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Population exposure to particulate-matter and related mortality due to the Portuguese wildfires in October 2017 driven by storm Ophelia

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ABSTRACT

In October 2017, hundreds of wildfires ravaged the forests of the north and centre of Portugal. The fires were fanned by strong winds as tropical storm Ophelia swept the Iberian coast, dragging up smoke (together with Saharan dust from north-western Africa) into higher western European latitudes. Here we analyse the long-range transport of particulate matter (PM_{10}) and study associations between PM_{10} and short-term mortality in the Portuguese population exposed to PM_{10} due to the October 2017 wildfires, the worst fire sequence in the country over the last decades. We analysed space- and ground-level observations to track the smoke plume and dust trajectory over Portugal and Europe, and to access PM_{10} concentrations during the wildfires. The effects of PM_{10} on mortality were evaluated using satellite data for exposure and Poisson regression models. The smoke plume covered most western European countries (including Spain, France, Belgium and the Netherlands), and reached the United Kingdom, where the population was exposed in average to an additional PM_{10} level of 11.7 $\mu g/m^3$ during seven smoky days (three with dust) in relation to the reference days (days without smoke or dust), revealing the impact of the wildfires on distant populations. In Portugal, the population was exposed in average to additional PM_{10} levels that varied from 16.2 to 120.6 $\mu g/m^3$ in smoky days with dust and from 6.1 to 20.9 $\mu g/m^3$ in dust-free smoky days. Results suggest that PM_{10} had a significant effect on the same day natural and cardiorespiratory mortalities during the month of October 2017. For every additional 10 $\mu g/m^3$ of PM_{10}, there was a 0.89% (95% confidence interval, CI, 0–1.77%) increase in the number of natural deaths and a 2.34% (95% CI, 0.99–3.66%) increase in the number of cardiorespiratory-related deaths. With rising temperatures and a higher frequency of storms due to climate change, PM from Iberian wildfires together with NW African dust will tend to be more often transported into Northern European countries, which may carry health threats to areas far from the ignition sites.

1. Introduction

On October 16th, 2017, parts of the United Kingdom woke up to a strange reddish sky, which made the headlines of the day (Moore, 2019). The event was the result of Storm Ophelia picking up sands from the Sahara Desert in North Africa and particles from uncontrolled Portuguese wildfires (Harrison et al., 2018; NASA, 2017; Osborne et al., 2019). The phenomenon was noticeable all over western Europe. Whilst is not unusual for Europe to be struck by tropical ex-hurricanes, storm Ophelia stood out due to its location and trajectory as the farthest east storm of its strength ever formed (Met Éireann, 2018). Ophelia's strong winds enhanced the intensity of the Portuguese wildfires, already fuelled by an unusually hot and dry season (Turco et al., 2019; Sánchez-Benítez et al., 2018), while dragging up fire-generated pollutants into NW Europe and potentially affecting populations very far from the wildfire episodes.

The fire season of 2017 was severe in many regions of Southern Europe, with large wildfires taking place in southern France, Italy,

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Portugal, and Spain associated with unusually intense droughts and heatwaves (Change, 2017; Sánchez-Benítez et al., 2018). These events caused extensive economic and ecological losses and even human casualties (Change, 2017), being particularly tragic in Portugal, the country commonly most affected in terms of ignition density and burnt area (Mateus and Fernandes, 2014): a record of about 500 000 ha total burned area and more than 120 fatalities in the 2017 fires. The case of October was marked by strong and persistent southern winds caused by the close passage of hurricane Ophelia moving northwards.

With uncontrolled wildfires comes the release of large amounts of particulate matter (PM) (composed of PM_{10} and $PM_{2.5}$, i.e. particles with aerodynamic diameter below 10 µm and 2.5 µm, respectively) into the environment, together with other combustion products (such as carbon dioxide, carbon monoxide, nitrogen oxides, sulphur dioxides, and volatile organic compounds) (Nadal et al., 2016; Rovira et al., 2018). All of them may suffer from atmospheric transport over large distances, contributing to an increase of their levels in regions far from the ignition sites, posing distant populations at risk (Kollanus et al., 2016).

The Lancet Commission on Pollution and Health has recognized PM as a major threat for human health across the globe (Landrigan et al., 2018) and in 2016, the World Health Organization (WHO) estimated that 4.2 million premature deaths per year occurred worldwide due to the exposure to $PM_{2.5}$ (WHO, 2016). A study by Beelen et al. (2014), which combined the results of 22 European studies in 367,251 people, found a 7% increase in mortality with each 5 $\mu g/m^3$ increase in $PM_{2.5}$. Similarly, a 1% increase in mortality with each 10 $\mu g/m^3$ increase in PM_{10} was found in different epidemiological studies (WHO, 2017).

Regarding forest fires, a recent study evaluating short-term effects of PM_{10} on mortality in 10 southern European cities in Spain, France, Italy and Greece (during wildfires in the period 2003–2010), has reinforced these estimates (Faustini et al., 2015). Using satellite data for exposure assessment and Poisson regression models, the authors concluded that PM_{10}-related mortality was higher on smoky days than in non-smoky days (natural mortality increased up to 1.10%, respiratory mortality up to 3.90% and cardiovascular mortality up to 3.42%). The increased mortality on smoky days may be explained through the hypothesis that small effects cause clinical events when experienced by individuals who are already susceptible due to existing chronic or acute diseases (Atkinson et al., 2014). Moreover, PM_{10} from forest fires was found to increase the mortality more than PM_{10} from other sources, suggesting different chemical compositions and hence different potential toxicities (Faustini et al., 2015). Thus, estimates of mortality due to exposure to wildfire-generated PM and related contaminants are fundamental to manage health resources and public funds.

To assess human exposure to wildfire-generated pollutants it is crucial to track the trajectory of the smoke plume and to assess the concentrations of pollutants at ground level. Satellite images and dispersion models provide reliable information on smoke trajectory and dust outbreaks, but not on ground-level incidence, which can only be given by fixed monitors. Integrated approaches making use of both instruments (satellite images and ground-level monitors) have been used as a method to enhance human exposure estimations (Faustini et al., 2015; Li et al., 2019).

Therefore, making use of satellite images and ground-level monitors, the aims of this study were: (i) to analyse the long-range transport of smoke and PM_{10} from the Portuguese wildfires in October 2017 over Europe; (ii) to study the associations between PM_{10} and short-term mortality in the Portuguese population exposed to PM_{10} due to the wildfires and Saharan dust in October 2017. This approach will allow a clearer understanding of the impact that extreme wildfire events can have on human life, and to which extent (spatially and in terms of mortality) are these impacts significant.

2. Material and methods

In this study, satellite images were analyzed to establish the backward trajectory of the Portuguese wildfires smoke and NW African dust in October 2017, to assess which countries were affected by the smoke and dust and in which days. Days without neither smoke nor dust were considered reference days. To confirm the trajectory, the daily ground-level measurements of PM_{10} from the available air quality monitoring stations of the affected areas over the selected time period were compared with the space-level observations.

The PM_{10} ground-level measurements in smoky days with dust and in dust-free smoky days were then used to: (i) calculate daily PM_{10} exposure increments (PM_{10}-DEI, Daily Exposure Increments) in relation to PM_{10} observed in reference days; (ii) study the associations between PM_{10} exposure with short-term (same-day) natural and cardiorespiratory mortalities during October 2017 in a retrospective cohort study where deaths in days with exposure were compared with deaths in days without exposure.

Details of the methods are provided below.

2.1. Space-level observations

The backward trajectory of the 2017 October Portuguese wildfires' smoke and NW African dust was assessed based on the Navy Aerosol Analysis and Prediction System (NAAPS). The NAAPS, run by the US Naval Research Laboratory, is a global forecast model that predicts smoke aerosol concentrations in the troposphere (model description and data available at http://www.nrlmry.navy.mil/aerosol). Predicted surface smoke and dust concentrations are provided on a 1° × 1° grid (i.e. about 110 km longitude and 55 km latitude resolution in western Europe) at 6-h intervals. For October 2017, 116 predictions were available, corresponding to four predictions per day (no data was available for days 4 and 5).

For each country covered by the Portuguese wildfires' smoke, and for each district in Portugal, days were classified as: (i) smoky days with dust; (ii) dust-free smoky days; (iii) days without either smoke or dust (reference days). During the month of October there were no smoke-free dusty days in Portugal. A day was considered smoky and/or dusty when the NAAPS model indicated a surface smoke concentration > 1 $\mu g/m^3$ and/or a surface dust concentration > 20 $\mu g/m^3$, respectively (the minimum threshold displayed by the NAAPS models); and when more than one third of the space unit considered (country or district) was affected.

2.2. Ground-level observations (air quality monitoring stations)

Mean daily PM_{10} concentrations for October 2017 in mainland Portugal were obtained from hourly concentrations of 52 fixed air quality monitoring stations, covering 14 out of 18 Districts (Fig. 1). Mean daily concentrations of carbon monoxide (CO), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2), and maximum daily concentrations of ozone (O_3), were also obtained from the same stations. Some studies have reported increases in CO as a possible indirect indicator of exposure to fires (van Donkelaar et al., 2011; Wang et al., 2010; Zeng et al., 2008), while NO_2, SO_2 and O_3 have been associated with mortality and thus may be confounders in this study (WHO, 2013).

Data was provided by the Portuguese Environment Protection Agency (APA, at https://qualar.apambiente.pt/qualar/), the regulatory body that manages air quality in Portugal. Maximum daily temperatures, also a risk factor for mortality, were obtained from the Portuguese Institute for Sea and Atmosphere (IPMA, 2017; Stafoggia et al., 2008).

In the United Kingdom, mean daily PM_{10} concentrations for October 2017 were obtained from hourly concentrations of 65 air quality monitoring stations, covering England (48 stations), Scotland (7), Wales (5) and Northern Ireland (5) (Fig. 1). Data was provided by the

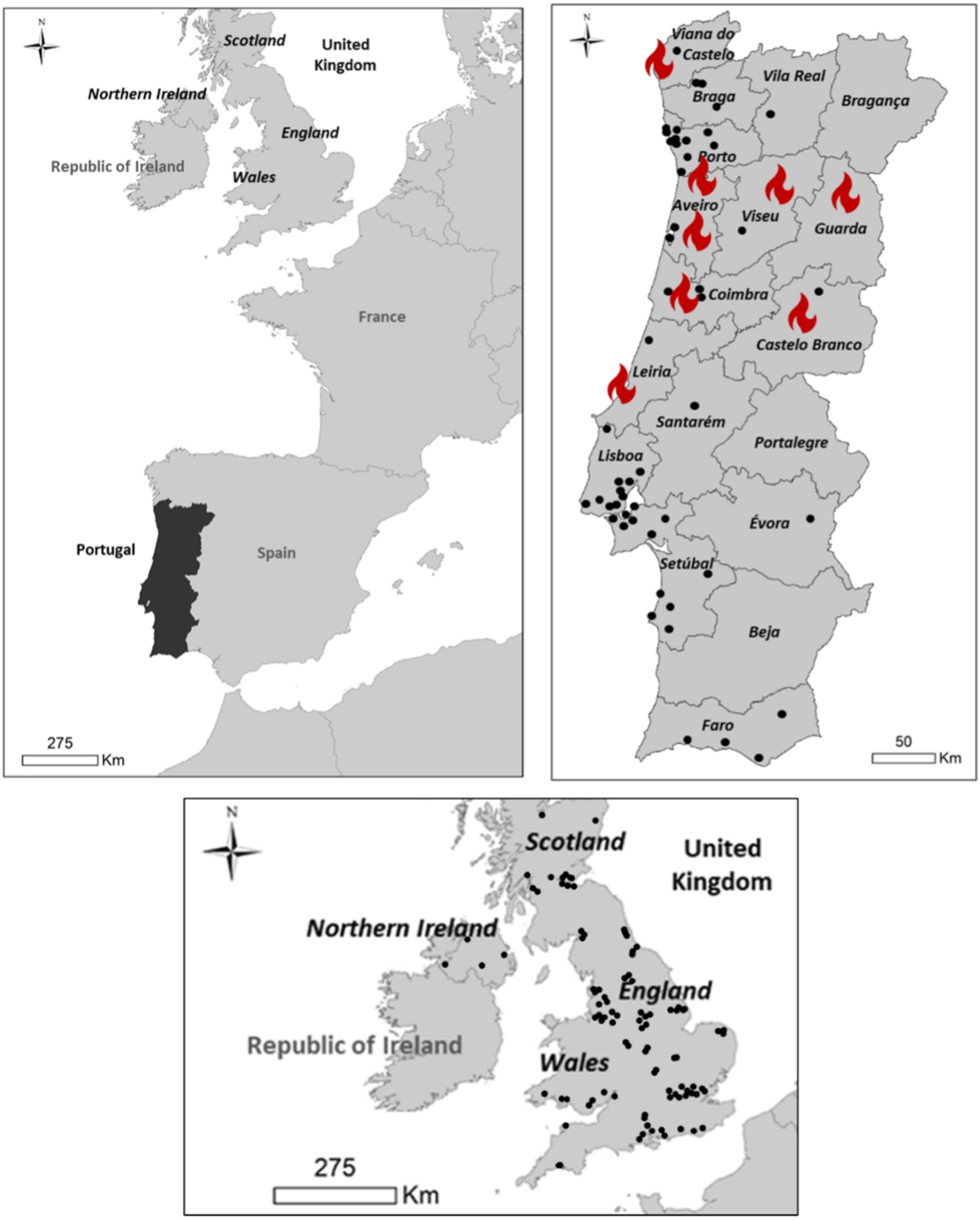

Fig. 1. (Up left) Location of Portugal and the United Kingdom in western Europe. (Up right) Sites of the continuous air quality monitoring stations in each District of Portugal (dark circles) and Districts with most forest fires in October (flame symbol). No stations operate in Bragança, Guarda, Portalegre and Beja Districts. (Bottom) Sites of the continuous air quality monitoring stations in the United Kingdom. .
Adapted from https://uk-air.defra.gov.uk/interactive-map

Department for Environment, Food & Rural Affairs (DEFRA, 2019), licenced under the Open Government Licence (OGL) (https://uk-air.defra.gov.uk/data/).

2.3. Daily exposure increments (PM_{10}-DEI)

It is widely accepted that human exposure to PM_{10} within cities is mainly due to sources other than wildfires and dust, which tend to camouflage wildfire originated PM_{10} (Cesari et al., 2016; Clappier et al., 2017). One of the strategies followed to overcome this constraint is to consider only measurements from urban background monitoring stations. However, in Portugal, this strategy means that data from a high number of stations is left aside. To avoid reducing the number of stations in the study, we assume PM_{10} from wildfires is added to the baseline concentrations measured at each monitoring station, independently of its location. For each station, the PM_{10} baseline concentrations corresponded to the minimum daily average found during the reference days, i.e., days without neither smoke nor dust in October

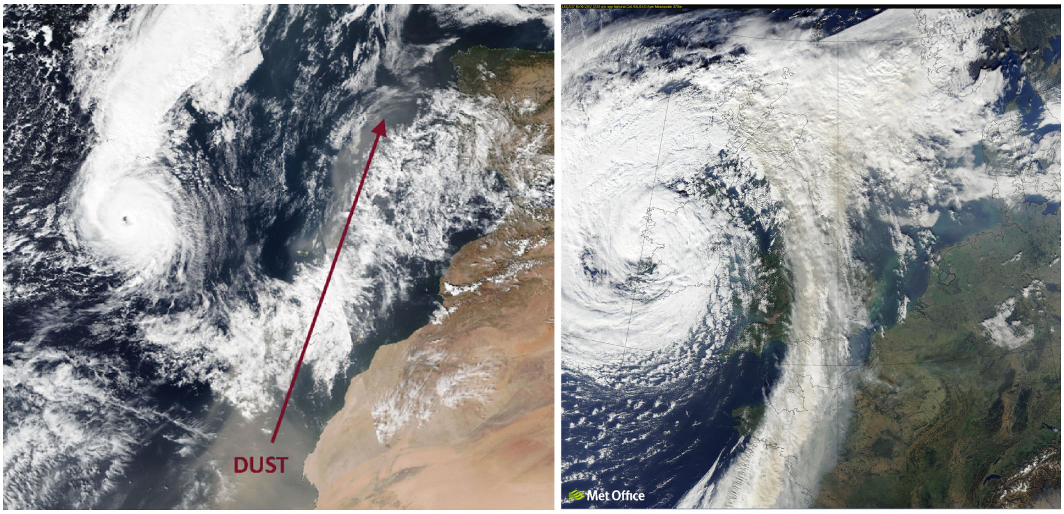

Fig. 2. (Left) Saharan desert dust between 1300 and 1500 utc on 14 October 2017 being transported towards the UK ahead of the Ophelia weather system (adapted from Moore, 2019). (Right) Saharan dust and Portuguese wildfires smoke brought over the UK by Ophelia (RGB-composite images from the VIIRS instrument on the NOAA/NASA Suomi NPP satellite).

2017. Because the reference days were within the same month of the wildfires, it may happen that some PM is still detectable in those days. Using the minimum daily average as a baseline, we are minimizing this influence. Moreover, we considered the reference days within the same season to avoid the influence of seasonal variation.

The baselines were then subtracted to the PM_{10} daily mean concentrations obtained in smoky days (with and without dust) and these values were considered as PM_{10}-DEI (Daily Exposure Increments) in relation to the baseline concentrations. For each District in Portugal and for each smoky day (with and without dust), the average PM_{10}-DEI obtained for all monitoring stations was calculated within that District. Whenever there was only one station in the District, only the PM_{10}-DEI from that station was used. Districts without monitoring stations were removed from the analysis. Regarding the UK, the average PM_{10}-DEI was computed for England, Wales, Scotland and Northern Ireland.

2.4. Health data

Daily death counts due to natural (International Classification of Diseases - ICD-10, codes A00-R99, excluding injuries, poisoning and external causes) and cause-specific mortality (cardiorespiratory, codes I00-I99 for cardiovascular, and J00-J99 for respiratory) were collected for each District of Portugal and all-age residents. Cardiovascular and respiratory deaths were considered together, to minimize the absence of data. Mortality and population data were provided by Statistics Portugal (INE, 2018).

2.5. Associations between PM_{10} and mortality for the Portuguese population

The associations of daily PM_{10} levels measured by ground-level observations, and the type of exposure assessed by satellite (smoky days with dust and dust-free smoky days in relation to reference days), with the same day natural and cardiorespiratory mortalities, were studied during October 2017. The same day mortalities were considered as short-term effects. The effect estimates were obtained for each District in Portugal using Poisson regression models. To investigate potential confounders of the daily levels of other pollutants, we included in the model PM_{10} and alternatively NO_2 (24 h averages), SO_2 (24 h averages) and O_3 (24 h maximum). Only Districts with more than 80% of available data were considered. Daily maximum temperature was further introduced in the model. The district-specific associations were then pooled to generate overall associations between PM_{10} and natural and cardiorespiratory mortalities employing a random-effect meta-analysis with restricted maximum likelihood (REML) estimation. The heterogeneity among models was quantified using I^2 statistics.

The results were expressed as the Relative Risk (RR) of natural or cardiorespiratory mortality with a 95% confidence interval (95% CI). For PM_{10}, results were calculated for an increase of 10 $\mu g/m^3$ to be comparable with previous studies. The RR was then converted into the incremental percentage of mortality per each 10 $\mu g/m^3$ increase in PM_{10} concentration.

Finally, the obtained overall associations were employed to calculate the short-term natural and cardiorespiratory deaths related to PM_{10} in October 2017, using the District-specific PM_{10}-DEI. The daily number of deaths attributable to the PM_{10}-DEI by this method was calculated for all the smoky days with dust (10) and the dust-free smoky days (14) in each District, as well as the sum of PM_{10}-related deaths in all mainland Portugal during October 2017. The baseline mortality was assumed to be the mortality observed during the reference days.

The regression models were performed using IBM SPSS Statistics 25.0 software, and meta-analyses with the open source software OpenMetaAnalyst (Wallace et al. 2012).

3. Results

3.1. Long-range transport over Europe and the United Kingdom

Satellite observations revealed that smoke from the Portuguese wildfires together with Saharan dust was transported northwards by storm Ophelia's strong winds, reaching all western European countries including Spain, France, Belgium, the Netherlands and the UK (Harrison et al., 2018) (Figs. 2 and 3). From these, the UK was the one affected only by the October 2017 Portuguese wildfires' smoke (Osborne et al., 2019; Moore, 2019). The remaining countries were cumulatively impacted by smoke from other country's wildfires, so they were not considered in the ground level observations.

The smoke plume from the Portuguese wildfires covered the UK for seven days, three of which concomitant with Saharan dust (Fig. 4). Daily averages for PM_{10} concentrations peaked (approximately 2-fold the concentrations reported for reference days) on days 16 (smoky-day with dust) and 18 (dust-free smoky-day). The population was exposed on average to an additional PM_{10} level of 11.7 $\mu g/m^3$ during those seven smoky days (three with dust), revealing the impact of the wildfires on distant populations. England and Wales were the regions with the highest exposures (mean PM_{10}-DEI of 15.2 and 17.3 $\mu g/m^3$, respectively) (Table 1).

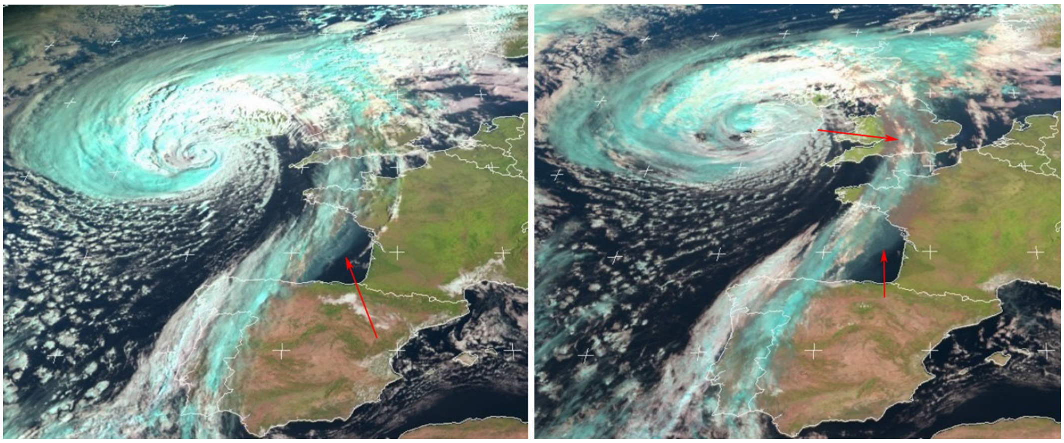

Fig. 3. Meteosat-10′s SEVIRI Natural colour RGB images on 16 October 2017, 09 UTC (left) and 12 UTC (right). Smoke at 09 UTC travelled over the Bay of Biscay and into southwest UK. The 12 UTC image shows the smoke over northwest France and parts of east UK.

3.2. Concentrations of PM_{10} in Portugal

In Portugal, the smoke from the October 2017 wildfires covered the country for 24 days, ten of which concomitant with Saharan dust (Fig. 5). This resulted in abrupt but short-lived concentration increases in PM_{10} during those days. Daily averages for PM_{10} were higher on days 10 (a dust-free smoky-day), 16 (a smoky day with dust) and 28 (a smoky day with dust), reaching mean concentrations of 43.9 ± 17.9 (mean ± standard deviation), 76.8 ± 103.0 and 40.3 ± 18.9 $\mu g/m^3$, respectively (2- to 5-fold the concentrations detected on reference days). From these, the peak on day 10 was concurrent with a peak in CO concentration, confirming the wildfire origin of PM_{10} (van Donkelaar et al., 2011; Wang et al., 2010; Zeng et al., 2008). The other two major PM_{10} episodes were also simultaneous with peaks in CO, but to a lesser extent, suggesting a high contribution of PM originated from Saharan dust.

The mean values displayed in Fig. 5 are for the entire country, so there is a high variability in the levels of PM, depending on the proximity of the air quality monitoring stations to the wildfires, especially on day 16. For example, in the District of Leiria (with one of the highest incidences of ignitions, see Fig. 1), PM_{10} concentrations were as high as 708.5 $\mu g/m^3$ on day 16, while in areas distant from the fires the concentrations were lower. In the capital Lisbon (100 km to the south –upwind- of the nearest wildfires), the levels of PM_{10} exceeded by more than 10 $\mu g/m^3$ the background levels in 18 of the 24 smoke-affected days. And in 5 of those days the daily health safety thresholds defined by WHO were surpassed. Lisbon had a population of over 2,250,000 inhabitants in 2017 (INE, 2018), which means a large number of people was exposed to these high levels of PM. Nevertheless, Fig. 5 illustrates a general increase on PM_{10} levels not only in Lisbon, but also across the country on smoky days when compared with reference days.

3.3. Daily exposure increments (PM_{10}-DEI)

The exposure of the Portuguese population to PM_{10} was estimated for each of the 14 Districts with available PM data, during smoky days with dust, dust-free smoky days and both (Table 2). As the entire country was affected by the wildfires smoke, all 14 Districts were considered. For each of them, the DEI were obtained by deducting the minimum daily mean concentration of PM_{10} reported for the reference days. Fig. 6 displays the mean DEI for PM_{10} during the 24 smoky days (with and without dust) in October 2017. The highest exposures were found for the District of Leiria with PM_{10}-DEI of 59.8 $\mu g/m^3$, peaking on smoky days with dust (120.6 $\mu g/m^3$), mainly due to the PM value reported for day 16 (Fig. 5). Most of the surrounding Districts also displayed high exposures, with PM_{10}-DEI between 21 and 30 $\mu g/m^3$. PM_{10}-DEI was never below 10 $\mu g/m^3$ in the targeted Districts (see Fig. 6).

Daily exposure increments were also calculated separately for smoky days with dust and dust-free smoky days (Table 2), however it becomes difficult to disentangle the contribution of PM_{10} from dust and from smoke, as there were no smoke-free dusty days. Additionally, the most severe and intense wildfires occurred in the period between

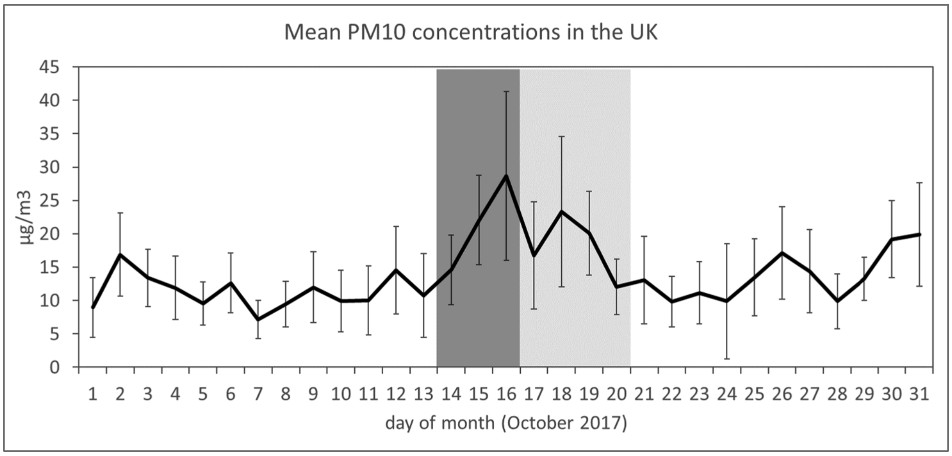

Fig. 4. Mean daily PM_{10} concentrations with respective standard deviations in October 2017 from 65 air quality monitoring stations in the United Kingdom (England, Wales, Scotland and Northern Ireland). Gray bars correspond to wildfire smoke days without dust (light gray) and to wildfire smoke days with dust (dark gray).

Table 1
Additional population exposure to PM_{10} (PM_{10}-DEI) for the United Kingdom as estimated from air quality monitoring data.

		Daily exposure increments Day of month (October 2017)							Mean		
	United Kingdom	14	15	16	17	18	19	20	Smoky days with dust	Smoky days dust-free	Smoky days Total
1	England	7.9	18.8	24.8	12.7	20.8	16.1	5.7	17.0	13.8	15.2
2	Scotland	10.6	7.5	7.6	1.9	5.8	12.6	6.9	8.6	6.8	7.5
3	Wales	15.6	19.9	40.6	15.5	12.5	8.9	8.6	25.3	11.3	17.3
4	Northern Ireland	8.6	5.7	8.2	3.3	8.4	5.5	6.5	7.5	5.9	6.6

October 12th and 17th, which was concurrent with Saharan dust outbreaks.

3.4. Mortality overview

In Portugal, total daily mortality by all except external causes (accidents and poisoning) peaked on several occasions during October 2017 (Fig. 5, bottom). From a total of 7807 deaths, the highest incidence was reported on day 3 (day without smoke or dust, a reference day) with 298 deaths, immediately after a peak on the daily maximum temperature (Fig. 5, middle). The second highest peak was seen on day 16 with 288 deaths, which coincides with the highest peak on PM_{10} concentration (Fig. 5, top and bottom). Other natural mortality peaks were reported on days 12, 18, 20 and 27. Cardiorespiratory deaths in October 2017 totalled 3152 and peaked on day 16 (136 deaths), followed by days 20 and 3 (126 and 122, respectively). These figures contrast with the smaller number of deaths in the previous month, September 2017, which totalized 7017 natural and 2715 cardiorespiratory deaths (data not shown). Mortalities in November 2017, after the sequence of wildfire episodes, totalized 8134 natural and 3388 cardiorespiratory deaths.

3.5. Associations between PM_{10} and mortality

Poisson regressions performed to estimate the number of natural and cardiorespiratory deaths, based on the exposure to PM_{10} and the type of exposure (to smoke with and without dust in relation to non-smoky days) are displayed in Table 3. The results of the pooled estimates reveal that PM_{10} had a significant effect on the same day natural and cardiorespiratory mortalities. For every additional 10 $\mu g/m^3$ of PM_{10}, there was a RR of 1.009 (95% CI, 1.000 to 1.018), which corresponds to a 0.89% increase in the number of natural deaths, a statistically significant result, $\rho = 0.047$. Regarding cardiorespiratory deaths, for an additional 10 $\mu g/m^3$ of PM_{10}, there was a RR of 1.024 (95% CI, 1.010 to 1.038), which corresponds to a 2.34% increase in the number of deaths, also statistically significant, $\rho = 0,001$ (Table 3). Although not significant, there was an indication of a slightly higher effect of exposure in dust-free smoky days than in smoky days with dust (Table 3).

These results were partially confounded by other pollutants, as evidenced by the two-pollutant models (Table 4). The association between PM_{10} and both natural and cardiorespiratory mortality was slightly affected after controlling for NO_2, SO_2 and O_3. In most cases, the effect estimates remained positive, though losing statistical significance, except for deaths due to cardiorespiratory causes after controlling for O_3 in which the association kept its significance.

3.6. Number of deaths attributable to PM_{10} from the wildfires of October 2017

The number of deaths attributable to PM_{10} during the wildfires of October 2017 was found to be 100 due to natural causes and 38 due to cardiorespiratory afflictions (SM1 and SM2). The number of deaths in each District is a combination of the population size and the exposure level (PM_{10}-DEI) listed in Table 2. Regarding natural deaths, the highest contribution (26 cases) was from the District of Lisbon, the most populated area of the country, followed by the District of Leiria (17 cases), where the exposure was highest (Fig. 7). These two Districts were also the ones where the number of cardiorespiratory deaths prevailed, with 10 cases each (SM2).

4. Discussion

The results of this study reveal that the concentrations of PM_{10} increased during the Portuguese wildfires of October 2017 all over the country, reaching extremely high levels in Districts more closely impacted by the wildfires. Not only Portugal was affected by smoke and dust, but also northern European countries, such as the UK, as confirmed by both space-level observations and ground-level measurements of PM_{10}. Although the increase on PM concentrations was not extreme, it unveils a future risk that wildfires in Mediterranean countries may contribute to considerable increments of PM concentrations in northern European countries, which could result on health effects (including death), especially in susceptible populations (Reid et al., 2016).

Despite the short duration of the wildfires, which produced a limited amount of data to be statistically analysed, natural and cardiorespiratory mortalities were found to be associated with PM_{10}, being the effect of PM_{10} slightly stronger on dust-free smoky days than on smoky days with dust. The reason could be related to the chemical composition of PM. Whereas in dust-free smoky days, PM is mainly wildfire-originated, in smoky days with dust a considerable amount of PM is wind-blown desert mineral particles (Saharan dust) (EEA, 2012). The health effects of wildfires are probably due to PM (fine and ultrafine) but may also be due to other combustion-related pollutants such as inorganic gases and VOCs, and to temperature increases generated by nearby fires (Naeher et al., 2007; Yao, 2014; Rovira et al., 2018; Nadal et al., 2016). For instance, NOx emissions by wildfires enhance the secondary formation of tropospheric ozone which in turn can strongly affect human health (Martins et al., 2012: Reid et al., 2019).

Some experimental and toxicological studies have reported that particles from wood fires have higher toxicity than particles from other sources, including non-combustion causes such as dust (Pope et al., 1999; Schwartz et al., 1999; Naeher et al., 2007; Henderson et al., 2011). These toxicological studies usually focus on lung damage and have consistently reported tracheobronchial cell injuries, changes in the immune cell morphology of the lungs and diminishing ventilator responses (Naeher et al., 2007). However, epidemiological studies have reported conflicting effects of particles on cause-specific mortality on smoky days (Analitis et al., 2012; Johnston et al., 2011; Hänninen et al., 2009; Sastry, 2002; Morgan et al., 2010) or very similar effects of PM_{10} on smoke-affected and smoke-free days (Dennekamp and Abramson, 2011; Morgan et al., 2010). This may be due to different wildfire-generated pollutants, including PM, for which the concentration and chemical profile depend on each wildfire. Notably, on the fuel loading and type of fuel (*e.g.* the combustion of eucalyptus and pine produces smoke that is more toxic than from other species) (Kim et al., 2018), and on the burning conditions, which could favour the production of incomplete combustion products (*e.g.* temperature, slow vs. fast

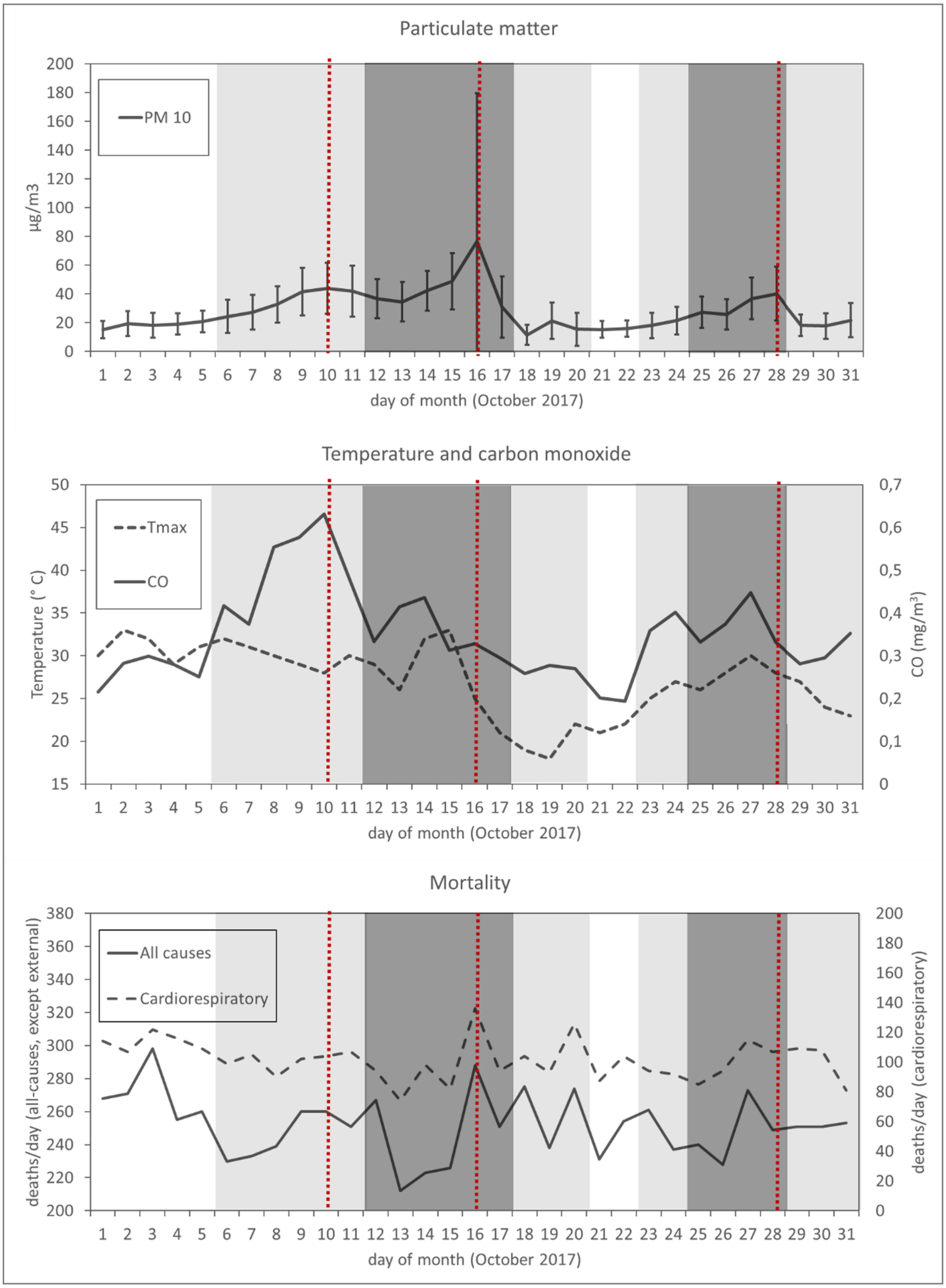

Fig. 5. October 2017 air pollution, metereology and daily deaths in Portugal. (Top) Mean daily concentrations of PM_{10} from 52 air quality monitoring stations. Main peaks of PM are represented by red vertical lines. (Middle) Daily maximum hourly temperature (°C) and 24-h average carbon monoxide (CO) concentrations. (Bottom) Daily total natural mortality (by all except external causes - accidents and poisoning) and by cardiorespiratory causes, showing peaks in mortality. Gray bars correspond to wildfire smoke days without dust (light gray) and to wildfire smoke days with dust (dark gray). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

burning, etc.) (Wentworth et al., 2018). Other reasons for different findings across studies may be: (i) the magnitude and duration of the exposure to PM from a given fire; (ii) the underlying health status of the population; and (iii) the size of the population.

Cause-effect relationships between wildfire-originated pollutants (including PM) and health outcomes are always difficult to establish. Wildfires are usually related to temperature increases, which is a well-known factor contributing to premature mortality. High temperatures have been reported to enhance the effects of PM on mortality, especially in cardiac patients, already more susceptible than other patients (Qian et al., 2008). In our study, one of the peaks of natural mortality that occurred in a day with neither smoke nor dust, could have been related to the effect of temperature alone as it followed a peak of maximum temperatures.

Table 2
Additional population exposure to PM_{10} (PM_{10}-DEI) for each District in Portugal as estimated from air quality monitoring data.

		Daily exposure increments (μg/m³) Day of month (October 2017)																								Mean		
	Districts	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	23	24	25	26	27	28	29	30	31	Smoky days with dust	Smoky days dust-free	Smoky days Total
1	Aveiro	13.8	15.7	39.9	42.9	35.8	26.2	26.1	23.9	32.9	56.4	57.7	26.5	4.9	13.2	3.0	8.4	13.1	19.3	18.3	34.9	21.0	5.5	4.7	6.4	31.7	16.7	22.9
2	Braga	20.6	16.4	17.7	12.9	17.3	17.2	11.2	14.4	22.1	17.8	25.6	21.3	3.6	1.6	3.3	2.1	7.1	14.0	10.8	12.9	12.2	5.1	3.2	2.4	16.2	9.3	12.2
3	Castelo Branco	51.6	30.0	14.7	57.5	54.5	38.9	26.8	21.3	26.9	33.2	4.8	6.8	0.0	ND	ND	0.0	0.0	0.0	15.2	40.9	26.5	4.3	0.0	0.0	20.2	20.9	20.6
4	Coimbra	14.0	14.5	10.5	31.8	41.1	26.2	5.4	2.1	35.2	26.9	55.7	18.7	0.0	17.4	1.9	6.6	2.2	4.5	12.3	27.6	19.1	1.5	0.0	2.0	20.7	12.1	15.7
5	Évora	2.4	14.1	21.0	18.9	27.5	30.2	33.3	23.6	37.7	41.0	41.8	82.3	4.3	15.3	25.8	0.0	5.7	8.9	12.0	11.5	34.6	6.8	3.8	15.7	32.6	13.7	21.6
6	Faro	7.9	15.0	10.3	16.3	17.7	15.6	29.1	20.0	24.7	21.1	42.8	10.9	1.9	8.3	22.7	4.4	9.9	14.4	7.6	8.5	20.1	9.3	14.4	18.0	19.9	12.3	15.4
7	Leiria	3.5	11.5	21.1	19.4	21.6	14.9	42.6	39.8	26.4	82.3	696.8	101.5	25.0	18.6	0.0	12.3	22.2	23.0	27.3	45.2	ND	ND	ND	0.7	120.6	14.2	59.8
8	Lisboa	14.2	12.5	25.6	36.4	43.3	46.3	29.3	27.5	36.2	40.8	49.5	9.1	0.7	8.9	2.4	11.8	14.8	21.3	20.3	31.1	43.5	5.4	8.4	15.0	30.9	17.6	23.1
9	Porto	12.7	12.9	20.5	23.0	24.5	17.0	18.7	18.9	22.1	24.7	44.2	12.2	0.3	5.2	2.1	2.7	4.9	10.6	10.0	16.7	11.9	3.4	1.4	2.1	19.0	9.5	13.4
10	Santarém	14.1	35.4	15.7	43.6	46.4	39.3	27.2	10.3	24.2	35.4	70.5	53.8	0.0	0.0	0.0	0.4	0.5	8.6	7.7	34.8	28.7	2.4	0.0	5.8	30.1	14.5	21.0
11	Setúbal	16.5	26.4	25.6	33.1	34.3	37.0	31.1	25.6	35.5	42.1	61.8	20.3	2.5	14.6	5.4	8.0	10.5	18.3	13.7	28.3	41.4	12.9	10.2	18.2	31.8	18.2	23.9
12	Vila Real	5.8	2.9	3.8	21.6	15.5	18.5	14.6	29.4	34.8	ND	ND	ND	1.8	2.6	0.0	1.8	3.8	4.4	9.2	40.3	22.3	4.4	2.7	0.0	22.1	6.1	11.4
13	Viseu	0.1	0.0	4.3	36.9	33.6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	15.0	ND

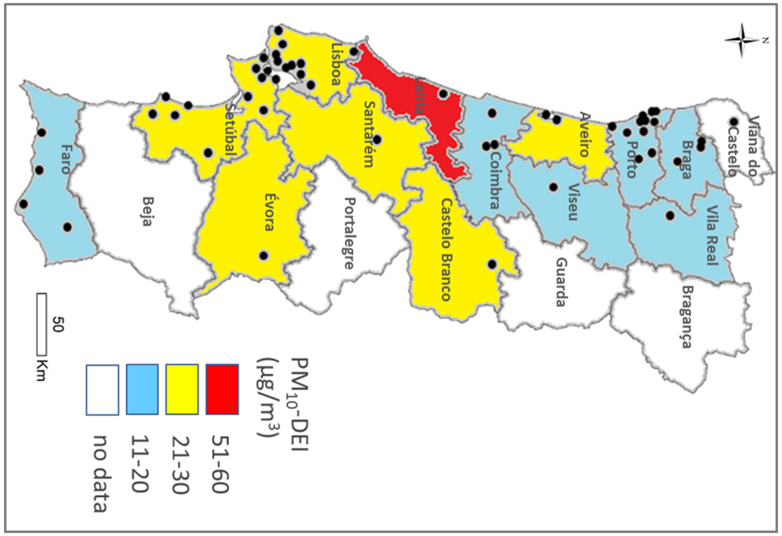

Fig. 6. Additional population exposure to PM_{10} (mean Daily Exposure Increments – DEI) during the 24 smoky days (with dust and dust-free) in October 2017 as estimated from the air quality monitoring data. Additional information in Table 2.

Another reason for the strongest effect of PM_{10} on dust-free smoky days, compared to smoky days with dust, could derive from a clearer perception of the exposed populations towards dust-PM, since these particles, usually larger than those originated by wildfires, have a strong impact on atmospheric visibility, causing visual discomfort. Additionally, in October 2017 the dust was blown by Ophelia's strong winds, which may have contributed to an enhanced awareness and consequent display of protection measures adopted by the affected populations. However, this trend was not significant in the regression analysis.

In general, the effects of PM_{10} on mortality seemed to be slightly confounded by NO_2 and SO_2 levels during October 2017 (suggesting an effect from urban and industrial emission sources), but not by O_3. But even taking that into consideration, the increase in natural and cardiorespiratory mortalities associated with PM_{10} found in this study (0.89% and 2.34% per 10 μg/m³ of PM_{10}, respectively) is consistent with the estimates reported by Faustini et al. (2015). The fact that natural mortality is less affected by PM_{10} than cause-specific mortality was also previously reported (Analitis et al., 2012; van Donkelaar et al., 2011; Johnston et al., 2011; Johnston et al., 2012; Faustini et al., 2015). In the study of Faustini et al. (2015), which aimed to analyse the effects of wildfires and PM on mortality in 10 southern European cities, the authors found that the effects of PM_{10} on smoky days were higher than on smoke-free days, accounting for 1.10% of the natural mortality, 3.42% of the cardiovascular mortality and 3.90% of the respiratory mortality. The current study differs from this one in a few key aspects. First, the analysis covered only a short-term period (one month), while Faustini et al. (2015) spanned over an 8-year interval, which potentially enhances the robustness of the dataset. Second, PM_{10} and mortality data was considered for most Districts in the entire country (except those without available data), while Faustini et al. (2015) focused exclusively in cities, which likely makes it more difficult to disclose the

Table 3

Pooled estimates (from random meta-analysis) of the effects of PM_{10} ($10\ \mu g/m^3$) and type of exposure (dust-free smoky days and smoky days with dust) on short-term natural and cause-specific mortality (cardiorespiratory) in Portugal in October 2017. Significant results for $\rho < 0.05$ are in bold. RR: relative risk; p-het: p value of the heterogeneity test. Number of Districts included in the analysis: 11 for natural mortality and 9 for cardiorespiratory mortality.

	Deaths attributed to:											
	Natural causes						Cardiorespiratory causes					
	RR	95% CI		ρ	I^2(%)	p-het	RR	95% CI		ρ	I^2(%)	p-het
PM_{10}	**1.009**	**1.000**	**1.018**	**0.047**	0.397	0.162	**1.024**	**1.010**	**1.038**	**0.001**	0.077	0.341
Type of exposure												
Smoky days with dust	0.902	0.784	1.039	0.154	47.717	0.043	0.938	0.790	1.113	0.461	0.000	0.665
Dust-free smoky days	0.967	0.888	1.053	0.443	19.438	0.296	0.941	0.803	1.103	0.453	24.621	0.185

contribution of wildfires to PM increases. Fixed air quality monitoring stations located in large cities monitor pollutants from anthropogenic sources, such as road traffic, domestic heating, shipping, industries or power generation. Therefore, routine air monitoring may fail to unveil the atmospheric pollution attributable to forest fires (Analitis et al., 2012; Faustini et al., 2015). Moreover, the October 2017 wildfires produced smoke and PM that covered the whole country, affecting both urban and rural environments.

One of the limitations of our study is the lack of spatial representativeness in some Districts. Most of the air quality monitoring stations in Portugal is located within or nearby large cities; and industrial complexes along the coast and inland Districts are less represented in terms of PM data. We also assumed that the population of each District was exposed to PM_{10} concentrations measured by the stations located in that District, which carries a degree of uncertainty. Another limitation is the short time frame of the study (one month), which may reduce the robustness in the application of the regression models. The number of deaths registered during October 2017 was higher than in September 2017, but it was smaller than in November 2017. If October 2017 may be compared with September in terms of temperature and wildfire pattern; it cannot be compared with November when the temperature dropped, and the flu season started. Finally, the absence of smoke-free dusty days made it difficult to accurately disentangle the contribution of PM10 from dust and from smoke. But even if the interpretation of the results has to observe the caution advised by these considerations, the study of extreme acute events like the October 2017 wildfires in Portugal is of the utmost importance and has to be done with the available data, in order to find ways to mitigate their effects, particularly under the current scenario of changing climate.

The estimated number of deaths (100 of natural and 38 of cardiorespiratory causes) obtained in this study assumed increases in the daily natural and cardiorespiratory mortalities of 0.89% and 2.34%, respectively, per $10\ \mu g/m^3$ increment of PM_{10}, as obtained in the regression analysis. The Portuguese wildfires in October 2017 were dramatic, carrying a feeling of insecurity among the whole population, which may have caused an effect on susceptible patients with pre-existent cardiac diseases. The chemical composition of the Portuguese wildfire-generated PM might have had higher toxicity than other wildfires. And finally, the extremely high concentrations of PM could have had an influence on the number of deaths.

5. Conclusions

With climate change the number of months with record-breaking high temperatures tends to rise, which points towards an increase of uncontrolled wildfires. In fact, the fire alert season in Portugal usually covers the months of July to September. So, the episodes of October (the most violent and extended of 2017 in the country) happened with the fire combat display already reduced. This month was characterized by high temperatures and strong winds from storm Ophelia, which contributed synergistically to the high intensity of the wildfires and the long-range transport of smoke from fires and dust from North Africa. In this period, for every additional $10\ \mu g/m^3$ of PM_{10}, there was an increase of 0.89% in the number of natural deaths and of 2.34% in cardiorespiratory-related deaths. And as seen by the PM levels in the UK, the effects can be transported to distant places and provoke unforeseen disruptions in tackling them, especially in countries where wildfires are not (yet) a significant issue. A joint European action is needed to establish inter-country prevention strategies, hand in hand with the continuation of studies assessing the risks of these extreme events, likely to be enhanced under the current climate change projected scenarios.

CRediT authorship contribution statement

Sofia Augusto: Conceptualization, Investigation, Methodology, Writing - original draft. **Nuno Ratola:** Conceptualization, Investigation, Methodology, Writing - review & editing. **Patricia Tarín-Carrasco:** Conceptualization, Investigation, Writing - review & editing. **Pedro**

Table 4

Pooled estimates (from random meta-analysis) of the effects of PM_{10} ($10\ \mu g/m^3$) on short-term natural and cause-specific mortality (cardiorespiratory) in Portugal in October 2017. Results from two-pollutant models. Significant results for $\rho < 0.05$ are in bold. RR: relative risk; p-het: p value of the heterogeneity test. Number of Districts included in the analysis for natural mortality: 11 for PM_{10}, 6 for SO_2, 10 for O_3; number of Districts included in the analysis for cardiorespiratory mortality: 9 for PM_{10}, 8 for NO_2, 6 for SO_2 and 8 for O_3.

	Deaths attributed to:											
	Natural causes						Cardiorespiratory causes					
	RR	95% CI		ρ	I^2 (%)	p-het	RR	95% CI		ρ	I^2 (%)	p-het
No other pollutant	**1.009**	**1.000**	**1.018**	**0.047**	0.397	0.162	**1.024**	**1.010**	**1.038**	**0.001**	0.077	0.341
NO_2	1.016	0.983	1.049	0.347	18.891	0.213	1.036	0.973	1.103	0.267	30.418	0.106
SO_2	1.027	0.990	1.066	0.159	27.210	0.203	1.013	0.961	1.068	0.626	0.080	0.467
O_3	1.009	0.996	1.022	0.195	3.145	0.178	**1.023**	**1.009**	**1.038**	**0.002**	0.000	0.895

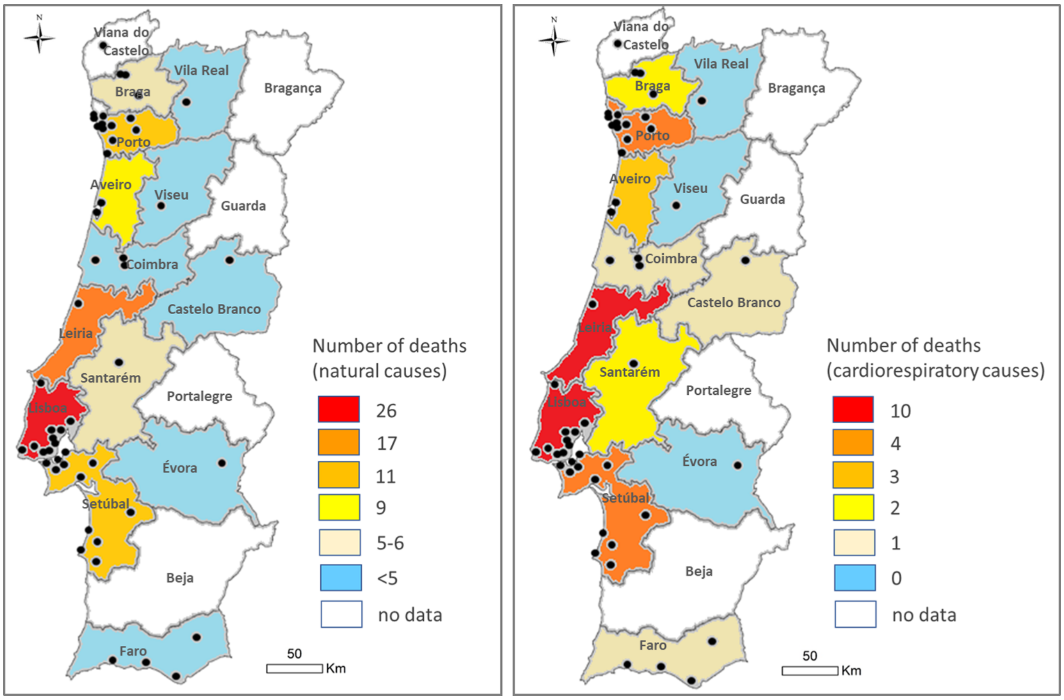

Fig. 7. (Left) Number of natural deaths attributable to PM_{10} from the wildfires of October 2017 in Portugal; additional information in SM1. (Right) Number of cardiorespiratory deaths attributable to PM_{10} from the wildfires of October 2017 in Portugal; additional information in SM2.

Jiménez-Guerrero: Conceptualization, Investigation, Writing - review & editing. **Marco Turco:** Conceptualization, Investigation, Writing - review & editing. **Marta Schuhmacher:** Investigation, Writing - review & editing. **Solange Costa:** Investigation, Writing - review & editing. **J.P. Teixeira:** Investigation, Writing - review & editing. **Carla Costa:** Investigation, Writing - review & editing.

Declaration of Competing Interest

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

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2020.106056.

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