	−0.014	0.000	0.664
CARDIOxPM10	0.876	0.067	0.004	0.012	0.026	0.000
CARDIOxPM25	−0.534	0.202	0.000	−0.008	0.078	0.000
CARDIOxO3	1.296	0.310	0.000	0.018	0.119	0.000
CARDIOxNO2	2.253	0.179	0.000	0.031	0.068	0.000
CARDIOxCO	1.163	0.272	0.000	1.623	0.104	0.000
PMA						
CARDIOxTEMP	−2.737	0.632	0.000	−0.054	0.251	0.000
CARDIOxRH	0.223	0.011	0.265	0.004	0.004	0.035
CARDIOxWS	9.821	0.118	0.000	0.188	0.046	0.000
CARDIOxPM10	0.715	0.089	0.001	0.014	0.035	0.000
CARDIOxO3	−0.282	0.050	0.014	−0.006	0.020	0.000
CARDIOxNO2	0.789	0.123	0.000	0.015	0.048	0.000

Table 2. Comparative results of Linear and Poisson regression analyses for the associations between Cardiorespiratory Mortality (CARDIO) and environmental variables in Lisbon Metropolitan Area (LMA) and Porto Metropolitan Area (PMA).

LMA; β =−2.737 in PMA) (Table 2). Poisson regression quantified a corresponding reduction in relative risk of 4.3% per unit increase in temperature in LMA and 4.8% in PMA. Relative humidity was positively associated with mortality in LMA (β =1.000 in linear regression), with a 1.5% increase in relative risk per unit rise in Poisson regression (Table 2). In PMA, the association was weaker and only borderline significant in Poisson regression (β = 0.004), and non-significant in linear regression (β = 0.223) (Table 2).

Air pollutants emerged as important contributors to cardiorespiratory mortality. PM_{10} was positively associated with mortality in both regions (β = 0.876 in LMA; β = 0.715 in PMA), with Poisson regression showing a 1.2% and 1.0% increase in relative risk per unit rise in LMA and PMA, respectively (Table 2). NO_2 exhibited a stronger association with mortality, with linear regression coefficients of β = 2.253 in LMA and β = 0.789 in PMA (Table 2). Poisson regression indicated a 3.0% and 2.0% increase in relative risk per unit rise in NO_2 in LMA and PMA, respectively.

For $PM_{2.5}$ in LMA, linear regression showed a significant negative association (β=−0.534), while Poisson regression confirmed a small but significant reduction in relative risk per unit increase (β=−0.008) (Table 2) These results suggest that $PM_{2.5}$ impacts may differ from PM_{10}. CO in LMA demonstrated a significant positive association in linear regression (β = 1.163) (Table 2), indicating that higher CO levels are associated with increased mortality. However, Poisson regression highlighted a relative risk increase of 1.6% per unit rise in CO (β = 0.016), suggesting an important impact on cardiorespiratory outcomes.

Discussion

The annual analysis shows that the average CARDIO mortality rate of PMA is 19.67% higher than that of LMA. LMA experiences higher temperatures, with a 9.30% increase compared to PMA, while PMA's minimum temperature is 6.42% lower. LMA also has a wider humidity range and 17.20% higher maximum wind speeds, although PMA has higher average wind speeds with more variability. PM_{10} levels are similar in both regions, consistently exceeding annual 2021 WHO guidelines, but PMA has greater variability (4.28%) and higher maximum concentrations. O_3 levels are 42.88% higher in Lisbon, while NO_2 concentrations are comparable, with greater variability in Porto (2.57%). Available only for LMA, $PM_{2.5}$ levels remained stable but above 2021 WHO guidelines and CO showed a steady trend over the period.

Monthly analysis of these variables revealed regional differences between LMA and PMA. Both areas had the highest CARDIO rates in January and the lowest rates in September, with PMA having consistently higher mortality rates. LMA had higher temperatures throughout the year compared to PMA, with both regions following similar seasonal temperature patterns. Relative humidity peaked in December and was lowest in August, with higher averages in PMA. Wind speeds showed similar patterns, although PMA had higher average speeds and greater monthly variability. In terms of air pollutants, PM_{10} concentrations were similar on average in both regions, but PMA had higher peaks, and more variability influenced by factors such as anthropogenic emissions, wildfires, and Sahara dust events[28,45]. O_3 levels were higher in Lisbon, with higher peaks, while Porto had stable concentrations. The O_3 result is possibly related to its increased photochemical production in spring, summer, and autumn season months (longer daylight hours)[12,36,37,46–48]. While NO_2 and VOCs act as key precursors, nitric oxide (NO) depletes O_3[47,48,49]. Surface O_3 negatively impacts human health, particularly the respiratory system[36,37]. Its concentration varies due to factors such as proximity to O_3 precursor sources, geographic location, and meteorological conditions, making it challenging to explain surface trends and fluctuations[12,36,37,46–48].

Monthly NO_2 levels were generally higher in PMA, although Lisbon had higher peak concentrations. The variability of NO_2 was higher in Porto. In Portugal, NO_2 emissions, predominantly from the energy and transportation sectors, are significantly higher in urban areas than in suburban and rural regions, and also serve as precursors for PM_{10}[38,47]. In contrast, O_3 concentrations are typically higher in rural areas, following the general pattern of O_3 levels being highest in rural locations and lowest in urban areas with heavy traffic[37,46]. $PM_{2.5}$ concentrations in the LMA were stable with occasional peaks, while CO levels were consistent with a narrow range; these pollutants were only for the LMA.

The seasonal Mann-Kendall test indicated a statistically significant increasing trend in cardio-respiratory mortality in PMA, but not in LMA, suggesting a more persistent seasonal rise in PMA. Cold weather was associated with higher mortality in both regions, particularly during winter, consistent with[14]. Relative humidity in LMA followed a clear seasonal pattern, whereas PMA exhibited more variability. Wind speeds were higher in summer for LMA while PMA had stronger winds in winter. PM_{10} concentrations showed no significant seasonal trend in either region, though higher levels were observed in some summers. Ozone peaked in spring without long-term trends, and NO_2 levels showed a significant downward trend in both metropolitan areas. In LMA, winter $PM_{2.5}$ and CO concentrations were higher, but only CO demonstrated a significant decline.

Seasonal wind patterns are an important factor to the dispersion of pollutants in both Lisbon (LMA) and Porto (PMA). In winter, southeast-southwest winds dominate, with south winds reaching the highest speeds. Southwest winds during the winter lead to increased concentrations of PM_{10}, NO_2, $PM_{2.5}$ and CO. By autumn, the southeast-southwest winds return, maintaining high wind speeds and pollutant concentrations. In Portugal, anticyclone circulation further impacts winter pollution, with southeast-southwest winds transporting pollutants from nearby regions and contributing to higher air pollutant concentrations[49,50,56]. In addition, surface roughness and boundary layer dynamics affect local air quality[51,52], demonstrating the complexity of urban wind patterns and their impact on pollution levels. The pollutant dispersion is shaped by a combination of wind patterns, atmospheric variability, and surface properties[49–52,56]. The relationship between atmospheric circulation patterns, such as the North Atlantic Oscillation (NAO), and health outcomes, including hospital admissions for cardiovascular disease, has been studied in Lisbon[56]. Research has shown that while the NAO is not directly associated with hospital admissions, it is significantly associated with increased levels of pollutants such as CO, $PM_{2.5}$, NO_2 and SO_2, which in turn increase the likelihood of hospitalization[56].

Several studies have examined the relationships between meteorological factors, air pollutants, and both short-term[2,4,5,8–14,23–27,29–31] and long-term[22–24,36–40] health outcomes. However, despite previous studies[6,15–27], a deeper understanding of the seasonal impact of these factors on mortality in urban areas is still needed. A study of climate and mortality in Lisbon (1835–2012) found a significant shift in seasonal mortality patterns, with a pronounced winter peak since the 1940s[3]. This shift is attributed to factors such as demographic and socioeconomic changes, improved sanitation, nutrition, and medical advances[3]. This pattern is consistent with the results of this current study, which shows that in both regions, LMA and PMA, CARDIO rates are highest in winter, decrease in spring, and reach their lowest levels in summer, reflecting the influence of seasonal temperature variations.

A large multi-country observational study[26] analysing data from 384 locations in 13 countries and 74.2 million deaths (1985–2012) found that 7.71% of mortality was attributable to non-optimal temperatures, with significant variation between countries. Cold temperatures contributed to 7.29% of mortality, while heat contributed to 0.42% and extreme temperatures accounted for 0.86% of total deaths[26]. In the United States, cold spells are associated with an elevated mortality risk, with projections indicating a decline in cold-related deaths across 209 cities between 1960 and 2050, depending on regional climate differences[25]. In Europe, regions with relatively mild winters, such as Portugal, have shown high vulnerability to cold temperatures[18,27]. In Spain, heat waves were responsible for 16.5% of summer mortality, while cold waves contributed to 12.9% of winter mortality[44]. Similarly, in Korea and Japan (1992–2015), while the risk from heat waves decreased over time, their mortality burden increased in the 2010s due to a rise in frequency[21]. Conversely, both the risk and mortality burden from cold spells have increased over the decades[21]. Although temperature-related mortality is well established in scientific studies, it is critical to examine how other atmospheric factors, including key meteorological variables and air pollutant concentrations, affect human health together. Combining pollutant-meteorological factors provides a comprehensive understanding of how these combined hazards can influence health outcomes[6].

In this regard, the current study used a combined approach of contingency tables, chi-square tests and correspondence analysis (CA) to evaluate the monthly association of air pollutants and meteorological variables with cardiorespiratory mortality rates in the LMA and PMA. The quartile-based categorization of these variables (low, medium, high) provides mid-term exposure standards and reveals associations. The results from CA and chi-square tests complemented linear and Poisson regression findings, presenting consistent associations while also revealing differences in the strength and significance of relationships across regions. These variations reveal the importance of a multifaceted approach to capture the complexity of environmental impacts on mortality.

A strong association between lower temperatures (L_TEMP_LMA $\leq$ 12.78 [°C] and L_TEMP_PMA $\leq$ 11.90 [°C]) and increased cardiorespiratory mortality (H_CARDIO_LMA $\geq$ 190.76 [Deaths per 100 000 population] and H_CARDIO_PMA $\geq$ 230.15 [Deaths per 100 000 population]) is consistently observed in both regions. This association is supported by statistically significant Pearson's chi-squared tests, revealing that these associations do not occur at random. CA and contingency tables revealed that this relationship is most pronounced at extreme low temperatures (lowest quantile), indicating nonlinearity. Linear and Poisson regression confirmed these significant negative associations, with relative risk reductions of 4.3% in LMA and 4.8% in PMA per unit increase in temperature, showing a consistent inverse relationship between temperature and mortality across methods. These findings are reinforced by other studies about temperature and mortality in several regions[3,6,8,14–27,29,30,32,53].

The associations between CARDIO and relative humidity (RH) show regional differences. In LMA, there is a statistically significant relationship between H_CARDIO_LMA and high RH (H_RH_LMA ≥ 81.07 [%]), as well as between L_CARDIO_LMA and low RH (L_RH_LMA ≤ 66.26 [%]). Linear regression further supports this, showing a significant positive association, with Poisson regression confirming an increased relative risk of 1.5% per unit rise in RH. In contrast, the pattern in PMA is less pronounced, and the association between these categories is not statistically significant. Linear regression results and Poisson regression indicate that RH explains very little variability in mortality and lacks robust significance. These findings suggest that the impact of RH on cardiorespiratory mortality is region-specific, with significant effects observed in LMA but not in PMA. This variability may reflect differences in local climate, urban characteristics, or population vulnerability, revealing the need for regionally tailored public health strategies.

Additionally, statistically significant associations were found between H_CARDIO and low wind speed (L_WS) in both regions, with values of 2.28 [m/s] in LMA and 2.40 [m/s] in PMA, and between low CARDIO and high wind speed (H_WS) in both LMA (2.80 [m/s]) and PMA (2.99 [m/s]). However, in LMA, linear regression results and Poisson regression indicate that WS has no statistically significant impact on CARDIO. In PMA, linear regression reveals a significant positive association, with Poisson regression confirming a relative risk increase of 0.2% per unit rise in WS. These findings highlight a notable regional difference: while WS appears to play a trivial role in explaining CARDIO variability in LMA, it significantly associates with mortality in PMA. The contrasting results shows the importance of considering region-specific dynamics when interpreting the effects of WS on cardiorespiratory outcomes.

Importantly, the association of L_WS with high pollutant concentrations may explain some of the regional differences observed. Specifically, a significant association was observed between high monthly PM_{10} levels (H_PM10 ≥ 24.15 [μg/m³] in LMA and ≥ 23.36 [μg/m³] in PMA) and H_CARDIO mortality in both regions. Similarly, high monthly NO_2 levels (H_NO2 ≥ 24.42 [μg/m³] in LMA and ≥ 24.50 [μg/m³] in PMA) were significantly associated with high CARDIO mortality. In LMA, low $PM_{2.5}$ (≤ 8.07 [μg/m³]) and low CO (≤ 0.20 [mg/m³]) were linked to low CARDIO, while high $PM_{2.5}$ (≥ 11.77 [μg/m³]) and high CO (≥ 0.31 [μg/m³]) were associated with high CARDIO. Nevertheless, for $PM_{2.5}$, linear regression revealed a significant negative association, suggesting that $PM_{2.5}$ concentrations do not follow a straightforward positive trend with mortality. Poisson regression showing a significant reduction in relative risk per unit increase in $PM_{2.5}$. These results suggest that the effects of monthly $PM_{2.5}$ on monthly mortality may involve nonlinear dynamics or complex interactions with other variables. In contrast, CO exhibited a positive association with mortality. Linear regression demonstrated a significant positive relationship with mortality. Poisson regression quantified this relationship, showing a 1.6% increase in relative risk per unit rise in CO. While CO consistently emerges as a significant predictor of increased mortality, $PM_{2.5}$'s relationship appears more complex.

Seasonal southwest winds during winter appear to contribute to increased concentrations of PM_{10}, NO_2, $PM_{2.5}$, and CO, further compounding health risks in urban areas.

The strongest associations for PM_{10} and NO_2 with mortality were observed at high pollutant levels (H_PM10 and H_NO2), emphasizing a disproportionate increase in risk at extreme concentrations. These findings align with Poisson regression results, where PM_{10} showed a 1.0% increase in relative risk per unit rise in both regions, and NO_2 exhibited a stronger effect, with a 3% increase in LMA and 2.0% in PMA. Linear regression confirmed positive associations for monthly PM_{10} and NO_2, though these models assume constant effect sizes and may underestimate risks at extreme exposure levels. These associations suggest that reduced wind speed may exacerbate pollutant accumulation, increasing mortality, whereas higher wind speeds likely aid pollutant dispersion, reducing mortality risks.

Important to note that the methodology of this study facilitated the exploration of threshold-based relationships that extend beyond traditional linear regression. Correspondence analysis identified critical categorical thresholds, such as the association between low temperature and high mortality, which are not readily apparent in continuous data models. While regression models quantify these trends, they assume a linear or log-linear relationship and may miss complex patterns inherent in categorical data.

The association between O_3 and CARDIO categories displayed more complexity and regional variation. In LMA, low O_3 concentrations (≤ 46.98 [μg/m³]) were linked to high CARDIO, but this relationship was not statistically significant in PMA. This variation is likely due to the photochemical interactions between O_3 and nitrogen oxides (NO_x), where high NO_x emissions reduce O_3 near the ground in urban areas but may increase O_3 levels in downwind regions[46–52]. Importantly, while the analysis showed that low CARDIO mortality was linked to high O_3 concentrations, this only explained about 34.0% of the variance in LMA, suggesting that this relationship may require further investigation due to the low proportion of variance explained.

These associations are in accordance with several studies regarding the impact of air pollutant concentration on human health[4–13,31,33–40,53]. Statistically significant associations between PM_{10}, SO_2, NO_2 and O_3 levels and hospital admissions and mortality for respiratory and circulatory diseases in Lisbon, with air temperature and humidity contributing to increased admission rates[31,34,36–39,53]. A positive association between mean temperature and daily mortality in Lisbon and Porto[30] while a positive correlation between air pollutants (CO, NO, NO_2, SO_2, PM_{10}, and $PM_{2.5}$) and hospital admissions in Lisbon[31,53], linking these pollutants to cardiovascular and respiratory diseases in different age groups.

The quartile-based categorization of pollutant, meteorological, and CARDIO variables, followed by the application of contingency tables, correspondence analysis, chi-squared tests, linear regression, and Poisson regression provides important information about the combined effects of multiple variables on human health outcomes. This methodology, applied to LMA and PMA, showed that certain atmospheric conditions, including low temperature (L_TEMP), low wind speed (L_WS), and high levels of PM_{10}, NO_2, $PM_{2.5}$, and CO, were associated with increased cardiorespiratory mortality. The statistically significant associations observed in both Portuguese metropolitan areas (LMA and PMA) are consistent with findings from studies using different

methodologies, climate and regions[2–44,53]. In particular, the study shows the importance of evaluating not only individual atmospheric variables but also their combined effects on health outcomes. The mortality risk from extreme temperatures may be exacerbated by concurrent exposure to other hazards, emphasising compounding effects of multiple environmental factors occurring simultaneously in the same region, which place additional stress on the cardiorespiratory system.

Therefore, the quartile-based categorization of air pollutants and meteorological variables contributes to understanding their impact on health, particularly in urban environments, by capturing monthly variations and associations. These mid-term exposure standards offer a context-specific assessment important for evaluating health risks in cities. Derived from the interquartile range, these standards complement existing daily and annual guidelines set by the WHO or national/regional environmental agencies, while also providing a flexible framework for assessing public health risks associated with air pollution and weather conditions.

Furthermore, this methodology, applied in the LMA and PMA, is adaptable for other urban centres, enabling the identification of pollutants and meteorological factors linked to health problems. The strength of this approach lies in its ability to provide understanding of the complex relationships between air pollutants, meteorological variables, and cardiorespiratory mortality in urban settings. Its application contributes to environmental risk assessment by offering information about potential risk factors, thereby improving the knowledge of how atmospheric conditions affect public health.

Regarding LMA and PMA, given the observed patterns and associations presented here, it is evident that monitoring of $PM_{2.5}$ and CO concentrations in urban background stations would be beneficial for the PMA. The regional differences in meteorological patterns and pollutant concentrations between Lisbon and Porto underscore the need to specifically monitor $PM_{2.5}$ and CO in Porto to better understand the dynamics and health risks in the PMA. Establishing background monitoring stations in Porto would provide important data to identify local patterns, enabling more targeted interventions and public health strategies.

Conclusion

This study analysed monthly cardiorespiratory mortality, air pollutants, and meteorological variables in the Lisbon (LMA) and Porto (PMA) metropolitan areas, revealing regional differences. PMA exhibited a higher average cardiorespiratory mortality rate (202.94 [Deaths per 100 000 population]) compared to LMA (169.70 [Deaths per 100 000 population]). Differences in climate and air pollution levels were associated with these disparities, with LMA experiencing higher temperatures, broader humidity ranges, and stronger winds. Lower temperatures (≤ 13 [°C]) were consistently linked to increased mortality, as were elevated levels of PM_{10} (≥ 24 [μg/m³]) and NO_2 (≥ 24 [μg/m³]) in both regions, revealing the vulnerability of Portuguese largest urban areas to adverse environmental conditions. Multivariate statistical techniques, including contingency tables, correspondence analysis, and Pearson's chi-squared tests, confirmed significant associations between low temperature, low wind speeds, high pollutant concentrations, and increased mortality. These methods identified significant non-linear relationships, demonstrating how threshold effects—such as extreme low temperatures and elevated pollutant levels—can disproportionately amplify mortality risks. The seasonal Mann-Kendall test indicated no significant trend in LMA, but an increasing trend of 2.14 [Deaths per 100 000 population] per month in PMA. Variability in air pollutant levels, particularly PM_{10}, NO_2, and O_3, further highlighted regional disparities, with PMA experiencing more pronounced peaks in pollutant levels, while LMA had higher O_3 concentrations. The findings emphasise the combined effects of monthly temperature, pollutants, and meteorological variables on health, underscoring the importance of multifactorial approaches to environmental health assessment. Associations between monthly low temperatures, low wind speeds, and elevated levels of PM_{10}, NO_2, $PM_{2.5}$, and CO were strongly linked to higher cardiorespiratory mortality, with particularly pronounced effects in PMA for wind speed, PM_{10}, and NO_2. This suggests that atmospheric dynamics, such as pollutant dispersion and accumulation, differ between regions and exacerbate health risks. The study also reveals the need for improved $PM_{2.5}$ and CO monitoring in PMA to better understand their health impacts. In conclusion, this study demonstrates the importance of evaluating both individual and combined atmospheric variables in public health. The quartile-based approach offered a dynamic framework for assessing medium-term exposure risks, offering context-specific benchmarks that complement existing daily and annual guidelines. This approach can guide public health policy, particularly in urban environments, by addressing the complex and compounding effects of multiple environmental stressors. The results illustrate how variations in climate and air quality dynamics between LMA and PMA influence cardiorespiratory mortality and public health outcomes. Focusing on large metropolitan areas, specifically Portuguese LMA and PMA, this study contributes to environmental risk assessment analysis by providing important information on the complex relationships between environmental factors (pollutant-meteorological variables) and public health (CARDIO) in urban environments. The findings also align with the United Nations' 2030 Agenda for Sustainable Development, particularly the goals related to health, environmental protection, and sustainable urbanization[42]. In addition to supporting the development of environmental policies, scientifically based mid-term standards can provide tangible benefits in creating healthier and more resilient urban spaces.

Limitations

While the findings of this research are significant, it is essential to acknowledge and address its inherent limitations. First, although the study identifies significant correlations, it does not establish direct causality. Some potential confounding factors—such as socioeconomic conditions, individual health behaviors, and access to healthcare—were not included in the analysis. These variables are known to significantly influence the relationship between environmental factors and mortality[20,58,59]. Studies have shown that individuals with lower Socioeconomic Status (SES) often reside in areas with higher environmental risks, such as increased pollution or

substandard housing, which can lead to health issues, including respiratory and cardiovascular diseases, thereby elevating mortality rates[12,13,18,20,58–60]. Poor housing conditions, characterized by exposure to lead, mold, and indoor pollutants, are more prevalent among low-income populations[12,13,18,20,58–60]. We were unable to account for indoor temperature, relative humidity and air pollutants. These environmental hazards contribute to adverse health outcomes, such as chronic illnesses, increasing mortality risk[18]. Furthermore, health behaviors, including diet, physical activity, and substance use, are shaped by socioeconomic factors, underscoring the critical role of these variables in mortality outcomes[20].

The use of monthly averages, while seems effective for assessing medium-term trends, may smooth the impact of short-term extreme events, such as heat waves, which can temporarily increase mortality. However, the overall trends observed remain valid, as monthly data still capture fluctuations in mortality and pollution levels across broader timeframes. Future research could supplement this analysis with daily data to provide valuable information of such extreme events.

Additionally, factors like seasonal flu and viral outbreaks, which can influence cardiorespiratory mortality—particularly in sensitive groups such as the elderly and individuals with comorbidities—were not explicitly accounted for in this study. Also, assuming that elderly have reduced outdoor activities, indoor exposures might be a larger contributor to personal exposure than in other populations. Future studies should include these variables to refine the analysis further. It would also be important to investigate the impact of medium-term assessments of air pollutants and meteorological variables on hospital admissions, which could offer complementary knowledge into the public health effects of environmental exposures. Another consideration is the impact of COVID-19 lockdowns on pollutant concentrations and their potential influence on mortality patterns. With the emergence of the COVID-19 pandemic, governments imposed severe restrictions on socio-economic activities, putting most of the world population into a general lockdown in March 2020. The lockdown in Portugal, March-May 2020, reduced air pollutant levels, with a mean reduction of 41% for NO_2 and 18% for PM_{10}[62]. These reductions were more pronounced in traffic-related sites, where NO_2 levels decreased by over 60% in some monitoring stations, and in urban background sites, compared to rural areas[61]. While these reductions likely influenced the pollutant levels analyzed in this study, the year 2020 was retained in the dataset to ensure a comprehensive analysis across the entire study period. Importantly, despite reductions in absolute concentrations, the monthly behavioral patterns of the variables remained consistent. The long-term trends identified before this period remain robust and relevant. Another limitation is the presence of missing data due to periods when the monitoring station was not operational, which may introduce some uncertainty. Despite these limitations, the study's findings provide a strong foundation for understanding the effects of air pollutants and meteorological factors on public health.

Methods

This study examines Portugal's two largest metropolitan areas, the Lisbon Metropolitan Area (LMA) and the Porto Metropolitan Area (PMA). Located in southwestern Europe on the Iberian Peninsula, Portugal borders the Atlantic Ocean to the west and south (**Fig. S1**). The country's climate varies regionally, with the south having a hot-summer Mediterranean climate (*Csa*) and the north a mild-summer Mediterranean climate (*Csb*).

The LMA, centred around Lisbon, is the largest urban area in Portugal, comprising 18 municipalities with a population of 2 823 329 inhabitants[55], and covering an area of 3 015.24 km². LMA has a Mediterranean climate with mild, wet winters and warm to hot, dry summers. Conversely, The PMA, centred around Porto, is the second largest metropolitan area, including 17 municipalities and a population of 1 743 272[57] and spans an area of 2 040.31 km². PMA features a Mediterranean climate with mild, wet winters and warm, dry summers.

Environmental and health outcome data

Figure S1 shows the geographic distribution of air quality stations, indicated by green circles, and meteorological stations, purple circles, used in this study. The characteristics of the stations are described in the **Supporting Information SI**. Air pollution data for this study were obtained from the Portuguese Environment Agency's QualAR online air quality database (APA; https://qualar.apambiente.pt). The focus was the urban background stations within the metropolitan areas to represent the general air quality conditions. These stations are typically located away from major local pollution sources such as industrial facilities or traffic intersections and provide a more representative picture of the overall air quality in the region. It is also expected that the urban background stations will provide a more comprehensive view of the long-term air quality experienced by the population at large, which is critical for epidemiological assessments. Hourly near-surface concentration data for five air pollutants (PM10 [µg/m³], PM2.5 [µg/m³], CO [mg/m³], O3 [µg/m³], and NO2 [µg/m³]) were collected from 2011 to 2020. Data were collected from 15 QualAR stations located in the LMA and 5 QualAR stations located in the PMA (Figure S1). In the LMA, PM10, PM2.5, CO, O3, and NO2 concentrations were available from the Qualar online database for the entire study period. For the PMA, only PM10, O3 and NO2 data were available.

The meteorological data were provided by the Portuguese Institute for Sea and Atmosphere (IPMA; www.ipma.pt/). Specifically, hourly data were extracted from six meteorological stations in the LMA and four in the PMA, all part of the IPMA network. Meteorological data includes near surface air temperature (TEMP) [°C] at 1.5 m, relative humidity (RH) [%] at 1.5 m, wind speed (WS) [m/s] and direction (WD) [°] at 10 m. The goal was to capture the full range of temporal variations in these critical meteorological parameters.

The meteorological parameters and pollutant concentrations were calculated by averaging the measurements from all sites in each metropolitan area on a daily, monthly, and annual basis. These calculations were determined based on valid data for days with more than 75% (18 h) of data were available, ensuring a robust dataset for subsequent analysis and interpretation. The 12 months are categorised as follows: Spring (March, April, and May), Summer (June, July, and August), Autumn (September, October, and November), and Winter (December, January, and February). The wind direction categories are as follows: 337.5° to 22.5° (North-N), 22.5° to 67.5°

(Northeast-NE), 67.5° to 112.5° (East-E), 112.5° to 157.5° (Southeast-SE), 157.5° to 202.5° (South-S), 202.5° to 247.5° (Southwest-SW), 247.5° to 292.5° (West-W), and 292.5° to 337.5° (Northwest-NW).

Monthly mortality data for 2011–2020 for the Lisbon Metropolitan Area (LMA) and Porto Metropolitan Area (PMA) were obtained from the National Statistics Institute (INE; https://www.ine.pt/).To account for potential confounders in mortality rates related demographic factors, population growth and proportion of individuals with differences in age structure were adjusted using Age-Standardised Mortality Rates (ASMR). The ASMR is a weighted average of age-specific mortality rates per 100 000 population that adjusts for differences in the age distribution of the population, allowing comparisons between regions with different demographic structures. Mortality rates were calculated for each age group (0–14, 15–24, 25–64 and 65+) and sex using the INE annual population estimates for LMA and PMA to account for large seasonal fluctuations in mortality. The rates were expressed per 100 000 population for each group. The age-specific mortality rates were then multiplied by the proportion of each age group in a standard population, based on WHO guidelines[43].

The variable CARDIO [Deaths per 100 000 population] represents the monthly sum of deaths from specific causes related to diseases of the circulatory system (ICD-11: 1B40 - BE2Z), diseases of the respiratory system (ICD-11: CA00 - CB40), pneumonia (ICD-11: CA40 - CA40. Z), Chronic Obstructive Pulmonary Disease (ICD-11: CA20.Z - CA22.Z) and Asthma (ICD-11: CA23 - CA23.3), based on the International Classification of Diseases, 11th Revision (ICD-11; https://icd.who.int/browse11/l-m/en). CARDIO mortality data from the INE were available only on a monthly basis. This methodology ensures that mortality rates are adjusted for age structure differences. By aggregating deaths by cause and age, the study estimates regional age-cause-specific mortality rates on different demographic groups in both metropolitan areas. This standardised approach enhances the accuracy and comparability of cardiorespiratory mortality across LMA and PMA, while accounting for age distribution and population growth. Confirmed deaths corresponding to code ICD-11 RA01 (COVID-19, coronavirus infection disease) were not considered. It is important to acknowledge that the pandemic places additional stress on healthcare systems, which may contribute to an increased mortality burden. As a result, evaluating health indicators during a pandemic is particularly challenging, even for conditions unrelated to the virus.

For trend analysis, monthly data were subjected to seasonal Mann-Kendall tests to assess the statistical significance of trends in each variable's time series. This test accounts for intra-annual periodic fluctuations, ensuring accurate results by considering the cyclical behaviour of these variables.

Confounding related to seasonality was controlled by modelling each variable with seasonality with a periodic function[54] to account for seasonal variation in the time series data:

$$y = \beta_{\circ} + \beta_1 sin\left(\left(\frac{2\pi}{P}\right)t\right) + \beta_2 cos\left(\left(\frac{2\pi}{P}\right)t\right) + \in_t$$

where $\beta_{\circ}$ is the intercept, β_1 and β_2 are the coefficients of the trigonometric functions, P is the period, $\in_t$ is the error term, and t is time[54]. This approach ensures that seasonal effects inherent in the data are considered and allows the isolation of other important patterns or relationships (such as trends, interventions, or associations) before applying contingency tables, Pearson's chi-squared test, or correspondence analysis (CA). Incorporating sine and cosine terms with appropriate periodicity captures and removes the seasonal component, allowing to focus on underlying trends and effects[54].

Association statistical analysis

In environmental epidemiology, accurately categorising air pollutants, meteorological variables, and cardio-respiratory mortality is essential for understanding their relationships. A Spearman correlation analysis was conducted to evaluate the relationship between paired meteorological and air pollutant variables, with statistical significance assessed using p-values. A correlation was considered significant when the p-value was less than 0.05. To further assess multicollinearity, the Tolerance Index (TI) was calculated for each variable pair. TI values were interpreted using standard cut-off points: TI > 0.2 indicates no concern for multicollinearity, TI between 0.1 and 0.2 suggests moderate multicollinearity, and TI < 0.1 signals strong multicollinearity. After assessing multicollinearity, a combined approach using contingency table analysis, correspondence analysis, and chi-squared tests was used to categorise all variables (PM_{10}, $PM_{2.5}$, CO, O_3, NO_2, wind speed, temperature, relative humidity, and CARDIO). This method emphasises the importance of categorising variables and provides an alternative to correlation analysis for validating associations.

To operationalize the methodology, the variables were categorised based on quartiles (Q) - a statistical partitioning method that divides data into four equal parts. These quartiles effectively divide the variables into three ranges: Low (0–25%, values below the first quartile, Q1), Medium (25–75%, values within the interquartile range between the third and first quartiles, Q3 and Q1), and High (75–100%, values above the third quartile, Q3). This categorization serves the dual purpose of facilitating the analysis of continuous variables and providing a clearer lens for examining patterns and trends. The quartile-based categorization process has an additional benefit - it allows the creation of monthly standards, named as medium-term exposure, for each variable according to quantitative values related to the categorised low, medium, and high. This strategic approach enhances the understandability of the results and introduces a refined perspective on how environmental factors affect public health monthly, called mid-term exposure assessment.

After the quartile-based categorizations, contingency tables were created cross-tabulating categorised levels monthly of air pollutants and meteorological variables with CARDIO. Then, the chi-squared test[56] was applied in the categorised data to assess the independence between pollutant-meteorological variables (considered as independent variables) and CARDIO (considered the dependent variable). The null hypothesis (H_0) states that there is no significant relationship between these variables, thus assuming independence, while the alternative

hypothesis (H_1) states that there is a significant relationship, which means that the pair of variables exhibit dependence. This statistical method goes beyond traditional linear correlation analysis and enriches our understanding of the complex relationships between atmospheric conditions and health outcomes.

The associated *p-value* obtained from the test is instrumental in determining the statistical significance of the observed association. If the *p-value* ≤ 0.05, it indicates that the null hypothesis is very unlikely, leading to its rejection. In this case there is statistical evidence that supports the observed association. Conversely, if the *p-value* > 0.05, it indicates that the null hypothesis is very likely, and it is either reported as "fails to reject", and there is no statistical evidence that supports an association between the two variables.

Finally, correspondence analysis (CA)[57], a multivariate statistical technique, was used to explore associations. This technique facilitates the visualisation of relationships within high-dimensional categorical data and provides insight into their structure. CA is a method that visually represents the factor scores (coordinates) for both the row and column points of a contingency table in a low-dimensional space. This method ensures that the positions of the row and column points are consistent with their associations in the contingency table. The components indicate the percentage of variance explained. Component 1 explains the most variance, followed by Component 2, and so on. Effective dimension reduction occurs when the initial dimensions capture a large portion of the variability.

This methodology was applied to air pollutants, meteorological variables, and CARDIO data. These quartile divisions served as monthly standards, allowing for an assessment of mid-term exposure to hazard pollutant concentration and meteorological factors during the study period. Through the creation of categorical variables based on quartiles, the application of the chi-squared test, and the use of correspondence analysis, the study conducts a robust exploration of the complex relationships between atmospheric conditions and health outcomes in the Lisbon and Porto metropolitan areas.

This methodology was compared with a regression-based approach that employed linear and Poisson regressions to evaluate relationships between cardiorespiratory mortality rates and environmental variables for Lisbon (LMA) and Porto (PMA). In linear regression, the model

$$Y = \alpha + \beta X + \epsilon$$

was employed, where Y represented the mortality rate (CARDIO), the continuous variable, X was the independent variable (e.g., temperature or pollutants), α was the intercept, β was the slope, and ϵ denoted residual errors. The estimate of β represents the expected absolute change in for each unit increase in . Results were interpreted using *p-value* ($p < 0.05$ indicated significant relationships).

In contrast, Poisson regression accounted for the count-based nature of mortality rates, with the model defined as.

$$log\,(E(Y)) = \alpha + \beta X,$$

where positive or negative coefficients (β) indicated whether an increase in X heightened or reduced mortality, respectively. Y is the discrete count variable with Poisson distribution and β indicates the effect of the independent variable on the log mortality rate and

$$100 \times (e^{\beta} - 1)$$

express the result as the relative change in the expected outcome.

Linear regression modeled direct relationships between continuous variables, while Poisson regression accounted for count-based mortality data and non-linear relationships. Importantly, in linear regression, the change in Y is absolute (linear) and directly derived from the coefficient β while in Poisson regression, the change in Y is relative (percentage-based and non-linear) and calculated by exponentiating the coefficient β. Coefficients, R-squared values, and p-values from linear regression provided information into the magnitude and direction of associations, while Poisson regression coefficients quantified the effect of variables on mortality counts. Model fit was assessed using R^2 for linear regression and pseudo R^2 for Poisson regression. Model assumptions (linearity, independence, and error distribution for linear regression; absence of overdispersion for Poisson regression) were tested to ensure validity.

This approach not only contributes to the advancement of environmental risk assessment, but also provides important information on the multifaceted dynamics between environmental factors and public health in urban areas.

Data availability

Air pollution data: Data on concentrations of PM10, PM2.5, CO, O3, and NO2 used in this study were obtained from the public air quality database QualAr, provided by the Portuguese Environmental Agency (APA). These data are freely available at https://qualar.apambiente.pt/downloads. Users must manually select the options:

- **Station type**: Background
- **Area type**: Urban or Suburban
- **Year**: Select the years of interest (2011-2020)

Once the criteria are selected, users must download the data for each station individually by clicking on the station name. The names and characteristics of the QualAr air quality stations used in this work are listed in Table S1 of the Supplementary Information.

Mortality data: The data on cardiorespiratory diseases (CSD, RSD, PNEU, and COPD) for Portugal were provided by the National Institute of Statistics (**INE**). These data are publicly available but require a formal re-

quest via email to INE. The data can be requested through their website at https://www.ine.pt/ or by contacting them directly via email. The data are available on a municipal scale, as described in Table S2 of the Supplementary Information. The information can be consulted on the INE Portal - Database - Theme: Health - Subtheme: Mortality by causes of death - Geographic Level: Municipality - Select the indicator (Óbitos (N.º) por Local de residência (NUTS - 2013), Sexo, Grupo etário e Causa de morte (Lista sucinta europeia). Once you have selected the indicator, you can modify the table to suit your needs by disaggregating the dimensions that make it up (reference period, geographic location, variables, etc.). To do this, click on the "Change selection conditions" option, which is located above the data table, and then choose the dimension or dimensions that you want to disaggregate. Finally, click on "View table" to obtain the table with the disaggregated data. Monthly data of specific cause of death should be requested by contacting them directly by email (ine@ine.pt).

Meteorological data: Meteorological data on temperature, relative humidity, wind speed, and wind direction were obtained from the Portuguese Institute of Sea and Atmosphere (**IPMA**). These data are also publicly available but require a formal request via email to IPMA. For more information, visit https://www.ipma.pt/pt/index.html. The characteristics of the IPMA meteorological stations used in this work are listed in **Table S2** of the **Supplementary Information**. Finally, the monthly data used in this research are available within the Supplementary Information file at **Table S4**.

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Author contributions

ESFD: Formal analysis, Investigation, Supervision, Writing – original draft, Writing – review & editing, Methodology, Software, Validation, Visualization, Data curation, Funding acquisition. PSL: Writing – review & editing, Methodology, Software, Supervision, Data curation. LHR: Writing – review & editing, Methodology, Supervision, Funding acquisition. MJC: Writing – review & editing, Methodology, Supervision, Funding acquisition.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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