# Fire-Pollutant-Atmosphere Components and Its Impact on Mortality in Portugal During Wildfire Seasons

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**Key Points:**

- The combination of variables related to fire-pollutant-meteorology components through PCA efficiently helps to understand how these combined hazards affect cardio-respiratory mortality rates.
- Months with higher temperatures, lower relative humidity, larger wildfires, higher $PM_{10}$, $PM_{2.5}$, $NO_2$ and $O_3$ concentrations near the surface, presented higher cardiorespiratory mortality rates.
- Months inside the wildfire season with stable atmospheric conditions and cleaner air, presented lower cardiorespiratory mortality rates.

## Abstract

Wildfires expose populations to increased morbidity and mortality due to increased air pollutant concentrations. Data included burned area, particulate matter $PM_{10}$ and $PM_{2.5}$, carbon monoxide (CO), nitrogen dioxide ($NO_2$), ozone ($O_3$), temperature, relative humidity, wind speed, aerosol optical depth (AOD) and mortality rates due to Circulatory System Disease (CSD), Respiratory System Disease (RSD), Pneumonia (PNEU), Chronic Obstructive Pulmonary Disease (COPD), and Asthma (ASMA). Only the months of the 2011-2020 wildfire season (June-July-August-September-October) with a burned area greater than 1000 ha were considered. Multivariate statistical methods were used to reduce the dimensionality of the data to create two fire-pollution-meteorology indices (PBI and API), which allow us to understand how the combination of these variables affect cardiorespiratory mortality rate. Cluster analysis applied to PBI-API-Mortality divided the data into two Clusters. Cluster 1 included the months with lower temperatures, higher relative humidity, and high $PM_{10}$, $PM_{2.5}$, and $NO_2$ concentrations. Cluster 2 included the months with more extreme weather conditions such as higher temperatures, lower relative humidity, larger forest fires, high $PM_{10}$, $PM_{2.5}$, $O_3$, and CO concentrations, and high AOD. The two clusters were subjected to linear regression analysis to better understand the relationship between mortality and the PBI and API indices. The results showed a statistically significant (*p-value* $< 0.05$) correlation (r) in Cluster 1 between RSDxPBI ($r_{RSD} = 0.539$) and PNEUxPBI ($r_{PNEU} = 0.644$). Cluster 2 showed statistically significant correlations between RSDxPBI ($r_{RSD} = 0.464$), PNEUxPBI ($r_{PNEU} = 0.442$), COPDxPBI ($r_{COPD} = 0.456$), CSDxAPI ($r_{CSD} = 0.705$), RSDxAPI ($r_{CSD} = 0.716$), PNEUxAPI ($r_{PNEU} = 0.493$), and COPDxAPI ($r_{PNEU} = 0.619$). With climate change, the combined hazards of the Fire-Pollutant-Atmosphere Components are likely to have greater impact on health outcomes in the future.

**Keywords**: Air quality, Cluster analysis, Linear regression, Principal component analysis, Health impact.

## Plain Language Summary

The association between five cause-specific cardiorespiratory mortality and Pollutant-Atmospheric variables during wildfire seasons in Portugal were investigated. To this end, data of ambient atmospheric pollutants, meteorological variables, burned area, and mortality were used for exposure assessment. Through multivariate statistical methods it was found that in months with low-relative humidity, high-temperature, high-pollutions concentrations and high-wildfire activities, the incidence of cardiorespiratory mortality was higher. Aiming to enhance the knowledge on the effects of fire-pollutants-meteorological variables on health outcome, this study evaluates how the combination of multiple hazards impact on the country's population mortality during the fire seasons of 2011 to 2020.

# 1 Introduction

Exposure to poor air quality increases morbidity and mortality contributing significantly to the global burden of disease (Cohen et al., 2017). Air pollution - both household and ambient - remains responsible for 6.7 million deaths in 2019 (Fuller et al., 2022). In Europe, air pollution is the largest environmental risk and has a significant impact on the health of the European population (EEA, 2020). A significant proportion of premature deaths in Europe could be avoided annually if air pollution concentrations were reduced, particularly below World Health Organization (WHO) guidelines (Khomenko et al., 2021).

In Europe, important sources of air pollution are emissions from transportation, domestic heating, energy production, and industrial combustion (Malico et al., 2017), although emissions from wildfires during the fire season can significantly degrade air quality, as well as impact climate in different ways (Cattani et al., 2006; Santos et al., 2008). Wildfires emit large amounts of air pollutants that can be transported far from the source of origin affecting the air quality and human health (Janssen et al., 2012; Youssouf et al., 2014; Hua et al., 2014; Bowman et al., 2017; Machado-Silva et al., 2020; Augusto et al., 2020; Requia et al., 2021; Duarte et al., 2021; Tarín-Carrasco et al., 2021). Nevertheless, the combination of extreme drought and heat waves has been identified as a crucial factor for the occurrence of wildfires in Mediterranean forests and scrublands, leading to significant socioeconomic impacts (Ruffault et al., 2020) such as burn timber, make recreation and tourism unappealing, and affect agricultural production. Heat stress (high-temperature driven hazards) and wildfires are often considered highly correlated hazards, as extreme temperatures play a key role in both events (Vitolo et al., 2019; Sutanto et al., 2020).

On the other hand, emissions from wildfires can exacerbate the effects of heat stress on the human body, particularly in the cardiovascular and respiratory systems (Finlay et al., 2012). Primary emissions from wildfires that degrade air quality include particulate matter ($PM_{2.5}$ and $PM_{10}$), black carbon (BC), and gaseous substances such as carbon monoxide (CO), methane ($CH_4$), nitrous oxide ($N_2O$), and other combustion pollutants (Urbanski et al., 2008). Air pollution from biomass burning also contributes to the formation of secondary pollutants such as polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs), as well as ozone ($O_3$) formed by the photoreaction of nitrous oxides ($NO_x$) in the atmosphere (Jaffe et al., 2012).

Climate has a strong influence on global wildfire activity, with the frequency and intensity of wildfires increasing in many regions due to climate change (Moritz et al., 2014; Jolly et al., 2015; Couto et al., 2022). Wildfires occur at the intersection of dry weather, available biomass fuel and ignition sources (Moritz et al., 2005). According to Abatzoglou and Kolden (2013), weather conditions are the most important factors in regional fire extent. Meteorological variables such as temperature, relative humidity, precipitation, and wind speed independently influence the rate and intensity of wildfire spread. On the other hand, the coincidence of multiple weather extremes, such as the simultaneous occurrence of hot, dry, and windy conditions, results in more severe fires (Flannigan and Harrington, 1988; Couto et al., 2020). Several studies suggest that the coincidence of drought and high temperatures promotes larger fires in southern Europe (Viegas and Viegas, 1994; Pereira et al., 2005; Pereira et al., 2011; Pausas, 2004; Pausas, 2008; Chuvieco et al., 2009; Turco et al., 2013; Trigo et al., 2016; Turco et al., 2017; Turco et al., 2018; Turco et al., 2019). A better understanding of the impacts of climate change and extreme weather events on burned area development is critical for assessing regional vulnerabilities and mitigating their impacts (Turco et al., 2019).

Regarding the health effects of the exposure to wildfire smoke, epidemiologic studies showed an association between the exposure to wildfire smoke and the respiratory morbidity, with increasing evidence of an association with all-cause mortality (Reid et al., 2016). Pollutants from wildfires are a risk factor for adverse cardiovascular outcomes, particularly in vulnerable populations such as the elderly, pregnant women, and those of low socioeconomic status (Chen et al., 2021). Young and healthy individuals may also develop biological responses, including systemic inflammation and vascular activation (Chen et al., 2021). In Europe, several studies have been conducted on the health effects of population exposure to wildfire smoke (Hänninen et al., 2009; Youssouf et al., 2014; Foustini et al., 2015; Linares et al., 2018; Augusto et al., 2020; European Commission, 2020; Chas-Amil et al., 2020; Oliveira et al., 2020; Tarín-Carrasco et al., 2021; Brito et al., 2021; Barbosa et al., 2022). In all these works, different methods were used to show the importance of wildfires in Europe during the fire season as a public health problem.

Because Portugal is a highly fire-prone region due to existing vegetation and favorable weather conditions, further epidemiological studies on smoke exposure are essential. On the other hand, air pollution released by wildfires can be transported over long distances (Sicard et al., 2019; Osborne et al., 2019; Baars et al., 2019; Salgueiro et al., 2021), putting multiple populations at risk. In addition, wildfires in Portugal have a significant impact on air quality throughout Europe (Augusto et al., 2020; Tarín-Carrasco et al., 2021; Turco et al., 2019). Another important factor is that Portugal has an increasing elderly population - a group more prone to developing health problems and more vulnerable to weather extremes and the effects of climate change - and a decreasing younger population, according to INE (2022).

This work aims at evaluating the main interactions between the fire-pollutant-meteorology components and the mortality in Portugal during the annual wildfire season from 2011 to 2020. To this end, the effects of the $PM_{10}$, $PM_{2.5}$, CO, $NO_2$, $O_3$, temperature, relative humidity, wind speed, burned area, and aerosol optical depth (AOD) on mortality rates due to Circulatory System Disease (CSD), Respiratory System Disease (RSD), Pneumonia (PNEU), Chronic Obstructive Pulmonary Disease (COPD), and Asthma (ASMA) are investigated using multivariate statistical methods. Because small wildfires do not have a significant effect on mortality rates (Analitis et al., 2012), only the fire season months (June, July, August, September, and October) with a burned area greater than 1000 ha were considered in this study. With the objective of increasing the knowledge of the effects of fire, pollutants, and meteorological variables on health outcome, this study examines how the combination of several hazards affects the mortality of the country's population during the 2011-2020 fire season.

## 2 Materials and Methods

### 2.1. Study area

Portugal is located in southwestern Europe, on the Iberian Peninsula, facing the Atlantic Ocean on its west and south coasts (**Figure 1**), in the transition zone between subtropical and mid-latitude climates. The study site was strategically chosen due to spatiotemporal climate variability, as the population and ecosystems frequently suffer from intense natural hazards such as droughts, heat waves, and wildfires, which tend to become more intense and frequent under climate change (Turco et al., 2019). Continental Portugal has a temperate Mediterranean hot summer climate (Csa) in the south and a Mediterranean mild summer climate (Csb) in much of the north, with a small area with a mid-latitude steppe (BSk) climate. **Figure 1** also shows the distribution of population density (inhabitants/$km^2$) in Portugal and the background air quality (PT_QualAR) stations as well as meteorological (PT_METEO_IPMA) stations used in this work. The population density is higher in the northern and central coastal areas of Portugal (INE, 2021), where the QualAR and IPMA meteorology stations are most frequently located. All the data used on this work are in Supporting Information **S1**.

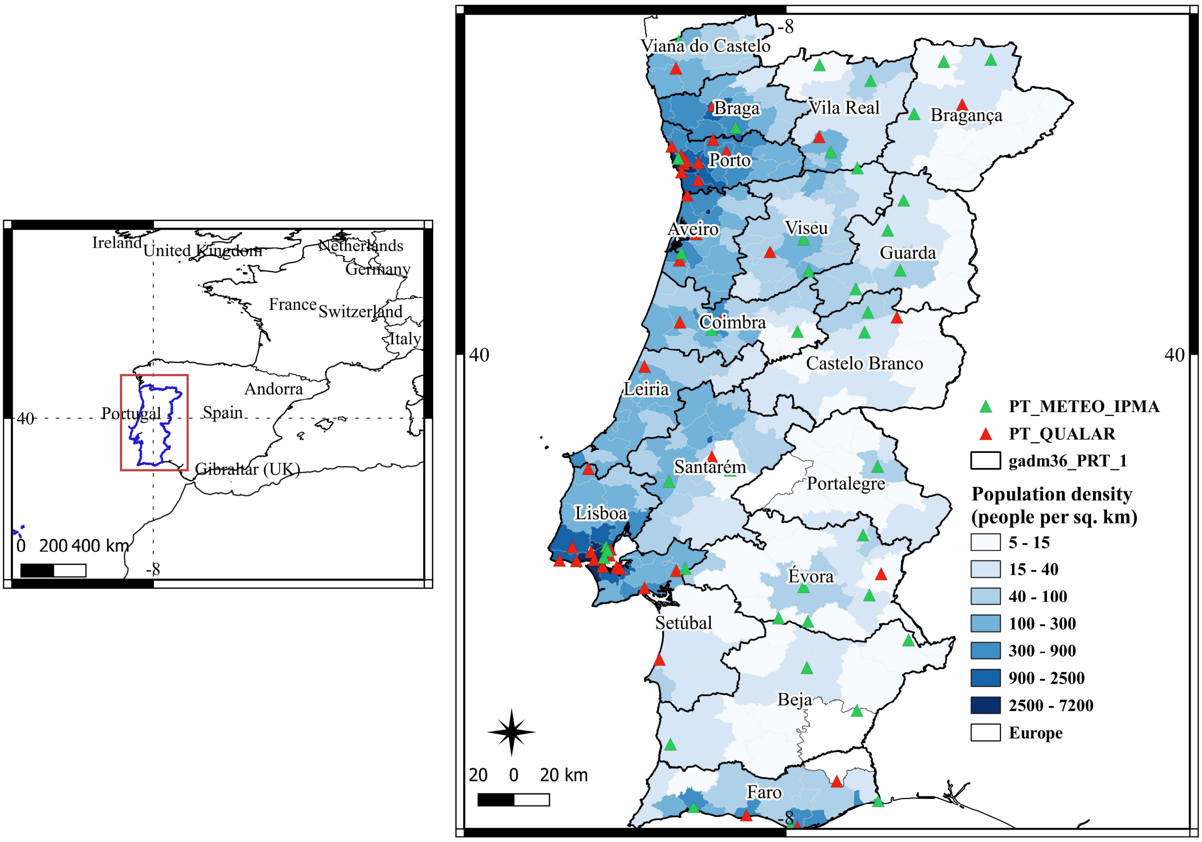



**Figure 1**: Location of Portugal in Western Iberia and the location of the 18 Portuguese continental administrative regions (districts). The map shows the distribution of population density (inhabitants/km$^2$) for each district. Data sources: INE - Annual estimates of resident population for 2021. The map also displays the background air quality (PT_QualAR) and meteorological (PT_METEO_IPMA) stations used in this work.

### 2.2. Burned area, air pollution and meteorological data

The burned area (Burned_Area; ha) data were obtained from the Portuguese Institute of Nature and Forest Conservation (https://www.icnf.pt/). These data correspond to monthly data taken from 2011 to 2020 in Continental Portugal. The burned area is obtained based on ground and satellite measurements according to the detailed information on the date and time of ignition and extinction of fire events (Pereira et al., 2011) and assessment of changes in fire regime due to different climate and fire management activities (Parente et al., 2016; 2019).

Air pollution data were obtained from the online air quality database (QualAR) of the Portuguese Environmental Agency (APA; https://qualar.apambiente.pt). The QualAR air pollution database also contains information on the type of station based on their locations (urban, suburban, and rural) and the type of emission impact (background, transport, and industrial), according to the Commission Decision 2001/752/ EC of October 17, 2001, (APA, 2008). The background stations are in geographic areas far from the influence of transportation routes, industrial areas, or other anthropogenic sources, making them a good tool for assessing wildfire impacts. The air quality network APA monitors pollutant concentrations in accordance with the requirements of European legislation (European Directive 2008/50/ EC of May 21, 2008).

Data used here refer to $PM_{10}$, $PM_{2.5}$, CO, $O_3$, and $NO_2$ hourly concentrations measured at 41 background stations distributed over Portugal (see red triangles in **Figure 1**) from 2011 to 2020. From the hourly data, the daily and monthly mean concentrations were calculated. The national monthly mean concentrations of $PM_{10}$, $PM_{2.5}$, CO, $O_3$, and $NO_2$ were used as five variables named PM10_Obs, PM25_Obs, CO_Obs, O3_Obs, and NO2_Obs for multivariate statistical analysis. To note that there are some gaps in the QualAR network registered data for $PM_{10}$, $PM_{2.5}$, CO, $O_3$, and $NO_2$ since ambient air monitoring procedures were varied over the years (2011-2020). Only APA validated data from monitoring stations reporting more than 75% of valid data of all possible data per year were considered.

The daily mean concentrations of $PM_{10}$, $PM_{2.5}$, and $NO_2$ were used to calculate the number of times that $PM_{10}$, $PM_{2.5}$, and $NO_2$ exceeded the daily WHO (2021) global air quality guidelines 2021 (15 $\mu g/m^3$ 24-hour average for $PM_{2.5}$, 45 $\mu g/m^3$ 24-hour average for $PM_{10}$, and 25 $\mu g/m^3$ 24-hour average for $NO_2$). Daily exceedances of the WHO guidelines for $PM_{10}$, $PM_{2.5}$, and $NO_2$ were counted monthly and included as three variables named WHO_PM10, WHO_PM25, and WHO_NO2 for multivariate statistical analysis.

Meteorological data on temperature (TEMP_Obs), relative humidity (RH_Obs), and wind speed (WS_Obs) from 43 meteorological stations in mainland Portugal (green triangles in **Figure 1)**, were provided by the Portuguese Institute of the Sea and Atmosphere (IPMA; www.ipma.pt/) for the period between 2011 and 2020.

Another important source of data for this work was the European Center for Medium-Range Weather Forecasts (ECMWF). The ECMWF operates services related to meteorology and atmospheric composition and the data are available through the Copernicus Atmosphere Monitoring Service (CAMS; https://ads.atmosphere.copernicus.eu) on behalf of the European Union, including those provided by the CAMS-Reanalysis. The CAMS-Reanalysis combines models with *in-situ* and remote sensing observations through data assimilation techniques. In this work, the CAMS-Reanalysis monthly averages of the aerosol optical depth at 550 nm (AOD_CAMs), black carbon aerosol optical depth at 550 nm (BC_AOD_CAMs) and dust aerosol optical depth at 550 nm (Dust_AOD_CAMs) were used. Aerosol optical depth (AOD) is a widely used parameter derived from satellite-based observations and defined as the integration of aerosol extinction into the total atmospheric column (Jiand et al., 2021). The data were obtained with a spatial resolution of 0.75° (~80 km) over Portugal for the period between 2011 and 2020. A validation of the CAMS global reanalysis can be found in Inness et al. (2019).

### 2.3. Health and population data

Monthly national mortality data for Portugal were provided by the National Institute of Statistics (INE) (INE; https://www.ine.pt/). These data refer to mortality from a specific cause in 2011-2020, based on the use of administrative data for statistical purposes from the Integrated System for Civil Registration and Identification (SIRIC) and the Information System for Death Certificates (SICO). Standardized mortality rates (per 100 000 inhabitants - all ages) were selected according to the International Classification of Diseases, version 10 (ICD-10): Circulatory System Diseases (CSD) (ICD-10: I00-I99); Respiratory System Diseases (RSD) (ICD-10: J00-J99); Pneumonia (PNEU) (ICD-10: J12-J18); Chronic Obstructive Pulmonary Disease (COPD) (ICD-10: J40-J44); and Asthma (ASMA) (ICD-10: J45-J46). Because most data exhibit seasonal variation, monthly data were used to examine within-year variability in environmental health data, focusing on the fire season in Portugal (June to October) for the period between 2011 and 2020. Since the monthly national mortality data from INE were not available by region or Nomenclature of Territorial Units for Statistics (NUTS), the used data corresponds to the entire mainland Portugal.

## 2.4. Statistical analyses

The impact of fires and meteorological, pollutant and atmospheric variables on the mortality rate was examined using intra-annual analyzes over the 10-year period 2011-2020. The standardized anomalies (Z) method was used to ensure that the different variables were weighted equally in the statistical analysis. Accordingly, the monthly values of each variable (X) are used to calculate their respective long term sample mean ($\bar{X}$) and standard deviation ($s$), and standardized anomalies (Z) for each month are then plotted as in equation *(1)*:

$$Z = \frac{(X - \bar{X})}{s} \quad (1)$$

The strength of the relationships between fire and atmospheric variables during the fire season in Portugal was assessed by a multivariate approach called Principal Component Analysis (PCA) based on the correlation matrix. Pearson correlation ($r$) measures a linear dependence between two variables. It is a parametric correlation test because it depends on the distribution of the data. Correlation test was used to evaluate the association between the variables. For the Pearson correlation, the variables should be normally distributed. Other assumptions include linearity and homoscedasticity. Linearity assumes a straight-line relationship between each of the two variables and homoscedasticity assumes that data is equally distributed about the regression line. To compare the *p-value* against a predefined significance level, one defines the maximum probability of rejecting the null hypothesis when in fact it is true (typically 5% or 1%), the tolerated error or significance level. Pearson's correlation coefficient was considered for *p-value* $< 0.05$.

The aim of PCA was to reduce the dimensionality of data. Dataset reduction was achieved by finding linear combinations (principal components) of the original variables that account for as much as possible of the original total variance. The PCA was applied to monthly fire data (Burned_Area), air quality variables (PM10_Obs, PM25_Obs, CO_Obs, O3_Obs, NO2_Obs, WHO_PM10, WHO_PM25, WHO_NO2, AOD_CAMs, BC_AOD_CAMs and Dust_AOD_CAMs) and meteorological variables (TEMP_Obs, RH_Obs and WS_Obs) to construct two PCs spatio-temporal pollutant-atmosphere interaction index called Pollutant-Burning Interaction (PBI) and Atmospheric-Pollutant Interaction (API). PCA transformed the actual correlated fire-pollutant-meteorological variables into a new set of orthogonal and uncorrelated components.

The classification of PBI and API indices was performed using *K-means* cluster analysis. In this regard, after performing the *K-means* cluster on PBI-API, the data were separated into two groups so that the samples within the same group are as similar as possible and the two different groups (clusters) are as different as possible in their composition.

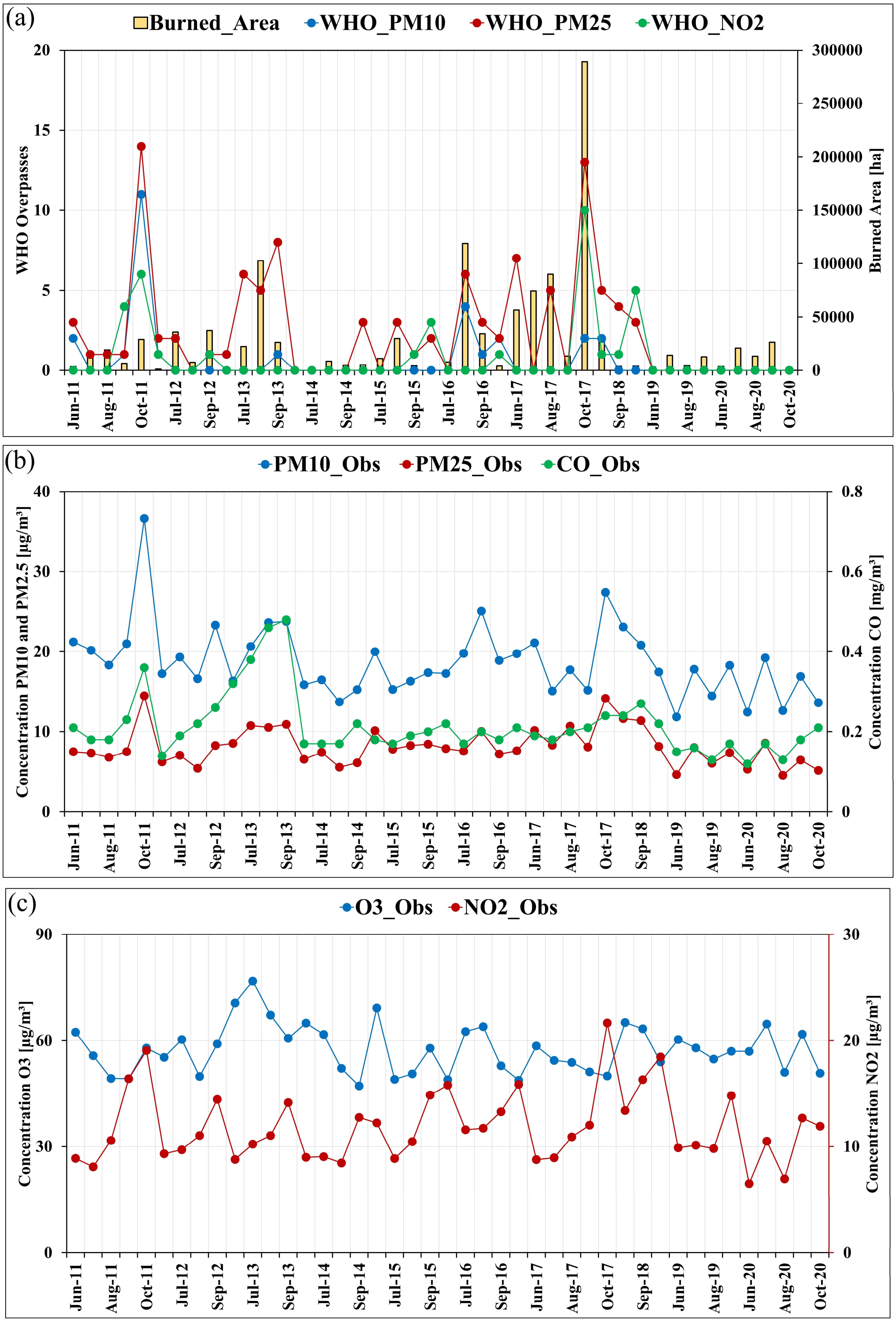
Finally, the two clusters were individually subjected to a linear regression procedure to examine the statistical relationship between the independent variables (PBI and API) and the dependent variables (CSD, RSD; PNEU; COPD; ASMA). Linear regression was applied separately for each dependent variable and the response variable (PBI and API) in each group. The collinearity of the variables was examined using Pearson's correlation test. Significant differences in scores between groups were tested at the *p-value* < 0.05 level unless otherwise noted.

## 3 Results and discussion

### 3.1. Burned area and air pollution

**Figure 2(a)** shows monthly Burned_Area and exceedances of WHO_PM10, WHO _PM25, and WHO _NO2 in Portuguese background stations from 2011 to 2020**. Figure 2(a)-(c)** also illustrates the importance of fires in increasing air pollution concentrations, as the monthly average $PM_{10}$, $PM_{2.5}$, CO, $O_3$ and $NO_2$ concentrations are higher in the months with larger burned area, such as October 2011, August 2013, August 2016, and October 2017. On the other hand, these months were characterized by favorable meteorological conditions for the development of large wildfires, such as relative humidity below 55% (**Figure 2(e)**), high wind speeds (**Figure 2(d)),** and the availability of dry vegetation for burning across the country. The different spatial distribution of wildfires together with the different weather conditions, may have contributed to the higher concentrations of $PM_{10}$, $PM_{2.5}$, $NO_2$ and CO in 2011 compared to 2017. Besides wind speed and direction greatly affect the dispersion and the local and regional transport of pollutants in the atmosphere.

**Figure 2(d)** shows AOD_CAMs, BC_AOD_CAMs, and Dust_AOD_CAMs from the global reanalysis ECMWF CAMS-Reanalysis. The correlation (*p-value* < 0.05) between AOD_CAMs, BC_AOD_CAMs, and Dust_AOD_CAMs and $PM_{2.5}$ (**Figure 3**) was 0.660, 0.690, 0.210, respectively. Although AOD represents the extinction integral of the total atmospheric column due to aerosols, over a given area, it does not directly measure the magnitude of particulate matter concentration, since the particles may be present at different atmospheric levels and not necessarily near the Earth's surface. Nevertheless, the observed air quality ($PM_{2.5}$) impacts were satisfactorily predicted in qualitative terms by the ECMWF CAMS-Reanalysis.


(a)
Burned_Area
WHO_PM10
WHO_PM25
WHO_NO2
WHO Overpasses
Burned Area [ha]
(b)
PM10_Obs
PM25_Obs
CO_Obs
Concentration PM10 and PM2.5 [µg/m³]
Concentration CO [mg/m³]
(c)
O3_Obs
NO2_Obs
Concentration O3 [µg/m³]
Concentration NO2 [µg/m³]
Jun-11
Aug-11
Oct-11
Jul-12
Sep-12
Jul-13
Sep-13
Jul-14
Sep-14
Jul-15
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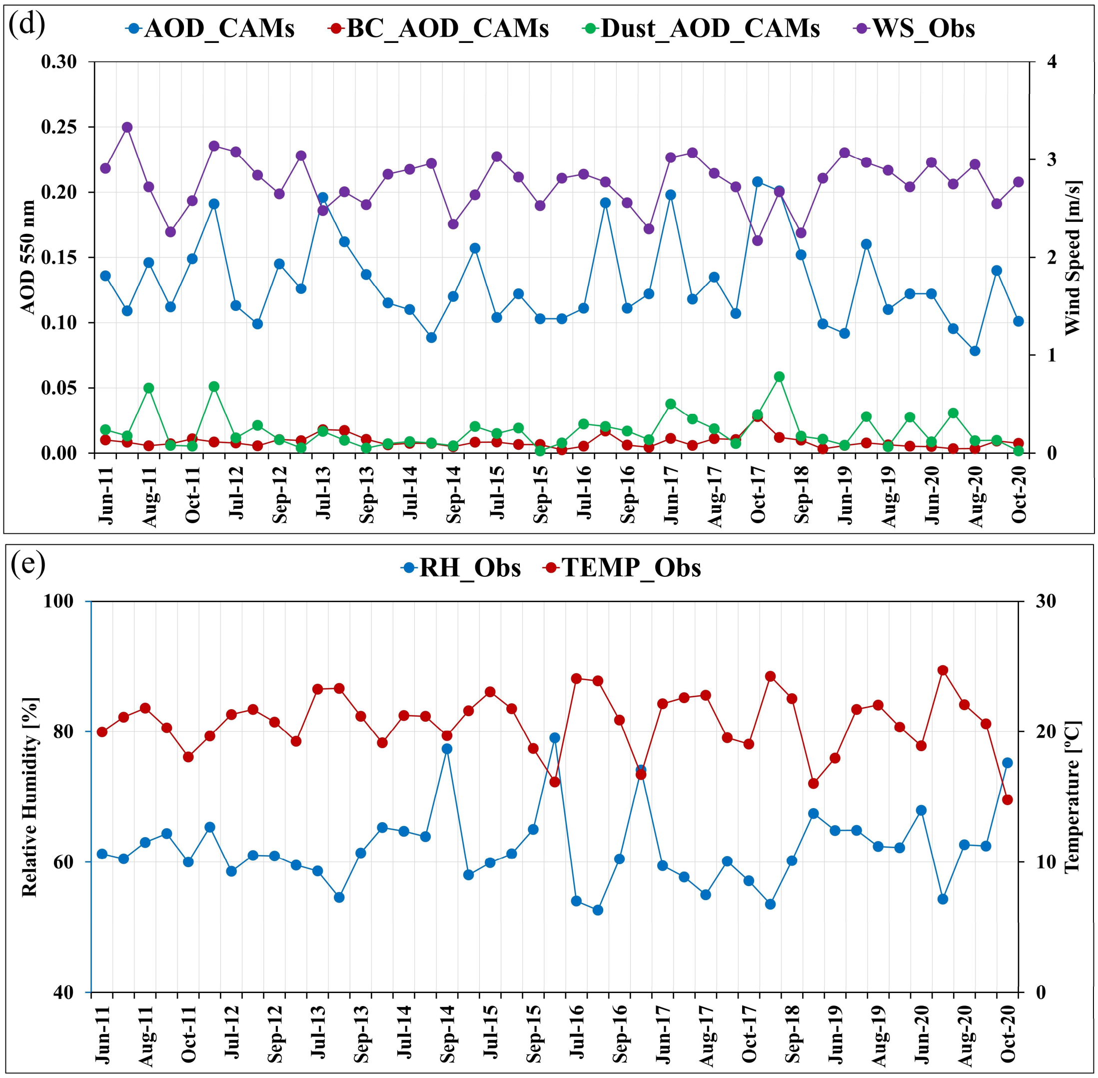



**Figure 2.** Monthly averages of several variables, from 2011 to 2020, during the fire season (June to October): **(a)** Burned_Area, WHO_PM10, WHO_PM25 and WHO_NO2 overpasses; **(b)** PM10_Obs, PM25_Obs and CO_Obs concentration; **(c)** O3_Obs and NO2_Obs concentrations; **(d)** AOD_CAMs, BC_AOD_CAMs, Dust_AOD_CAMs and WS_Obs; and **(e)** RH_Obs and TEMP_Obs.

### 3.2 Association between Fire-Pollutants-Meteorological components and mortality

The direct association between the variables fire-pollutant-meteorology and mortality is shown in **Table 1**. A significance test was performed to derive a *p-value* for the correlation coefficient between the variables by applying the function *corr.test*() (package *psych*; *R* software). The null hypothesis states that the correlation coefficient from which the sample was drawn is zero. The alternative hypothesis states that the correlation coefficient from which the sample was drawn is non-zero. If the probability is less than the usual 5% (*p-value* < 0.05), the correlation coefficient is called statistically significant. **Table 1** shows statistically significant (*p-value* < 0.05) positive correlation between RSD and PM10_Obs, PM25_Obs, CO_Obs, O3_Obs, WHO_PM25, AOD_CAMs and BC_AOD_CAMs ranging from 0.395 and 0.458. Statistically significant (*p-*

*value* < 0.05) positive correlation between PNEU and the previous variables ranging from 0.384 and 0.566 according to **Table 1**. **Table 1** also shows that the temperature and relative humidity had a low correlation with CSD, RSD, PNEU, COPD, and ASMA, and not significant (p-value > 0.05), which may lead to a misinterpretation of the effects of these variables on mortality rates during the summer period in Portugal. In this sense, by applying PCA to reduce the dimensionality of the data and constructing spatiotemporal pollutant-atmosphere interaction indices, it is possible to capture the relative contribution of each variable to the PCs and correlate them with health outcome. The PCs are linear combinations of the fire-pollutant-meteorological data.

**Table 1**: Correlation Matrix between the different variables (* *p-value* < 0.05).

| | CSD | RSD | PNEU | COPD | ASMA | PM10_Obs | PM25_Obs | CO_Obs | O3_Obs | NO2_Obs | WHO_PM10 | WHO_PM25 | WHO_NO2 | AOD_CAMs | BC_AOD_CAMs | Dust_AOD_CAMs | Burned_Area | TEMP_Obs | RH_Obs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CSD** | — | | | | | | | | | | | | | | | | | | |
| **RSD** | 0.267 | — | | | | | | | | | | | | | | | | | |
| **PNEU** | -0.059 | 0.844* | — | | | | | | | | | | | | | | | | |
| **COPD** | 0.440* | 0.543* | 0.205 | — | | | | | | | | | | | | | | | |
| **ASMA** | 0.406* | 0.109 | -0.147 | 0.634* | — | | | | | | | | | | | | | | |
| **PM10_Obs** | -0.075 | 0.453* | 0.521* | 0.181 | -0.035 | — | | | | | | | | | | | | | |
| **PM25_Obs** | -0.076 | 0.458* | 0.470* | 0.183 | -0.155 | 0.830* | — | | | | | | | | | | | | |
| **CO_Obs** | -0.178 | 0.422* | 0.566* | 0.094 | -0.077 | 0.581* | 0.604* | — | | | | | | | | | | | |
| **O3_Obs** | 0.174 | 0.417* | 0.384* | 0.365* | 0.016 | 0.255 | 0.337* | 0.375* | — | | | | | | | | | | |
| **NO2_Obs** | -0.090 | 0.203 | 0.206 | 0.010 | -0.012 | 0.588* | 0.558* | 0.358* | -0.187 | — | | | | | | | | | |
| **WHO_PM10** | 0.091 | 0.203 | 0.211 | 0.189 | -0.043 | 0.762* | 0.531* | 0.299 | 0.024 | 0.427* | — | | | | | | | | |
| **WHO_PM25** | 0.010 | 0.433* | 0.449* | 0.285 | 0.001 | 0.836* | 0.865* | 0.578* | 0.167 | 0.540* | 0.681* | — | | | | | | | |
| **WHO_NO2** | 0.062 | 0.202 | 0.211 | 0.08 | 0.053 | 0.543* | 0.522* | 0.194 | -0.249 | 0.781* | 0.484* | 0.625* | — | | | | | | |
| **AOD_CAMs** | 0.035 | 0.430* | 0.429* | 0.349* | 0.023 | 0.585* | 0.661* | 0.333* | 0.395* | 0.209 | 0.296 | 0.646* | 0.249 | — | | | | | |
| **BC_AOD_CAMs** | -0.019 | 0.395* | 0.430* | 0.140 | -0.040 | 0.574* | 0.688* | 0.483* | 0.320* | 0.273 | 0.278 | 0.705* | 0.412* | 0.749* | — | | | | |
| **Dust_AOD_CAMs** | 0.142 | 0.281 | 0.210 | 0.148 | -0.058 | 0.169 | 0.207 | -0.209 | 0.047 | -0.070 | 0.003 | 0.148 | 0.009 | 0.575* | 0.163 | — | | | |
| **Burned_Area** | 0.048 | 0.277 | 0.229 | 0.020 | -0.038 | 0.451* | 0.570* | 0.201 | -0.038 | 0.350* | 0.201 | 0.623* | 0.547* | 0.526* | 0.795* | 0.229 | — | | |
| **TEMP_Obs** | -0.042 | 0.197 | 0.189 | 0.009 | -0.043 | 0.127 | 0.222 | 0.036 | 0.373* | -0.371* | -0.136 | 0.014 | -0.389* | 0.284 | 0.221 | 0.435* | 0.17 | — | |
| **RH_Obs** | 0.061 | -0.286 | -0.293 | 0.028 | 0.172 | -0.401* | -0.488* | -0.183 | -0.503* | 0.119 | -0.14 | -0.328* | 0.059 | -0.378* | -0.486* | -0.373* | -0.421* | -0.773* | — |
| **WS_Obs** | 0.001 | -0.159 | -0.200 | -0.019 | -0.098 | -0.419* | -0.440* | -0.405* | 0.048 | -0.751* | -0.228 | -0.388* | -0.448* | -0.259 | -0.320* | 0.122 | -0.274 | 0.108 | -0.107 |

The results of PCA are shown in **Table 2** and **Figure 3**. These results show the explained variance resulting from the fire-pollutant-meteorology variable data. According to the criterion of the percentage of explained variance, the first two principal components explain more than 62% of the variance in the dataset. In the PC1 composition, PM25_Obs, WHO_PM25, PM10_Obs, BC_AOD_CAMs, AOD_CAMs, Burned_Area, WHO_NO2, NO2_Obs, CO_Obs, and WHO_PM10 make the largest contribution as shown by the results in **Table 2**. These variables account for more than 90% of the total explained variance in PC1. By its nature, PC1 is more strongly correlated with air pollutants emitted by wildfires during the fire season. For PC2, **Table 2** shows that the variables contributing more than 90% to the total explained variance are TEMP_Obs (23%), followed by RH_Obs (17.98%), NO2_Obs (13.56%), O3_Obs (10.91%), WHO_NO2 (10.51%), Dust_AOD_CAMs (8.37%), and WS_Obs (6.44%). PC2 is more correlated with months of higher temperature, lower relative humidity, higher ozone concentration near the surface as well as lower $NO_2$ concentration.

**Figure 3** shows the evaluation of each variable contribution for PC1 and PC2. The representation quality of the variables on the factor map is referred to as $cos^2$ (squared cosine, squared coordinates). A high $cos^2$ value indicates a good representation of the variable on the principal component, while a low $cos^2$ value indicates that the variable is not perfectly represented by the PCs. The closer a variable is to the correlation circle, the better its representation on the factor map. The gradient colors of the $cos^2$ also indicate good or poor representation of the variable in the correlation circle. **Figure 3** shows that the fire (Burned_Area) and pollutant variables (PM25_Obs, WHO_PM25, PM10_Obs, BC_AOD_CAMs, AOD_CAMs, Burned_Area, WHO_NO2, NO2_Obs, CO_Obs, and WHO_PM10) are highly correlated variables and strongly correlated with the PC1 (represented by the horizontal axis; *p-value* < 0.05). In PC2, the variables with the highest correlation and statistically significant (*p-value* < 0.05) are TEMP_Obs, RH_Obs, NO2_Obs, O3_Obs, WHO_NO2, Dust_AOD_CAMs, and WS_Obs.

Thus, PC1 and PC2 are the components that best represent the data distribution, and the *scores* are the projections of the data onto the principal components. In this sense, PC1 and PC2 *scores* are used as two pollutant-atmosphere interaction indices, where PC1 *score* represents the Pollutant-Burning Interaction (PBI), because the pollutants and burned area were strongly correlated and had a higher weight of PC1 formation. PC2 *score* represents the atmosphere-pollutant interaction (API) index because meteorological variables, ozone and dust presented higher weight than the pollutants in PC2 formation.

**Table 2**: Correlations between the original variables and the first two principal components (PCs; *p-value* < 0.05) and the contributions of each variable to the PCs.

| Variable | Correlation between Variables x PC | | Contribution of the variables (%) | |
|---|---|---|---|---|
| | **PC1** | **PC2** | **PC1** | **PC2** |
| **PM10_Obs** | 0.896 | -0.046 | 12.58 | 0.07 |
| **PM25_Obs** | 0.927 | 0.077 | 13.46 | 0.19 |
| **CO_Obs** | 0.609 | -0.051 | 5.82 | 0.09 |
| **O3_Obs** | 0.271 | 0.576 | 1.15 | 10.91 |
| **NO2_Obs** | 0.625 | -0.642 | 6.12 | 13.53 |
| **WHO_PM10** | 0.617 | -0.258 | 5.96 | 2.19 |
| **WHO_PM25** | 0.925 | -0.088 | 13.40 | 0.26 |
| **WHO_NO2** | 0.639 | -0.566 | 6.40 | 10.51 |
| **TEMP_Obs** | 0.147 | 0.842 | 0.34 | 23.31 |
| **RH_Obs** | -0.454 | -0.740 | 3.24 | 17.98 |
| **WS_Obs** | -0.524 | 0.443 | 4.31 | 6.44 |
| **Burned_Area** | 0.698 | 0.083 | 7.63 | 0.22 |
| **AOD_CAMs** | 0.738 | 0.359 | 8.53 | 4.24 |
| **BC_AOD_CAMs** | 0.810 | 0.227 | 10.27 | 1.70 |
| **Dust_AOD_CAMs** | 0.226 | 0.505 | 0.80 | 8.37 |

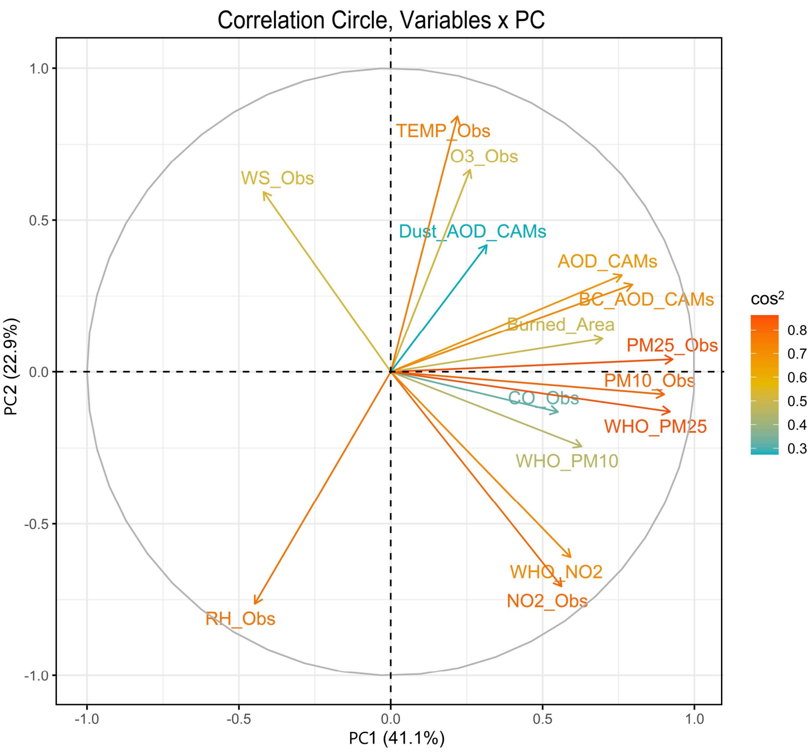
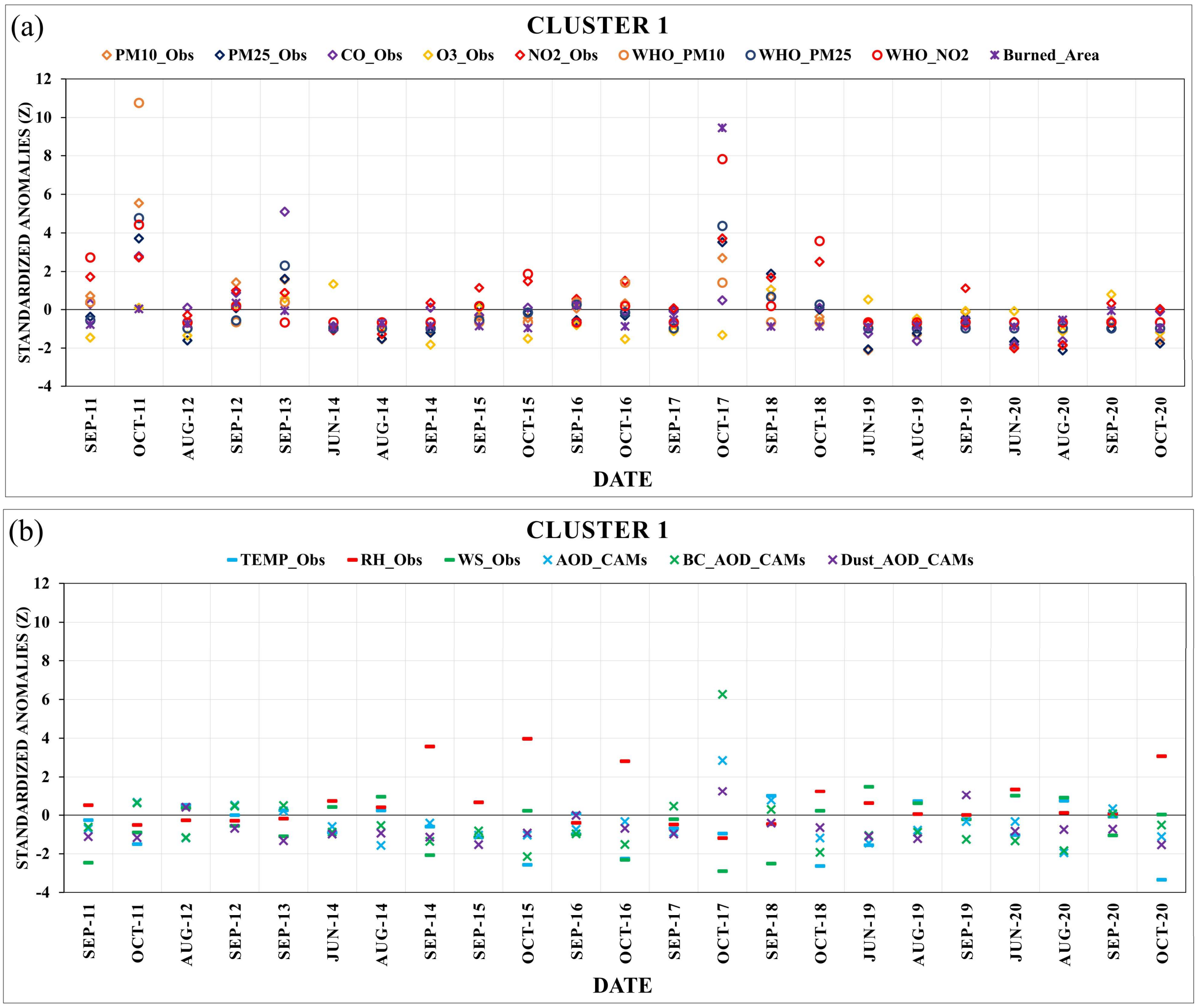



**Figure 3.** Principal component analysis (PCA) for monthly data. Vectors indicate the contribution of each variable fire-pollutant-meteorology to each PC1 and PC2. *cos*$^2$ represents the quality of the variables' representation on the factor map.

The monthly PBI, API, CSD, RSD, PNEU, COPD, and ASMA values were subjected to a Box-Cox transformation so that the variables resemble a normal distribution. This assumption allows confidence intervals to be constructed and hypothesis tests to be performed. Next, a *K-Means* cluster analysis was applied to the PBI-API-Mortality data to divide the dataset into two clusters, Cluster 1 and Cluster 2 (**Figure 4(a)-(d)**). Cluster 1 (**Figure 4(a)-(b))** includes the months inside the wildfire season with lower temperature, higher relative humidity, and higher $NO_2$ concentration near the surface. Cluster 1 also includes months with high $PM_{10}$ and $PM_{2.5}$ concentration. Cluster 2 (**Figure 4(c)-4(d))**, focuses mainly in the months of June, July, and August. These months represent summer in Europe and include the periods with the most extreme weather conditions, such as higher temperatures, lower relative humidity, larger forest fires, higher $PM_{10}$, $PM_{2.5}$, $O_3$, and CO concentrations near the surface, and high AOD.



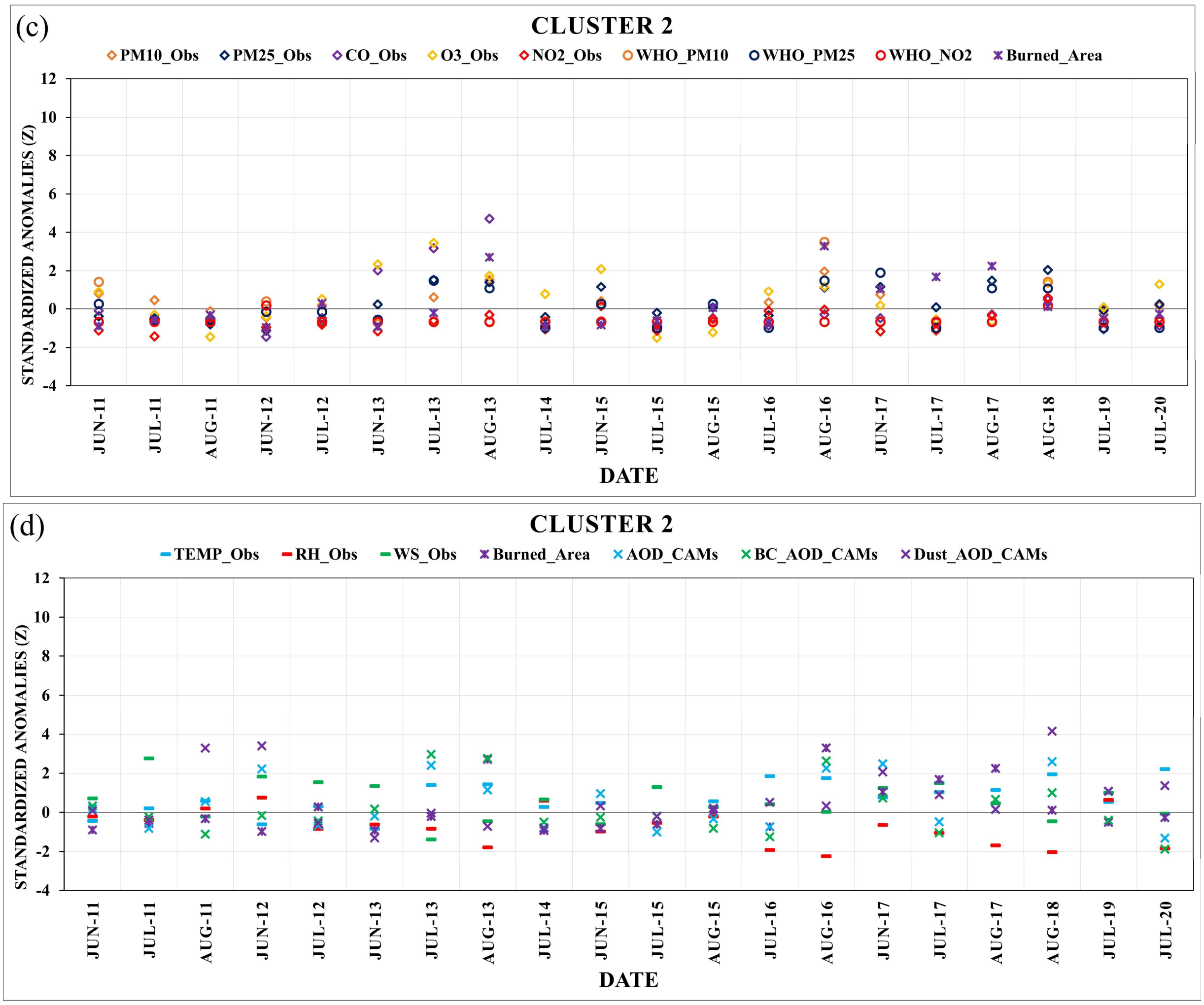



**Figure 4.** Intra-annual variability of standardized anomalies (Z-scores) of the variables PM10_Obs, PM2.5_Obs, CO_Obs, O3_Obs, NO2_Obs, WHO_PM10, WHO_PM25, WHO_NO2, TEMP_Obs, RH_Obs, WS_Obs, Burned_Area, AOD_CAMs, BC_AOD_CAMs, Dust_AOD_CAMs from 2011 to 2020: **(a)** Cluster 1 and **(b)** Cluster 2.

The two clusters were subjected to linear regression analysis to better understand the relationship between health outcomes (CSD; RSD; PNEU; COPD; ASMA) and pollutant-atmosphere interaction and atmospheric-pollutant interaction indices (PBI and API). From 2011 to 2020, the average number of deaths due to cardiorespiratory diseases (CSD; RSD; PNEU; COPD; ASMA) during the fire season in Portugal (June to October) was 7.15 (±0.5) deaths per hundred thousand habitant and per month (Dth $hd^{-1}$ $mh^{-1}$). From 2011 to 2020, the mean number of deaths due to CSD was 22.67 (±1.0) Dth $hd^{-1}$ $mh^{-1}$, while the number of deaths due to RSD was 7.86 (±0.6) Dth $hd^{-1}$ $mh^{-1}$, due to PNEU was 3.46 (±0.5) Dth $hd^{-1}$ $mh^{-1}$, due to COPD was 1.66 (±0.2) Dth $hd^{-1}$ $mh^{-1}$ and due to ASMA was 0.08 (±0.03) Dth $hd^{-1}$ $mh^{-1}$.

**Figure 5(b)-(c)** shows the relation between the different health outcomes and Pollutant-Atmosphere Interaction index for cluster 1. A strong statistically significant (*p-value* < 0.05) positive correlation was found between RSDxPBI ($r_{RSD}$ = 0.539) and PNEUxPBI ($r_{PNEU}$ = 0.644), while no statistically significant correlation was found between CSDxPBI, COPDxPBI and

ASMAxPBI, as shown in **Figure 5(a)**, **5(d)** and **5(e)**. The pollutant-atmosphere interaction index is highly correlated with $PM_{10}$, $PM_{2.5}$, CO, and $NO_2$ concentrations, as well as with WHO _PM10, WHO _PM25, and WHO _NO2 exceedances during the 2011-2020 fire season. For Cluster 1, the main cause of mortality due to RSD and PNEU can be associated with the high concentration of pollutants near the surface. Long-term exposure to $NO_2$, which is a toxic gas and a primary pollutant precursor of $O_3$ in the troposphere (Andino-Enriquez et al., 2018; Bortoli et al., 2009), is associated with hypertension, pulmonary dysfunction, and COPD (Lamichhane et al., 2018; Lyons et al., 2020). $NO_2$ also increases the risk of developing viral infections (Jurado et al., 2020; Pacheco et al., 2020). Augusto et al. (2020) showed that $PM_{10}$ released during the October 2017 megafires in Portugal had a significant impact on natural and cardiorespiratory mortality on smoky days. For each additional 10 µg/m$^3$ of $PM_{10}$, there was a 0.89% increase (95% confidence interval, 0-1.77%) in the number of natural deaths and a 2.34% increase (95% confidence interval, 0.99-3.66%) in the number of cardiorespiratory deaths.

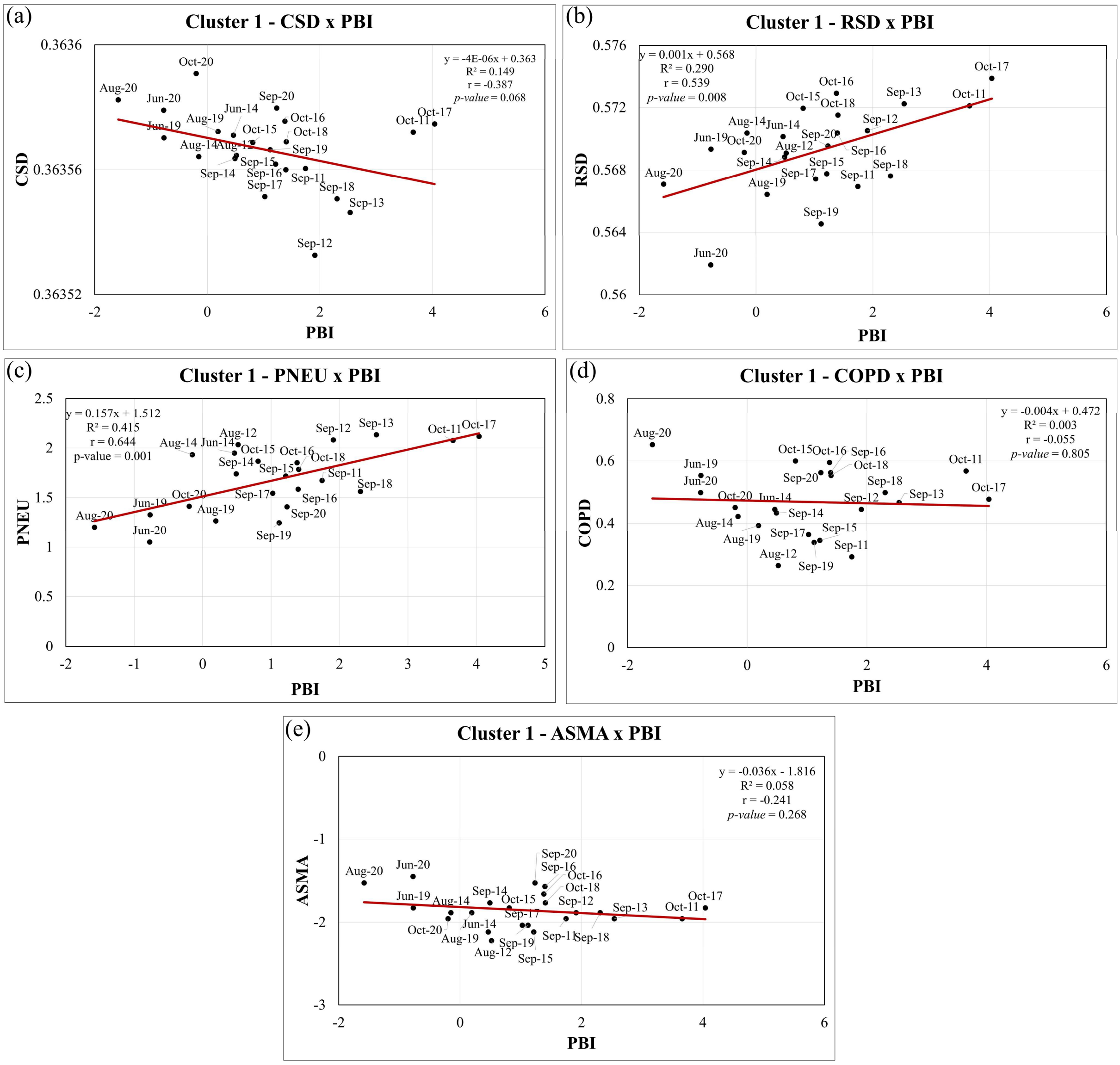


**Figure. 5.** Linear regression analysis between health outcomes and Pollutant-Atmosphere Interaction index PBI for Cluster 1: **(a)** CSDxPAI; **(b)** RSDxPAI; **(c)** PNEUxPAI; **(d)** COPDxPAI; **(e)** ASMAxPAI.

**Figure 6(a)-(e)** shows the relation between the different health outcomes considered and the Atmospheric-Pollutant Interaction index API for Cluster 1. In this case, the correlations between mortality causes and pollutant-atmosphere interaction (CSDxAPI, RSDxAPI, PNEUxAPI, COPDxAPI and ASMAxAPI) do not show statistically significance (p-value > 0.05). API was most strongly related to lower temperature and higher relative humidity associated with colder and wetter months in Cluster 1.

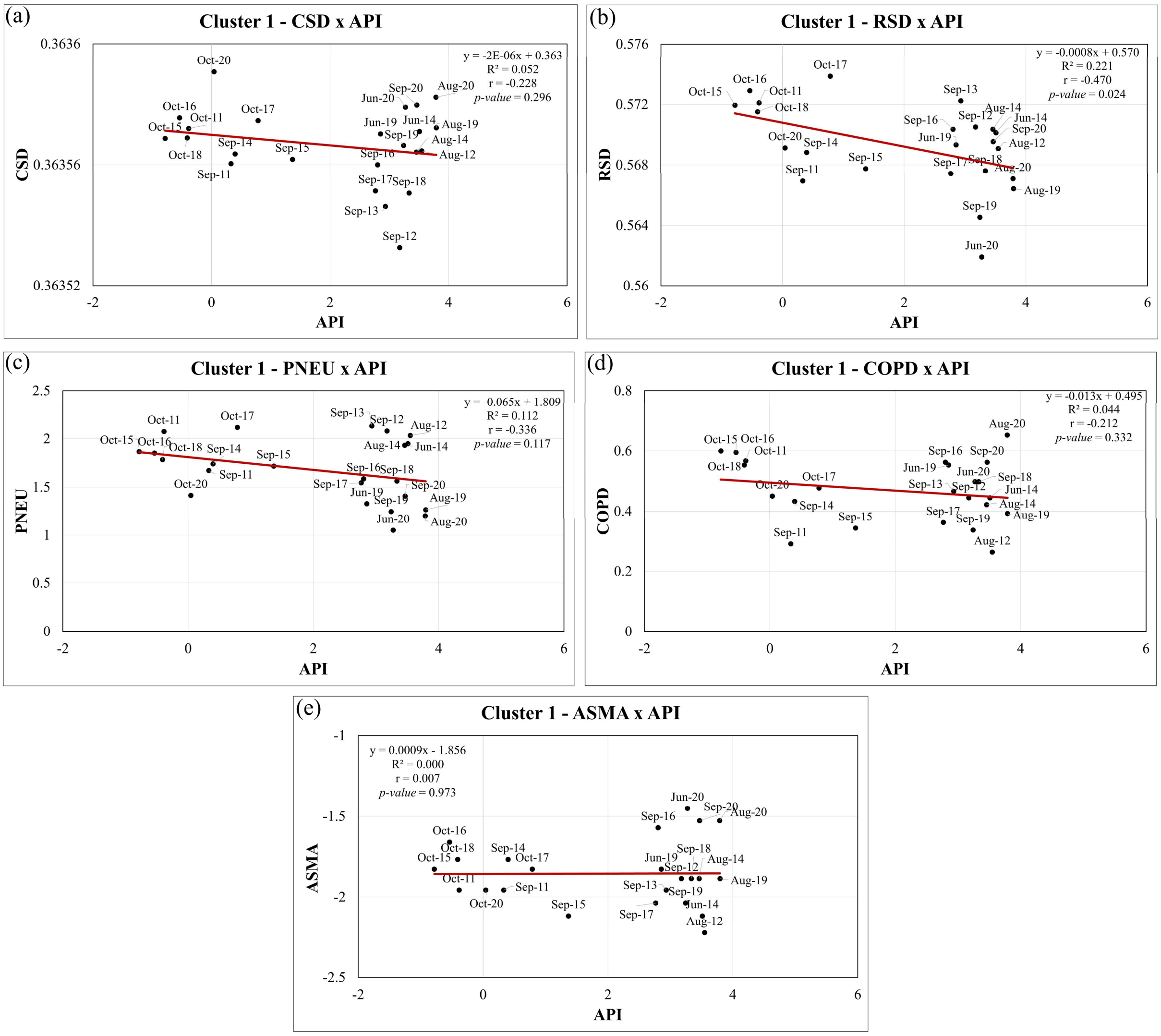



**Figure 6.** Linear regression analysis between health outcomes and Atmospheric-Pollutant Interaction index API for Cluster 1: **(a)** CSDxAPI, **(b)** RSDxAPI; **(c)** PNEUxAPI; **(d)** COPDxAPI; **(e)** ASMAxAPI.

The Cluster 2 mainly includes the months of June, July, and August, which are the warmest months of the year and the months when most wildfires occur. **Figures 7(b)**, **7(c)** and **7(d)** show statistically significant (*p-value* < 0.05) positive correlations between RSDxPBI ($r_{RSD}$ = 0.464), PNEUxPBI ($r_{PNEU}$ = 0.442) and COPDxPBI ($r_{COPD}$ = 0.456). Higher pollutant concentrations such as $PM_{10}$, $PM_{2.5}$, CO, and $NO_2$, along with large wildfires, low relative humidity, and low wind speed, contributed most to RSD, PNEU, and COPD deaths. **Figure 7(a)** and **7(e)** shows not statistically significant (*p-value* > 0.05) relationship between CSDxPBI ($r_{CSD}$ = 0.387) and ASMAxPBI ($r_{ASMA}$ = 0.125), although the correlation was positive. Nonetheless, linear regression was used as a diagnostic method to identify cause-of-death patterns during the fire season, suggesting that deaths due to CSD and ASMA also tend to increase due to extreme atmospheric conditions associated with fire-pollutant meteorology.

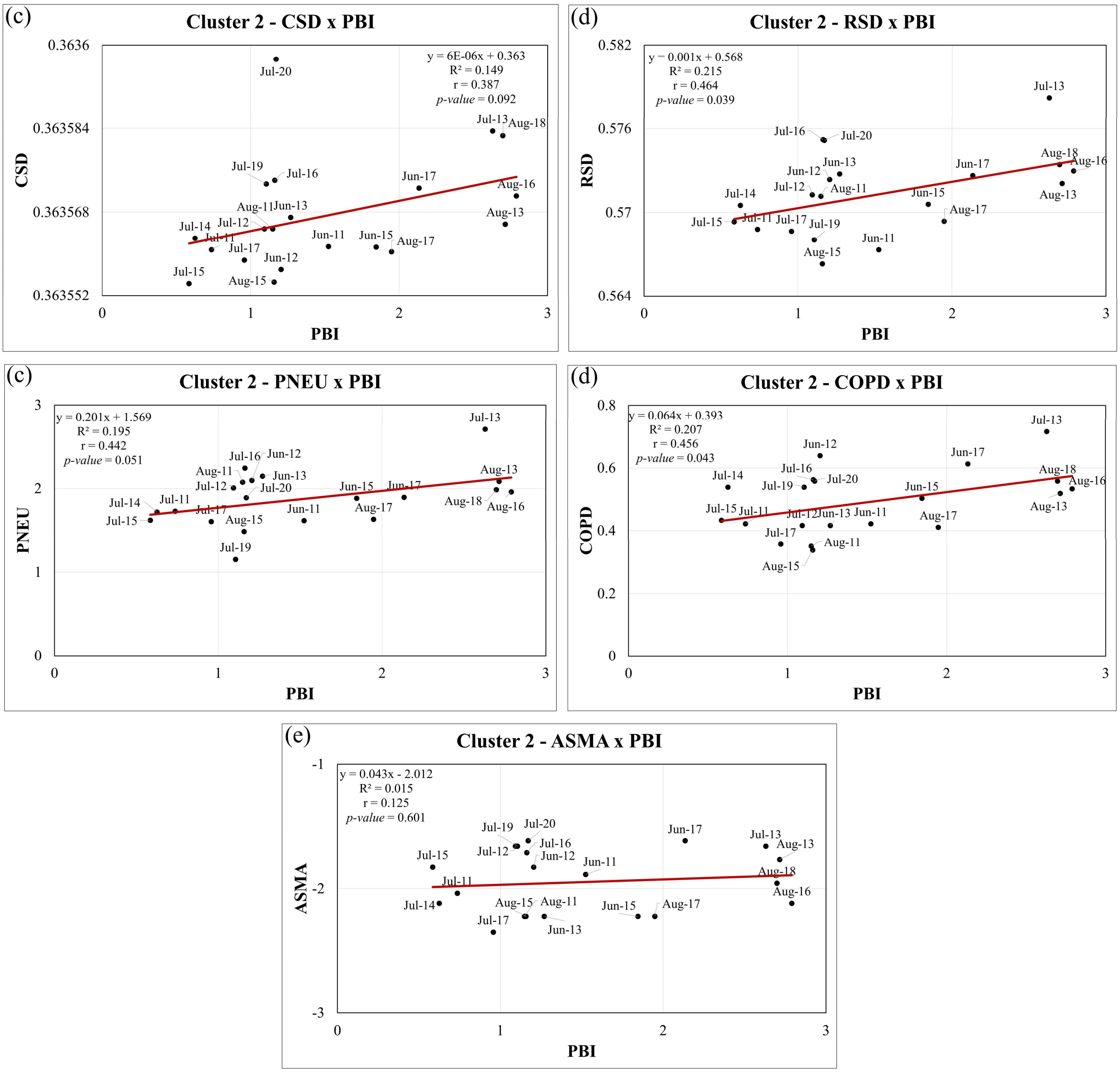


**Figure 7.** Linear regression analysis between health outcomes and and Pollutant-Atmosphere Interaction index PBI for Cluster 2: **(a)** CSDxPAI, **(b)** RSDxPAI; **(c)** PNEUxPAI; **(d)** COPDxAPI; **(e)** ASMAxPAI.

**Figure 8(a)-(d)** shows statistically significant (*p-value* < 0.05) correlations in Cluster 2 between CSDxAPI ($r_{CSD}$ = 0.705), RSDxAPI ($r_{CSD}$ = 0.716), PNEUxAPI ($r_{PNEU}$ = 0.493), and COPDxAPI ($r_{PNEU}$ = 0.619). The results show that the extreme weather conditions associated with high temperature, low relative humidity, high near-surface $O_3$ concentration, high Dust_AOD_CAMs, and high wind speed are strongly correlated with CSD, RSD, and COPD in Cluster 2, which mainly include the months of June, July, and August. **Figure 8(e)** shows not statistically significant (*p-value* > 0.05) correlations in Cluster 2 between ASMAxAPI ($r_{ASMA}$ = 0.364). However, the correlation was positive suggesting that asthma-related deaths also tended to occur more frequently in these months.

Baccini et al. (2008), Lin et al. (2009), Lin et al. (2013), Yang et al. (2012), Vitolo et al. (2019) reported the association between elevated temperature (heat stress) and adverse health outcomes such as cardiovascular and respiratory diseases. This work shows that the combination of smoke exposure from wildfires with heat stress due to high temperatures, low relative humidity, and high $O_3$ concentration near the surface can increase cardio-respiratory mortality and contribute to an increase in overall disease burden. The API index has also been associated with dust aerosols. Also dust aerosols play an important role in Europe due to dust storms from the Sahara Desert, many of them considered extreme events (Valenzuela et al., 2017). Studies show that cardiovascular hospitalizations increase after African dust storm episodes (Middleton et al., 2008; Neophytou et al., 2013).

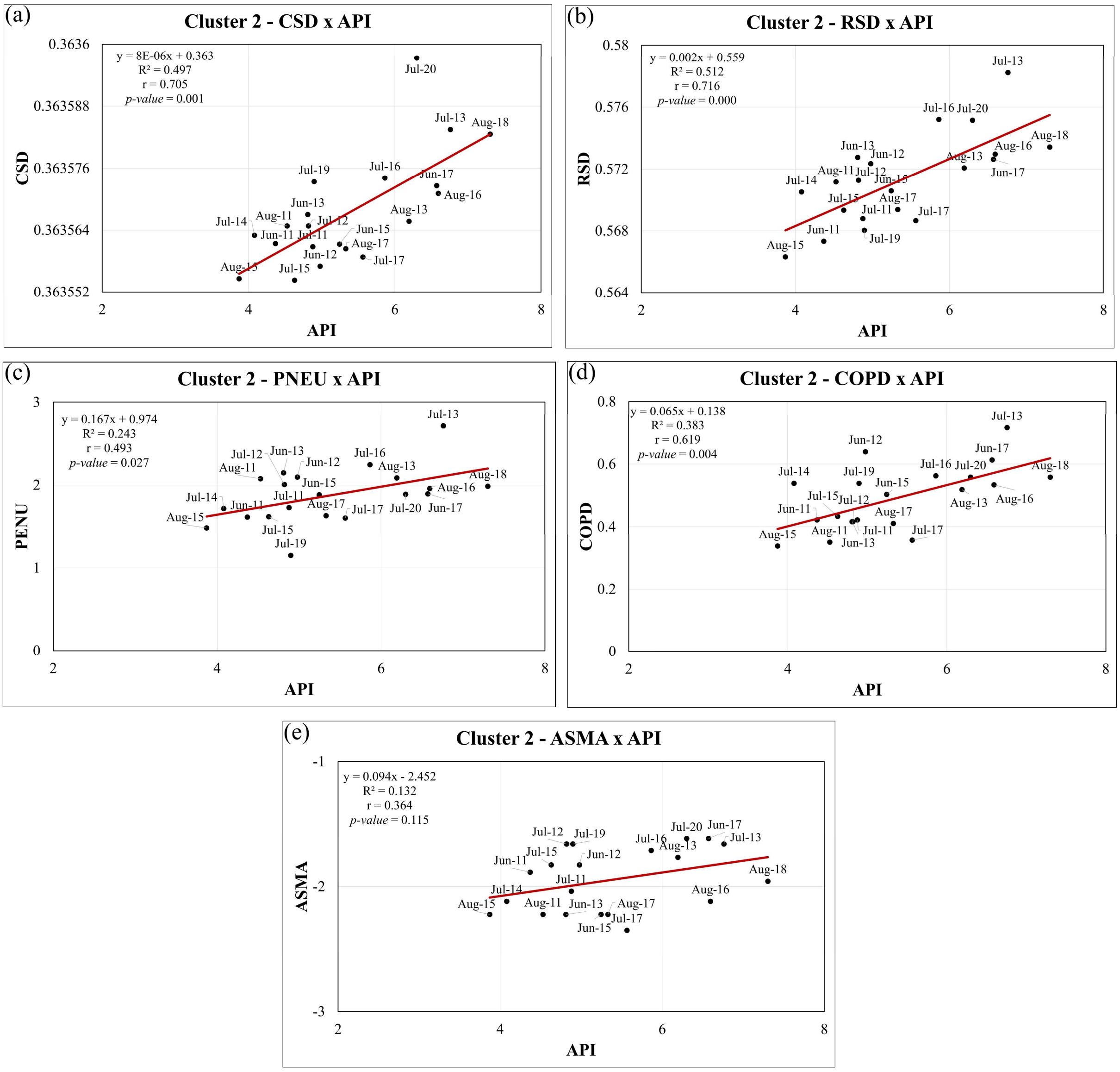



**Figure 8.** Linear regression analysis between health outcomes and Atmospheric-Pollutant Interaction index API for Cluster 2: **(a)** CSDxAPI, **(b)** RSDxAPI; **(c)** PNEUxAPI; **(d)** COPDxAPI; **(e)** ASMAxAPI.

Vitolo et al. (2019) reiterate that multiple hazards affecting the same region simultaneously can have significant impacts, as the consequences of one hazardous event are often exacerbated by interaction with another. This suggests the need for spatiotemporal information layers that identify hotspots of combined hazards (Vitolo et al., 2019). Here, we used multivariate statistical methods to create two fire-pollutant meteorology indices (PAI and API) from different environmental variables to understand how the combination of these variables affects mortality rates from cardio-respiratory disease. The results show that reducing the dimensionality of the database through PCA efficiently helps to understand how fire-pollutant meteorology indices can affect mortality rates.

## 4. Concluding remarks

A method combining fire, pollutant, and meteorological variables and using Principal Component Analysis (PCA) is proposed here, to produce two indices: Pollutant-Atmosphere Interaction (PBI) and Atmospheric-Pollutant Interaction (API). PAI better represents pollutants and the burned area because these variables were highly correlated and had a higher weight in PC1 formation. API represented the meteorological variables, $O_3$ and dust, as these variables were highly correlated and had a higher weight in PC2 formation. The objective was to understand how these two indices correlate with cardiorespiratory mortality rates due to CSD, RSD, PNEU, COPD, and ASMA during the fire season (June-July-August-September-October) from 2011-2020.

The PBI-API-Mortality dataset was divided into two clusters labeled Cluster 1 and Cluster 2, by applying *K-Means* cluster analysis. Cluster 1 included the months with lower temperatures, higher relative humidity, and higher $PM_{10}$, $PM_{2.5}$, and $O_3$ concentrations near the surface. Cluster 2 includes the months with higher pollutant concentrations such as $PM_{10}$, $PM_{2.5}$, CO, and $NO_2$ along with large forest fires, low relative humidity, and low wind speed. Cluster 2 also consists of the warmest months of the year and the months when most wildfires occur. The two clusters were subjected to linear regression analysis to better understand the relationship between health outcomes (CSD; RSD; PNEU; COPD; ASMA) and the PBI and API indices. The results showed a consistent association between the fire-pollutant-meteorology indices and cardiorespiratory mortality in Portugal during the wildfire season, specifically CSD, RSD, PNEU, COPD and ASMA.

We observed a statistically significant positive correlation in Cluster 1 between RSDxPBI and PNEUxPBI, $r > 0.50$. Cluster 2 showed statistically significant positive correlations between RSDxPBI, PNEUxPBI, and COPDxPBI, $r > 0.40$. Statistically significant correlations in Cluster 2 between CSDxAPI, RSDxAPI, PNEUxAPI, and COPDxAPI, $r > 0.50$. During months within the wildfire season with stable atmospheric conditions and clean air (Cluster 1), the cardiorespiratory mortality rates are lower.

With climate change, extreme weather events and uncontrolled wildfires tend to become more frequent. Thus, morbidity and mortality tend to increase if mitigation measures are not taken. A shared understanding of the health effects of fire, pollutants, and meteorology can help society and decision makers to be better prepared for extreme weather events and ensure that health services are able to mitigate public health consequences following a wildfire season.

## Declaration of competing interest

The authors declare no competing interests.

## Data Availability Statement

The data for this study are publicly available online or must be requested from the appropriate agencies. Observational data on surface air pollution were obtained from the online air quality database (QualAr) of the Portuguese Environmental Agency (APA) at https://qualar.apambiente.pt). Mortality data for Portugal were provided by the National Institute of Statistics (INE; https://www.ine.pt/). Meteorological data were provided by the Portuguese Institute of Sea and Atmosphere (IPMA; https://www.ipma.pt/pt/index.html) and the burned area data were provided by the Portuguese Institute of Nature and Forest Conservation (ICNF; https://www.icnf.pt/). ECMWF data are available through the Copernicus Atmosphere Monitoring Service (CAMS; https://ads.atmosphere.copernicus.eu).

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## Author contributions

Ediclê de Souza Fernandes Duarte: Conceptualization, Investigation, Methodology, Formal analysis, Wrote the manuscript. Vanda Salgueiro: Conceptualization, Investigation, Methodology, Writing - review & editing. Maria João Costa: Conceptualization, Investigation, Methodology, Writing - review & editing. Paulo Sérgio Lucio: Conceptualization, Investigation, Methodology, Writing - review & editing. Daniele Bortoli: Investigation, Writing review & editing. Miguel Potes: Investigation, Writing - review & editing. Rui Salgado: Investigation, Writing - review & editing.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi...

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