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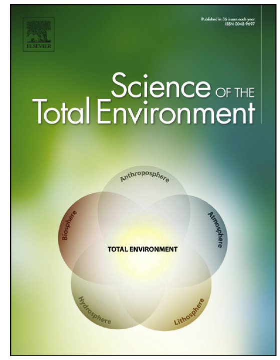

Drought effects on specific-cause mortality in Lisbon from 1983 to 2016: Risks assessment by gender and age groups

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DROUGHT EFFECTS ON SPECIFIC-CAUSE MORTALITY IN LISBON FROM 1983 TO 2016: RISKS ASSESSMENT BY GENDER AND AGE GROUPS

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ABSTRACT

Portugal (Southwestern Europe) experiences a high incidence of dry hazards such as drought, a phenomenon that entails a notable burden of morbidity and mortality worldwide. For the first time in the Lisbon district, a time-series study was conducted to evaluate the impact of drought measured by the Standardised Precipitation Index (SPI) and Standardised Precipitation-Evapotranspiration Index (SPEI) on the daily natural, circulatory, and respiratory mortality from 1983 to 2016. An assessment by gender and adult age population groups (45–64, 65–74, ≥75 years old) was included. To estimate the relative risks and attributable risks, generalised linear models with a Poisson link were used. Additionally, the influence of heatwaves and atmospheric pollution for the period from 2007 to 2016 (available period for pollution data) was considered. The main findings indicate statistically significant associations between drought conditions and all analysed causes of mortality. Moreover, SPEI shows an improved capability to reflect the different risks. People in the 45–64 year- old group did not indicate any significant influence in any of the cases, whereas the oldest groups had the highest risk. The drought effects on mortality among the population varied across the different study periods, and in general, the men population was affected more than the women population (except for the SPEI and circulatory mortality during the long study period). The short-term influence of droughts on mortality could be explained primarily by the effect of heatwaves and pollution; however, when both gender and age were considered in the Poisson models, the effect of drought also remained statistically significant when all climatic phenomena were included for specific groups of the total population and men.

This type of study facilitates a better understanding of the population at risk and allows the development of more effective measures to mitigate the drought effects on the population.

Keywords: Drought; Lisbon; Daily specific-cause mortality; Age group; Gender assessment

1. INTRODUCTION

In the Iberian Peninsula, drought is a common hydroclimatic extreme (Lorenzo-Lacruz et al., 2013; Coll et al., 2017; Vicente-Serrano et al., 2017) that has become more severe in recent decades (Vicente-Serrano et al., 2014; Andrade and Belo-Pereira, 2015; Spinoni et al., 2017) and drought events will likely continue to increase in both frequency and severity with climate change (Mishra and Singh, 2010; Boersma et al., 2017; Guerreiro et al., 2018; Spinoni et al., 2018; Spinoni et al., 2020; Wootzel et al., 2020). This phenomenon impacts the environmental, economic, ecological, and social sectors at both global and regional scale (Wilhite and Vanyarkho, 2000; Quiring, 2015) through negative effects on the quality, structure, and diversity of systems such as soil, air, vegetation, and water (Vicente-Serrano et al., 2020). Droughts also negatively impact public health, being responsible for a notable burden of morbidity and mortality (Yusa et al., 2015; Alpino et al., 2016; Watts et al.,2017; Salvador et al., 2020a). In this context, it has been suggested that different groups among exposed populations worldwide show different vulnerabilities to extreme climatic events. Rural agriculture workers, children, older people, women (particularly those who are pregnant), and people with low economic status or chronic diseases are considered the most susceptible (Alpino et al., 2016; Ebi and Bowen, 2016; Salvador et al., 2020a). However, it should be noted that there is regional variability in the relationship between gender, age, and vulnerability. Several studies have indicated that women had a greater risk of mortality associated with natural disasters than men and others showed that men were more affected in different regions (IPCC, 2014). The impacts of extreme climatic events and other environmental hazards are largely influenced by factors such as the exposure doses, sensitivity, and ability to respond when the extreme event strikes. Children (with higher breathing rates in relation to their body size) and people who spend more time outdoors or exercising outside (and thus breathing more deeply) are more exposed than (other) adults, and have an increased risk of health impacts attributable to the climate (Balbus and Malina, 2009; IPCC, 2014; EPA, 2016).

Droughts incorporate, or reflect, the effects of other extreme climatic events related to them. Drought periods are frequently linked to the incidence of stable weather systems such as surface high-pressure systems, and prolonged blocking, and stagnant conditions (García-Herrera et al., 2019; Haile et al., 2020¸ Vicente-Serrano et al., 2020), situations that can lead to reduction of air quality (e.g. Pope et al., 2014; Russo et al., 2014; Ordoñez et al., 2017). Extended periods of high atmospheric pressure trap temperature inversion layers that, when located above urban regions, concentrate and accumulate gas emissions (e.g. pollution from road traffic, heating or industry) (EEA, 2019). Atmospheric blocking can largely contribute to temperature anomalies increasing severe heat events in late spring and summer and cold in winter and early spring (Brunner et al., 2017; Woollings et al., 2018; Ormanova et al., 2020). In this context, droughts and high temperatures frequently promote the occurrence of wildfires (He et al., 2014; IPCC, 2014; Franchini and Mannucci, 2015; Sutanto et al., 2020), allowing higher suspended materials in the atmosphere (IPCC, 2014; Bell et al., 2018), and all these phenomena cause damaging effects on health (Finlay et al., 2012; Gasparrini et al., 2015a; 2015b;-Black et al., 2017; Huber et al., 2020¸ Machado Silva et al., 2020). These concatenated effects can lead to feedbacks and accelerate the development of the drought (Miralles et al., 2019; Zscheischler and Fischer, 2020), thereby increasing its severity or involving greater risks to human health when they are concurrent or cascading (Stanke et al., 2013; Bell et al., 2018; AghaKouchak et al., 2020). However, the mechanisms between all these phenomena are complex, and they can occur even without the presence of a drought. Nevertheless, drought could result in significant effects on health, including mortality through different environmental mechanisms associated with it, such as extreme temperatures or atmospheric pollution, among others as extreme cold events.

Although the majority of drought related fatalities occur in developing countries, wealthy countries can also indirectly suffer the negative health effects of droughts associated with heat stress, extreme cold events, atmospheric pollution, and economic impact, including cardiorespiratory diseases and mortality (UNDRR, 2019; Salvador et al., 2020a). However, the estimation of their consequences is difficult owing to the complexity in the quantification of drought severity, the determination of the beginning and end of the events, and because their effects are principally diffuse, indirect, and cumulative (Stanke et al., 2013; Salvador et al., 2020a; Sutanto et al., 2020; Vicente-Serrano et al., 2020). Moreover, different types of droughts can be distinguished (Marcos Valiente, 2001; Kallis, 2008; Mishra and Singh, 2010), which can affect human health differently.

Drought indices are crucial tools for monitoring and characterising this climatic extreme (Quiring, 2009) and quantifying the different impacts (Vicente-Serrano et al., 2012; Bachmair, 2016; Vicente-Serrano et al., 2017; Parsons et al., 2019). Thus, studies that are focused on the assessment of the capacity of different drought indices to quantify health effects, and the determination of which of these are the best proxies to reflect the occurrence of specific impacts on public health are needed (Salvador et al., 2020a). In Europe, and in particular in the Iberian Peninsula, only three recent studies conducted in Spain have attempted to evaluate the performance ability of two meteorological drought indices (the Standardised Precipitation Index (SPI) and Standardised Precipitation Evapotranspiration Index (SPEI)) to identify and quantify the impact on daily natural, circulatory, and respiratory mortality (Salvador et al., 2019; Salvador et al., 2020b; Salvador et al., 2020c). The main findings of these studies suggested small differences in the comparative performance of the SPI and SPEI; however, additional studies are required to obtain conclusive results worldwide. Specific differences were observed in terms of geographical distribution and higher risks of mortality, western Spain (northwest to southwest) being the most affected region. Moreover, in the particular analysis over NW Spain (Salvador et al., 2019), the mortality risk increased more strongly in the inland areas and was manifested primarily when droughts were measured by shorter accumulation periods.

On the other hand, another recent study conducted in the Western USA indicated an association between drought severity and the increase of mortality risk in older people in the period from 2000 to 2013, and suggested that in countries that previously suffered a fewer number of drought events, the population had a greater risk of cardiovascular diseases and mortality. However, that study surprisingly indicated a reduction of respiratory hospital admissions associated with drought periods (Berman et al., 2017). Conversely, the recent studies of Salvador et al. (2020b,c) evidenced the highest risk of drought events on daily respiratory-caused mortality compared to natural and circulatory mortality in peninsular Spain. Other studies have also indicated negative respiratory repercussions associated with drought conditions (Smith et al., 2014; Yusa et al., 2015; Alpino et al., 2016).

Portugal is a western region of the Iberian Peninsula prone to drought (Pires et al., 2010). The country suffers from a high exposure to intense heatwaves; these are frequently the main factors contributing to a higher risk of wildfires (Parente et al., 2018), which are associated with the exacerbation of cardiovascular and respiratory diseases and premature mortality from wildfire smoke (Franchini and Mannucci, 2015; Black et al., 2017, Machado-Silva et al., 2020). Extreme heat has caused notable effects on mortality in this country.

For instance, during the 2003 European heatwave, there was an estimated increase of 58% of the expected death, being older adults, and particularly women, the most affected groups (Trigo et al., 2009). Moreover, the occurrence of extreme cold temperatures has also been linked to significant impacts on mortality from circulatory and respiratory conditions in Portugal, particularly in Lisbon (Antunes et al., 2017). In fact, it is a European country with a very high rate of excess winter mortality (approximately 28%) (Healy, 2003).

In Portugal, the impact of drought on health remains unexplored. This study suggests the first detailed evidence of the link among drought phenomena measured over shorter time scales and specific-cause mortality in the district of Lisbon, considering an assessment by gender and age groups of the population. This can be helpful to obtain specific information on the structure of the population at risk and determinate the most vulnerable groups. Subsequently, the control of the short-term effects on daily mortality of the two a priori most influent mechanisms on health linked to drought were also included: heatwaves and atmospheric pollution.

2. MATERIAL AND METHODS

2.1. REGION OF STUDY: DISTRICT OF LISBON, PORTUGAL

Continental Portugal is located in the western part of the Iberian Peninsula. In this territory there is a marked variability in the spatial distribution of mean annual precipitation between the north (rainier regions) and south (dryer regions), and between the inland and coastal areas (Trigo and DaCamara, 2000; Santos et al., 2011). The weather conditions in Portugal are strongly influenced by both the position and magnitude of the Azores anticyclone, the effect of the Atlantic Ocean, and the influence of the Mediterranean Sea and North Africa (Parente et al., 2018). Among the eighteen districts that form continental Portugal, the Lisbon district (central Portugal) is the region of this study (38.72 latitude, -9.14 longitude, with approximately 2 million residents). This area was strategically chosen because it includes the homonymous capital city of the country, which is the largest urban area in Portugal, with the highest number of resident population (over 509, 515) and a population density of 5,092.4 per km^2 (National Statistical Institute/Instituto Nacional de Estatística, INE, 2020). It frequently experiences high temperatures owing to the urban heat island and strong exposure to pollution, which cause negative effects on health (Alcoforado et al., 2005; Casimiro et al., 2006; Trigo et al., 2009; Alves et al., 2010; Russo et al., 2014).

2.2 DEPENDENT VARIABLES

The number of daily natural (ICD10: A00-R99), circulatory (ICD10: I00-I99), and respiratory (ICD10:J00-J99) deaths were recorded in the district of Lisbon from 1983 to 2016. These data were provided by the National Institute of Statistics in Portugal. Moreover, the daily mortality data series was divided by gender obtaining the following groups: *total* (referring to the total population), *men*, and *women*, which were additionally separated by age group (0–9, 10–44, 45–64, 65–74, and ≥75 years old).

2.3 INDEPENDENT VARIABLE: DROUGHT INDICES

The SPI developed by McKee et al. (1993) and SPEI defined by Vicente-Serrano et al. (2010) were used to monitor the drought events. Both indices have the advantage of being multi-scalar, allowing the identification of different types of droughts and reflecting the responses of different systems based on several water deficit accumulation periods (Quiring, 2009; Stagge et al., 2015; Vicente-Serrano et al., 2012). The SPI is calculated from precipitation data and is based on the probability of precipitation for any time scale that is transformed to a standard normal distribution, with an average of zero and a standard deviation of one. The SPEI is calculated in a similar manner to the SPI. However, it is based on the climatic water balance, considering both precipitation and temperature variables (through the difference between precipitation and potential evapotranspiration) (Vicente-Serrano et al., 2010; Vicente-Serrano et al., 2012; Parsons et al., 2019). Thus, these indices can identify both wet (positive values of the series) and dry (values of the series below zero) events. Furthermore, the more negative the values of the SPEI/SPI, the more severe the drought conditions.

The time resolution of both drought indices is normally presented on a monthly or weekly scale (each month is divided into four periods as in Vicente-Serrano et al. (2017)). However, following studies by Berman (2017) and Salvador (2019; 2020b) with this type of analysis, linking droughts and health effects, a daily scale was used. Thus, from weekly series of drought indices, daily series were constructed assuming the same conditions for each seven-day interval during the studied period. The data series of precipitation, and maximum and minimum temperature of the Lisbon district needed for the calculation of drought indices calculation were downloaded from the daily gridded E-OBS dataset (Cornes et al., 2018) from the European Climate Assessment & Dataset project (ECA&D) available on a 0.1 degree regular grid from January 1950 to present (the database is continuously updated).

To calculate the SPEI and SPI, the SPEI R library was used (Begueria et al., 2014). To obtain the SPEI series, the potential evapotranspiration variable was first estimated based on the Hargreaves method, as recommended by Páscoa et al. (2017). Based on the original description of both indices and according to the methodology used by Spinoni et al. (2018) and Parsons et al. (2019), a gamma distribution was used to compute the SPI (McKee, 1993; EDO, 2020) and the log-logistic distribution to compute the SPEI (Vicente-Serrano et al., 2012) across the available period (1950 to 2017). Weekly data from 1983 to 2016 were then selected and daily series were constructed. Both indices were calculated for one month (and three months) of accumulation to quantify short (and short-to-medium) term droughts. Hereafter, the length of the time scales, is denoted as SPEI-n or SPI-n, where n is equal to "1" or "3".

2.4 CONTROL VARIABLES

The control of heatwaves and air quality variables during the sub-period from 2007 to 2016 was included in the analysis, where there was pollution data available, as these climatic hazards are frequently associated with droughts (Peterson et al., 2013). It has been demonstrated that in Europe, the incidence of concurrent and cascading dry hazards such as droughts, heatwaves, and forest fires is evident (e.g., Sutanto et al., 2020). These are important drivers for the deterioration of air quality, and both phenomena lead to harmful effects on respiratory and circulatory systems (IPCC, 2014; Watts et al., 2017).

Furthermore, time lags for the heatwaves and atmospheric pollutants of this study were calculated. So, the fact that the short-term effects of extreme heat temperatures on mortality occur immediately to four days later was taken into account (Guo et al., 2017). In the case of the atmospheric pollution, this effect can be delayed up to five days for PM_{10} and NO_2, and in the case of O_3, the impact on mortality can lag up to nine days. Hence, these lags were included in the Poisson models (Ortiz et al., 2017; Díaz and Linares, 2018; Salvador et al., 2020b).

2.4.1 Temperature of heatwave (T*hwave*)

It has been demonstrated that temperature has a U-shaped relationship with mortality (Tobías and Díaz, 2014). The temperature for the heatwaves (T*hwave*) was calculated using the maximum daily temperatures (T*max*) and the specific maximum temperature threshold for daily mortality associated with heat (T*threshold*) in Lisbon for the available sub-period from 2007 to 2016, following Díaz et al. (2015). In terms of its effect on mortality, T*hwave* was considered when the T*max* exceeded the T*threshold* value, as follows:

$$T_{hwave} = Tmax - Tthreshold \qquad \text{if } Tmax > Tthreshold$$
$$T_{hwave} = 0 \qquad \text{if } Tmax \leq Tthreshold$$

The daily T*max* series was obtained through an average of the daily T*max* series recorded at the reference stations of the Portuguese Institute for Sea and Atmosphere (IPMA) located in Lisbon, available online from the NOAA´s National Climatic Data Center (NCDC) (NNCDC CDO, 2019). The threshold value was 34 ºC, corresponding to the 93th percentile (see **Figure S1** in supplementary material).

2.4.2 Daily atmospheric pollution (PM_{10}, NO_2, and O_3)

The control of the short-term effect of air quality on the daily mortality in Lisbon from 2007 to 2016 was also included. For this purpose, the daily mean concentrations (µg/m^3) of particulate matter with an aerodynamic diameter of less than 10 µm (PM_{10}), nitrogen dioxide (NO_2), and ozone (O_3) were used.

From the air quality, pollutant data recorded at main monitoring stations situated in the district of Lisbon for each pollutant (*Entrecampos, Avenida da Liberdade, Olivais, Alfragide/Amadora, Cascais-Mercado, Loures,* *Mem-Martins*, *Alverca*, and *Laranjeiro*) were obtained online from the Portuguese Environmental Agency (QualAr, 2019). The data from the different stations were averaged to provide a single estimation of the daily concentration of each pollutant.

It has been indicated that PM_{10} and NO_2 have a linear relationship with mortality (Ortiz et al., 2017; Linares et al., 2018). However, O_3 registers a U-shaped relationship with mortality (similar to that registered by temperature), where the right branch of the curve indicates the increase of mortality associated with the increase in O_3 concentrations. Thus, this variable was parametrised according to the methodology of Díaz et al. (2018), and a new variable named O_3a was created to estimate the risks of O_3 on daily mortality as:

$O_3\ a = O_3 - O_3threshold$ if $O_3 > O_3threshold$

$O_3\ a = 0$ if $O_3 \leq O_3threshold$

The threshold ozone value of the Lisbon district from 2007 to 2016 was 67 (μg/m^3), corresponding to the 72th percentile (indicated in **Figure S2** in supplementary material).

2.5 MODELLING PROCESS TO QUANTIFY THE IMPACT OF DROUGHTS ON DAILY MORTALITY

Daily retrospective ecological time series studies were conducted to estimate the daily effects of droughts on natural, circulatory, and respiratory mortality using general linear models with a Poisson link, after which the effects of two environmental factors – heatwave temperatures and pollution levels – that are frequently associated with droughts were added to the models. First, the impact of droughts on each cause of daily mortality was evaluated conducting analyses of independent models for the SPEI-n and SPI-n (n = 1 and 3) from 1983 to 2016, and for SPEI-1 and SPI-1 from 2007 to 2016 when pollution data was available. Subsequently, for this last period (2007-2016), the temperature of heatwave was additionally controlled and included in the explicative models for those cases where a statistically significant association between the drought indices and daily mortality had been found. Finally, the control of variables related to air quality were also taken into account. Moreover, we also considered the trend of the series, the autoregressive nature of the dependent variable, and the seasonality of the series in the Poisson model through the use of sine and cosine functions corresponding to the periodicities indicated below: annual (365 days), six months (180 days), four months (120 days) and quarterly (90 days).

This methodology allowed the calculation of the relative risk (RR) of the variables that resulted statistically significant ($p<0.05$) from the estimator value obtained in Poisson models. RR values were calculated for each unit of increment for the indicator of the independent variable used and from these values, the percent of attributable risk (%AR) were calculated using the following equation: %AR = [(RR - 1) / RR] × 100 (Coste and Spira, 1991).

To determine the statistically significant variables, a "backward-step" process was conducted (e.g., Díaz and Linares (2018), Martinez et al. (2018), and Salvador et al., 2020b), starting with a model that included all the explained variables (including the considered lags) and subsequently individually and gradually removing those that displayed least statistical significance, obtaining a final model that included all significant variables ($p < 0.05$). Single models for SPEI-n and SPI-n were used and the process was conducted individually for daily natural, circulatory and respiratory mortality.

The complete statistical equation of the Poisson models used to estimate the risks of drought, heatwaves and atmospheric pollution is as follows:

$$Log\ E(Yt^r) = \alpha AR1 + \beta_t\, day_t + \gamma senX + \delta cosX + \cdots + \varepsilon\,(Thwave_t{}^r) + \vartheta \sum_{i=1}^{n=4} lagi\ Thwave_t{}^r$$
$$+ \mu\,(PM_{10t}{}^r)$$
$$+ \pi \sum_{i=1}^{n=5} lagi\ PM_{10t}{}^r + \rho\,(NO_{2t}{}^r) + \sigma \sum_{i=1}^{n=5} lagi\ NO_{2t}{}^r + \tau\,(O_3\ a_t{}^r)$$
$$+ \varphi \sum_{i=1}^{n=9} lagi\ O_3\ a_t{}^r + \omega\, drt_t{}^r + \theta\ cons$$

where Yt^r is the number of deaths on day *t* in the specific region (*r*). $\alpha AR1$ is the factor that control the autoregressive nature of the dependent variable from the autoregression of the first order of daily mortality, being α the regression coefficient value. Both the trend of the series ($\beta_t\, day_t$) and the seasonality (represented using sine and cosine functions that correspond to the different periodicities, X=360, 180, 120, 90 were analysed. β, γ and δ correspond to the respective coefficients. ω is the magnitude of the coefficient or estimator for drought in a region r using an annual continuous daily series of SPI or SPEI (denoted as drt) obtained for a specific time scale ($drt_t{}^r$) for a given region and study period. For the complete Poisson models, both the short-term effect of heatwaves [$\varepsilon\,(Thwave_t{}^r)$] and atmospheric pollutants, such as particulate matter with an aerodynamic diameter of less than 10 µm [$\mu\,(PM_{10t}{}^r)$], nitrogen dioxide [$\rho\,(NO_{2t}{}^r)$] and ozone [$\tau\,(O_3\,a_t{}^r)$], were controlled. In the equation, the lagged variables corresponding to high temperatures (lag=1-4), PM_{10}, NO_2 (both lag=1-5) and O_3 a (lag=1-9) were also indicated. The constant of each model was also included ($\theta\ cons$).

All analyses were conducted using the IBM SPSS Statistics and STATA v14.1 software.

3. RESULTS

3.1. DESCRIPTIVE ANALYSIS

The descriptive statistics of both the daily mortality by gender and age in the district of Lisbon across the period 1983 to 2016 is presented in **Table 1**. **Table 2** displays the descriptive analysis of both maximum temperature and air quality in the district of Lisbon for the sub-period 2007 to 2016, for which atmospheric pollution variables were available. **Figure 1** shows the daily SPEI-1 and SPI-1 series for Lisbon from 2007 to 2016, reflecting SPEI-1 drier conditions than SPI-1.

Table 1. Descriptive statistics corresponding to annual daily natural, circulatory and respiratory mortality of total population and sub-groups categorised by gender (men and women) and age ranges (0-9, 10-44, 45-64, 65-74, ≥75 years old) in the district of Lisbon from 1983 to 2016. %Pp= percentage of deaths; SD=Standard Deviation; m= minimum; M= maximum.

DISTRICT OF LISBON (PORTUGAL)															
POPULATION	Natural deaths					Circulatory deaths					Respiratory deaths				
	% Pp	Mean	SD	m	M	%Pp	Mean	SD	m	M	%Pp	Mean	SD	m	M
TOTAL	**(665383)** 100%	54	12	19	135	(286820) 43.11%	23	7.4	4	77	(59083) 8.89%	5	2.93	0	30
0-9	(6776) 1.02%	1	0.8	0	7	(168) 0.06%	0.01	0.12	0	1	(479) 0.81%	0.04	0.21	0	3
10-44	(29042) 4.36%	2	1.7	0	12	(4573) 1.59%	0.37	0.6	0	5	(1676) 2.84%	0.13	0.37	0	3
45-64	(107186) 16.11%	9	3.2	0	27	(30271) 10.55%	2	1.8	0	10	(5212) 8.82%	0.42	0.67	0	5
65-74	(136250) 20.48%	11	3.9	0	31	(53316) 18.59%	4	2.6	0	18	(9357) 15.84%	0.75	0.91	0	9
≥75	(386082) 58.02%	31	9.7	6	89	(198483) 69.20%	16	5.6	2	59	(42353) 71.68%	3	2.52	0	23
MEN	**(333035)** 50.05%	27	6.8	6	61	(125845) 43.88%	10	4	0	31	(31922) 54.03%	3	1.9	0	19
0-9	(3876) 1.16%	0.3	0.6	0	4	(95) 0.08%	0.01	0.09	0	1	(284) 0.89%	0.02	0.16	0	2
10-44	(19428)					(3107)					(1170)				

	5.83%	2	1.4	0	9	2.47%	0.25	0.51	0	4	3.67%	0.09	0.31	0	3
45-64	(70651) 21.21%	6	2.5	0	21	(21013) 16.70%	2	1.4	0	9	(3785) 11.86%	0.30	0.56	0	4
65-74	(82366) 24.73%	7	2.8	0	20	(31131) 24.74%	3	1.8	0	13	(6256) 10.59%	1	0.73	0	6
≥75	(156683) 47.05%	13	5	1	45	(70494) 56.01%	6	2.8	0	21	(20424) 63.98%	2	1.51	0	13
WOMEN	**(332347)** 49.95%	27	7.3	7	83	(160975) 56.12%	13	4.8	0	54	(27161) 45.97%	2	1.80	0	16
0-9	(2899) 0.87%	0.2	0.5	0	5	(73) 0.05%	0.01	0.08	0	1	(195) 0.72%	0.02	0.13	0	2
10-44	(9614) 2.89%	1	0.9	0	6	(1466) 0.91%	0.12	0.34	0	3	(506) 1.86%	0.04	0.21	0	3
45-64	(36535) 10.99%	3	1.8	0	11	(9258) 5.75%	0.75	0.91	0	7	(1427) 5.25%	0.11	0.34	0	3
65-74	(53884) 16.21%	4	2.3	0	17	(22185) 13.78%	2	1.52	0	11	(3101) 11.42%	0.25	0.52	0	4
≥75	(229399) 69.02%	18	6.3	3	62	(127989) 79.51%	10	4	0	47	(21929) 80.74%	2	1.63	0	15

Table 2. Descriptive analysis corresponding to annual data of daily maximum temperature (T*max*, in ºC), particulate matter with an aerodynamic diameter of less than 10 µm (PM_{10}), nitrogen dioxide (NO_2), and ozone (O_3) levels (in µg/m^3) for the district of Lisbon from 2007 to 2016. SD: Standard Deviation; m: minimum; M: maximum.

DISTRICT OF LISBON (PORTUGAL)				
Variables	**Mean**	**SD**	**m**	**M**
T*max*	21.[illegible]	6.29	0	39.83
PM_{10}	26.37	11.66	4.70	109.79
NO_2	32.57	14.80	6.88	100.23
O3	54.55	[illegible]	[illegible]	[illegible]

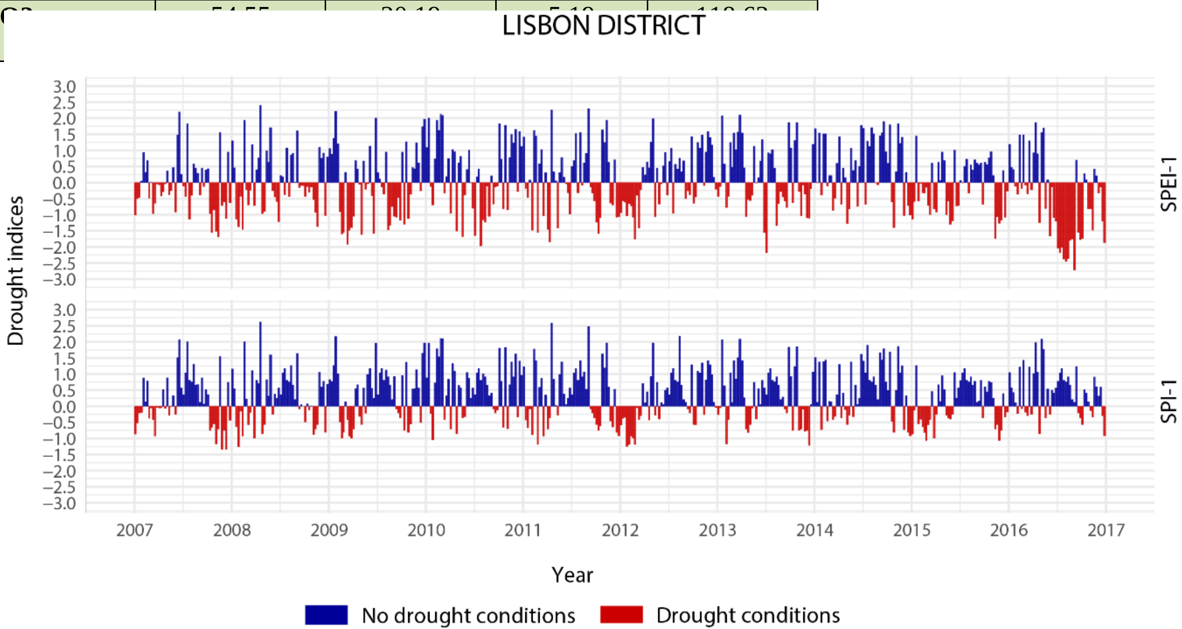

Figure 1. Daily temporal evolution of SPEI-1 and SPI-1 series calculated for the Lisbon district from 2007 to 2016. Dry (in red) and wet (in blue) spells are shown, representing drought and non-drought conditions, respectively. SPI/SPEI: Standardised Precipitation Index / Standardised Precipitation Evapotranspiration Index.

3.2. QUANTIFICATION OF SHORT-TERM EFFECTS OF DROUGHT ON SPECIFIC-CAUSE MORTALITY IN THE DISTRICT OF LISBON FOR 1983-2016

3.2.1 Risk assessment for total population and different age subgroups

The complete set of statistical values obtained in the Poisson models (coefficients, p-values, RRs, 95% confidence intervals of RRs and %AR) are described in **Table S1** (supplementary material). As the SPEI/SPI have negative values for drought periods, the negative sign of the coefficients obtained in Poisson models indicates a significant association between drought conditions and the different causes of deaths. **Figure 2** displays the RR values (with 95% confidence intervals) of the natural, circulatory, and respiratory mortality associated with drought events measured by the SPEI-1/SPI-1 in the total population of Lisbon and in adults grouped by age (45–64, 65–74, ≥75 years old) from 1983 to 2016. Only considered adults were considered because there were limited deaths among young people including children and adolescents (see Table 1). A comparison with the SPEI-3/SPI-3 is displayed in the supplementary material (**Figure S3**).

The main results from **Figure 2** indicate a statistically significant association between short-term drought events and the different causes of daily mortality, being higher the impact on respiratory-caused mortality (although the difference is not significant). In addition, among the different age categories of the population, people aged 75 years old and over were the group with highest risk and no statistically significant relationship between daily mortality and drought conditions was found for people aged 45 to 64.

Meanwhile, several differences were detected when the performance of the SPEI and SPI were compared. Only the SPEI-1 reflected the impact of drought on circulatory mortality, indicating a greater number of statistically significant associations for natural mortality in the different age groups. Overall, the SPEI-1 (the shortest time scale) reflected the risks on mortality among the different groups (particularly for natural and circulatory deaths) better than the SPEI-3. Conversely, the SPI-3 appeared to be more optimal than the SPI-1, particularly for natural cases of deaths (Figure S3 in supplementary material).

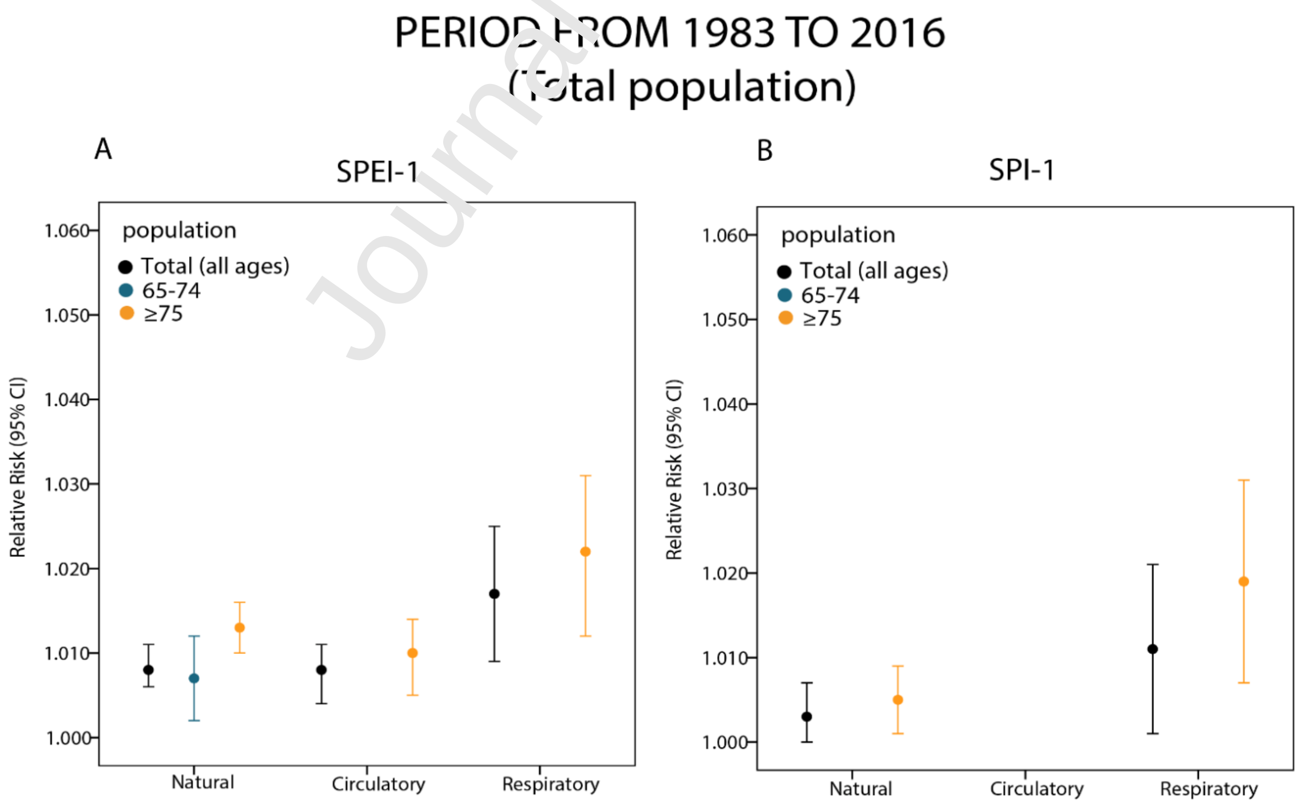

Figure 2. Significant Relative Risks (RRs) of daily natural, circulatory, and respiratory mortality of total population and adult age groups associated with drought events measured by: A) SPEI-1 and B) SPI-1. Both indices calculated for one month of accumulation. Upper and lower 95% confidence intervals are indicated with vertical bars. Only those groups for which there was a statistically significant association between drought conditions and daily mortality are shown.

3.2.2 Risks assessment by gender

When the population is categorised by gender, the results also indicate differences between the 65–74 and ≥75 groups (**Figure 3**). In the supplementary material, **Table S2** displays the significant statistic values obtained in the Poisson models. **Figure S4** presents the comparative results using the SPEI-1/SPI-1 vs. SPEI-3/SPI-3. The findings indicate that both women and men were affected by the drought conditions in terms of mortality. The SPEI also resulted in a better index for capturing and estimating the different risks on daily mortality. Moreover, when using the different time scales of the SPEI/SPI, similar findings were obtained in the gender analysis compared to those obtained for the total population (Figure S4).

Furthermore, a fluctuation of the drought risks on daily mortality between men and women was observed. Whereas the SPEI reflected a greater risk of droughts for women (especially in the group aged 75 years and over) for circulatory mortality (no significant association for men), the SPI indicated that men were the highest risk group, especially for natural and respiratory mortality (where there were limited significant associations in the case of women). Moreover, the affected people in the 65–74 group were men in all cases. On the other hand, the drought conditions measured by the SPEI did not identify gender differences in the risks of respiratory deaths (Figure 3, Figure S4).

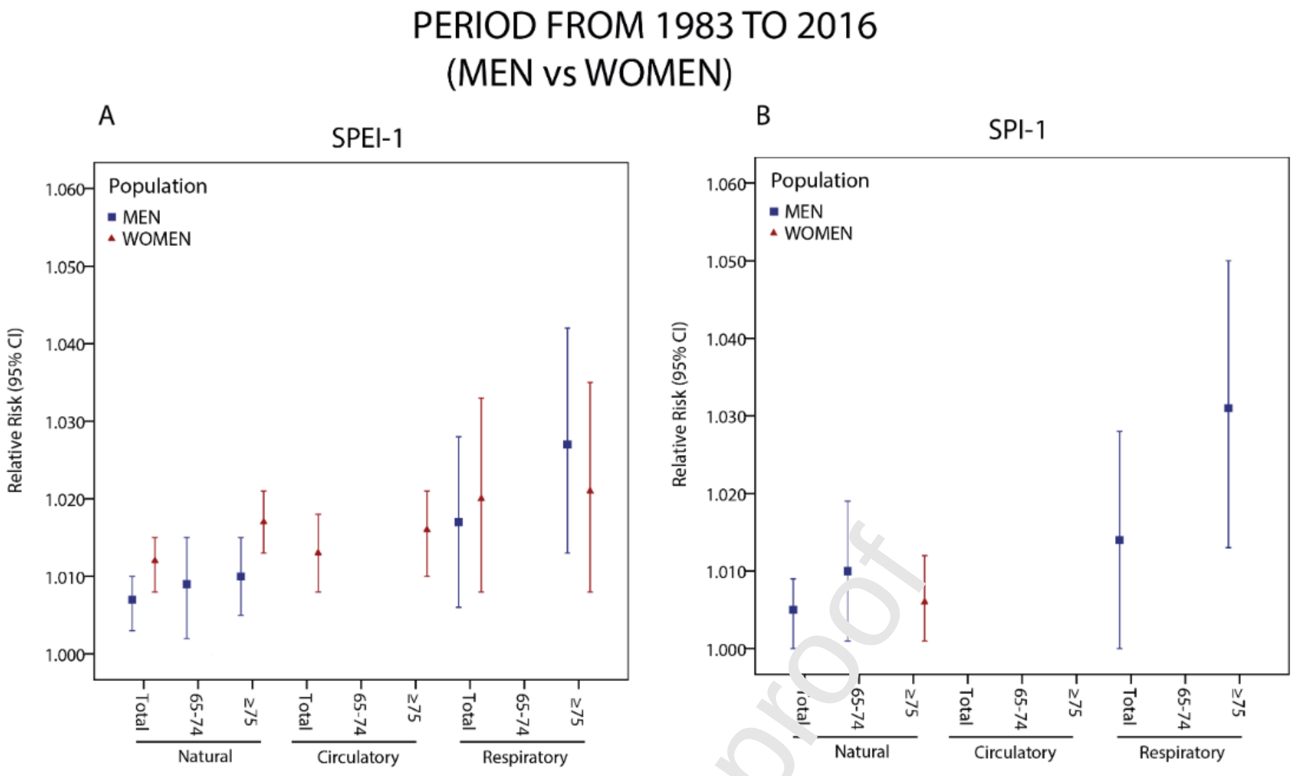

Figure 3. Significant Relative Risks (RRs) of daily natural, circulatory, and respiratory mortality across population separated by gender and categorised by advanced age group linked to occurrence of droughts conditions measured by: A) SPEI-1 and B) SPI-1. Both indices calculated for one month of accumulation. Upper and lower 95% confidence intervals are indicated with vertical bars. Only those groups for which there was a statistically significant association between drought conditions and daily mortality are shown.

3.3. SHORT-TERM IMPACT OF DROUGHT ON MORTALITY UNDER CONTROL OF HEATWAVES AND ATMOSPHERIC POLLUTION FOR THE SUB-PERIOD 2007–2016

As the period with pollution data available was shorter, we first re-quantified the effect of droughts measured over the short-term (SPEI-1/SPI-1) on the daily specific-cause mortality from the sub-period 2007–2016 (**Tables 3–4**). When only gender was considered in the analysis, differences in the risks of mortality linked to drought for men and women were hardly found (**Table 3**). However, when the population (total, men, and women) was categorised by adult age groups (**Table 4**), gender differences in the risk of mortality attributable to drought were particularly remarkable during this sub-period, men being more strongly affected than women.

Table 3. Significant Relative Risks (RRs) of daily natural, circulatory and respiratory mortality associated with drought events measured at short-term (SPEI-1/SPI-1, one month of accumulation) for the total population and separated by gender (men and women) of Lisbon district across the sub-period 2007 to 2016. P-value and coefficient values from the Poisson models, and the percentage of attributable risk (%AR = [(RR-1)/RR] × 100), are also displayed. The 95% confidence intervals (CI) for the coefficients and RR are also shown. SPEI/SPI= Standardised Precipitation Evapotranspiration Index / Standardised Precipitation Index.

DISTRICT OF LISBON					
Causes of mortality	**Population**	**p-value**	**Coefficients (95% CI)**	**RR (95% CI)**	**%AR**
Natural	**TOTAL**	**SPEI_1** (p=0.000)	-0.011 (-0.015, -0.007)	1.011 (1.007, 1.015)	1.088%
		SPI_1 (p=0.021)	-0.006 (-0.012, -0.001)	1.006 (1.001, 1.012)	0.60%
	MEN	**SPEI-1** (p=0.000)	-0.011 (-0.017, -0.005)	1.011 (1.005, 1.017)	1.09%
		SPI-1 (p=0.037)	-0.008 (-0.016, -0.000)	1.008 (1.000, 1.016)	0.79%
	WOMEN	**SPEI-1** (p=0.000)	-0.012 (-0.018, -0.007)	1.012 (1.007, 1.018)	1.19%
Circulatory	**TOTAL**	**SPEI_1** (p=0.001)	-0.011 (-0.019, -0.004)	1.011 (1.004, 1.019)	1.088%
	MEN	**SPEI-1** (p=0.015)	-0.013 (-0.024, -0.003)	1.013 (1.003, 1.024)	1.28%
	WOMEN	**SPEI-1** (p=0.025)	-0.011 (-0.020, -0.001)	1.011 (1.001, 1.020)	1.09%
Respiratory	**TOTAL**	**SPEI_1** (p=0.024)	-0.015 (-0.028, -0.002)	1.015 (1.002, 1.028)	1.48%
	MEN				
	WOMEN				

In the case of males, the daily natural and circulatory mortality attributable to droughts measured by the SPEI-1 was manifested for the 65–74 and ≥75 groups. In the case of women, mortality only occurred for the ≥75 group. When the age groups were included in the Poisson models, it was observed that the respiratory mortality in men aged 75 years old and older was significantly affected by short-term droughts using both the SPEI-1 and SPI-1 (any statistically significant association was observed for women).

Table 4. As Table 3 but splitting the total, men and women population into adult age groups.

DISTRICT OF LISBON					
Causes of mortality	**Population**	**Type of drought Index**	**p-value**	**Coefficients (95% CI)**	**RR (95%CI)**
Natural	**TOTAL**	**SPEI-1**	65-74 (p=0.004) ≥75 (p=0.000)	-0.015 (-0.025, -0.005) -0.012 (-0.017, -0.007)	1.015 (1.005, 1.025) 1.012 (1.007, 1.017)
		SPI-1			
	MEN	**SPEI-1**	65-74 (p=0.026) ≥75 (p=0.008)	-0.015 (-0.028, -0.002) -0.011 (-0.018, -0.003)	1.015 (1.002, 1.028) 1.011 (1.003, 1.018)
		SPI-1			
	WOMEN	**SPEI-1**	≥75 (p=0.000)	-0.015 (-0.021, -0.008)	1.015 (1.008, 1.021)
		SPI-1			
Circulatory	**TOTAL**	**SPEI-1**	65-74 (p=0.021) ≥75 (p=0.003)	-0.023 (-0.043, -0.004) -0.012 (-0.020, -0.004)	1.023 (1.004, 1.044) 1.012 (1.004, 1.020)
		SPI-1			
	MEN	**SPEI-1**	65-74 (p=0.018)	-0.030 (-0.055, -0.005)	1.030 (1.005, 1.057)
		SPI-1			
	WOMEN	**SPEI-1**	≥75 (p=0.007)	-0.014 (-0.024, -0.004)	1.014 (1.004, 1.024)
		SPI-1			
Respiratory	**TOTAL**	**SPEI-1**	≥75 (p=0.006)	-0.020 (-0.034, -0.006)	1.020 (1.006, 1.035)
		SPI-1	≥75 (p=0.038)	-0.019 (-0.037, -0.001)	1.019 (1.001, 1.038)
	MEN	**SPEI-1**	≥75 (p=0.013)	-0.026 (-0.046, -0.005)	1.026 (1.005, 1.047)
		SPI-1	≥75 (p=0.016)	-0.032 (-0.059, -0.006)	1.033 (1.006, 1.061)
	WOMEN	**SPEI-1**			
		SPI-1			

The improved capability of the SPEI to identify and quantify the different effects was more marked in the sub-period from 2007 to 2016. There were statistically significant associations between the droughts measured by the SPEI-1 and all analysed causes of mortality, whereas there were virtually no associations between the droughts and different causes of mortality using the SPI (Tables 3 and 4).

3.3.1. ADDITIONAL CONTROL OF HEATWAVES AND ATMOSPHERIC POLLUTION

First, the impact of droughts measured over the short-term was quantified, including the control of heatwaves in the statistical models (**Table S3**) for the significant groups in tables 3 and 4. Significant impacts on mortality were explained by the effect of the drought conditions and extreme temperatures. However, in specific cases, the statistical significance of the drought index was lost when T*hwave* was controlled in the model. This occurred, for instance, in the case of daily circulatory and respiratory mortality when age was not considered, or for circulatory mortality in the total population and among women 75 years old and above. Therefore, in the former cases, there should be other processes associated with drought that influences daily mortality while the signal of the latter remains significant.

Subsequently, the impact of droughts was evaluated while both the effect of heatwaves and atmospheric pollution remained controlled in the Poisson models (see **Table 5** and **6**). Table 5 displays the results obtained across the population segregated by gender, without differentiation by age. It can be observed that the statistically significant signal of the SPEI-1 and SPI-1 previously obtained is lost when extreme heat temperatures and the effect of PM_{10}, NO_2, and O_3 are included in the Poisson models, only remaining T*hwave* and pollution variables statistically significant. Thus, both mechanisms explain the significance obtained using the drought signal. Comparing the different pollutants, O_3 and NO_2 were the more strongly linked to mortality compared to PM_{10}. Qualitatively $O_3$was the pollutant associated with the highest risk of death (the highest RR values). It has been observed that all pollutants contribute to the natural mortality. NO_2 was mainly associated with daily circulatory-caused mortality, whereas O_3 was particularly related to respiratory outcomes.

Table 5. Statistically significant effects of droughts measured at short-term (SPEI-1/SPI-1, one month of accumulation) on daily natural, circulatory and respiratory mortality of the total, men and women populations adding the effect of heatwaves (Thwave) and atmospheric pollutants in the district of Lisbon for the sub-period 2007 to 2016. P-value and coefficients of the Poisson model, and relative risks (RRs) are displayed. The 95% confidence intervals (CI) of the coefficients and of the RRs are also included. SPEI/SPI= Standardised Precipitation Evapotranspiration Index / Standardised Precipitation Index. "-n" after the Thwave and each pollutant correspond to the lagged manifestation of their effects in days on daily mortality, ranging from 0 ("immediate") to 6 days.

DISTRICT OF LISBON					
SPEI-1/SPI-1 + THWAVE + POLLUTION					
Causes of mortality	**Population**	**Type of drought index**	**p-value**	**Coefficients (95% CI)**	**RR (95%CI)**
Natural	**TOTAL**	**SPEI-1**	Thwave-1 (p=0.000) Thwave-2 (p=0.000) Thwave-4 (p=0.013) NO_2-0 (p=0.002) NO_2-3 (p=0.006) O_3a-4 (p=0.028)	0.035 (0.021, 0.049) 0.031 (0.017, 0.045) 0.015 (0.003, 0.028) 0.0006 (0.0002, 0.0009) 0.0005 (0.0001, 0.0009) 0.0008 (0.0001, 0.0015)	1.036 (1.021, 1.050) 1.031 (1.017, 1.046) 1.015 (1.003, 1.028) 1.0006 (1.0002, 1.0009) 1.0005 (1.0001, 1.0009) 1.0008 (1.0001, 1.0015)
		SPI-1	Thwave-1 (p=0.000) Thwave-2 (p=0.000) Thwave-4 (p=0.013) NO_2-0 (p=0.002) NO_2-3 (p=0.006) O_3a-4 (p=0.028)	0.035 (0.021, 0.049) 0.031 (0.017, 0.045) 0.015 (0.003, 0.028) 0.0006 (0.0002, 0.0009) 0.0005 (0.0001, 0.0009) 0.0008 (0.0001, 0.0015)	1.036 (1.021, 1.050) 1.031 (1.017, 1.046) 1.015 (1.003, 1.028) 1.0006 (1.0002, 1.0009) 1.0005 (1.0001, 1.0009) 1.0008 (1.0001, 1.0015)
	MEN	**SPEI-1**	Thwave-0 (p=0.022) Thwave-2 (p=0.000) PM_{10}-0 (p=0.004) O_3a-6 (p=0.015)	0.020 (0.003, 0.037) 0.047 (0.031, 0.064) 0.0009 (0.0003, 0.0014) 0.0012 (0.0002, 0.0022)	1.020 (1.003, 1.038) 1.048 (1.031, 1.066) 1.0009 (1.0003, 1.0014) 1.0012 (1.0002, 1.0022)
		SPI-1	Thwave-0 (p=0.022) Thwave-2 (p=0.000) PM_{10}-0 (p=0.004) O_3a-6 (p=0.015)	0.020 (0.003, 0.037) 0.047 (0.031, 0.064) 0.0009 (0.0003, 0.0014) 0.0012 (0.0002, 0.0022)	1.020 (1.003, 1.038) 1.048 (1.031, 1.066) 1.0009 (1.0003, 1.0014) 1.0012 (1.0002, 1.002)
	WOMEN	**SPEI-1**	Thwave-1 (p=0.000) Thwave-2 (p=0.001) Thwave-4 (p=0.006) NO_2-3 (p=0.008)	0.047 (0.028, 0.067) 0.032 (0.012, 0.051) 0.023 (0.007, 0.040) 0.0007 (0.0002, 0.0012)	1.048 (1.028, 1.069) 1.033 (1.012, 1.052) 1.023 (1.007, 1.041) 1.0007 (1.0002, 1.0012)

			O_3a-1 (p=0.036)	0.0011 (0.0001, 0.0021)	1.001 (1.0001, 1.0021)
		SPI-1			
Circulatory	**TOTAL**	**SPEI-1**	Thwave-1 (p=0.000) Thwave-2 (p=0.001) Thwave-4 (p=0.000) NO_2-3 (p=0.001)	0.045 (0.022, 0.068) 0.038 (0.015, 0.062) 0.040 (0.021, 0.060) 0.0010 (0.0004, 0.0016)	1.046 (1.022, 1.070) 1.039 (1.015, 1.064) 1.041 (1.021, 1.062) 1.001 (1.0004, 1.0016)
		SPI-1			
	MEN	**SPEI-1**	Thwave-1 (p=0.001) Thwave-4 (p=0.001) NO_2-3 (p=0.013)	0.051 (0.022, 0.081) 0.048 (0.019, 0.078) 0.0012 (0.0002, 0.0021)	1.052 (1.02, 1.084) 1.049 (1.019, 1.081) 1.0012 (1.0002, 1.0021)
		SPI-1			
	WOMEN	**SPEI-1**	Thwave-1 (p=0.001) Thwave-2 (p=0.006) Thwave-4 (p=0.001) NO_2-2 (p=0.002)	0.051 (0.021, 0.081) 0.043 (0.012, 0.074) 0.043 (0.018, 0.069) 0.0013 (0.0005, 0.002)	1.052 (1.021, 1.084) 1.044 (1.012, 1.077) 1.044 (1.018, 1.071) 1.0013 (1.0005, 1.002)
		SPI-1			
Respiratory	**TOTAL**	**SPEI-1**	Thwave-0 (p=0.001) Thwave-3 (p=0.006) O_3a-4 (p=0.002)	0.064 (0.027, 1.000) 0.051 (0.015, 0.088) 0.0035 (0.0012, 0.0057)	1.066 (1.027, 2.718) 1.052 (1.015, 1.092) 1.0035 (1.0012, 1.0057)
		SPI-1			
	MEN	**SPEI-1**			
		SPI-1			
	WOMEN	**SPEI-1**			
		SPI-1			

Finally, an assessment by **adult age group (Table 6**) was carried out to detect if the significance of drought indices remained statistically significant when the previous commented phenomena were included in Poisson models. In fact, there were notable differences. For example, the significance of drought indices remained in specific subgroups within the total and male populations. Daily circulatory-cause mortality was only significantly associated with SPEI in men aged 65 to 74 years old. Therefore, the effect of drought on mortality could be explained by another mechanism that is not linked to high temperatures or pollution levels. Moreover, for this sub-group of the population, daily natural mortality was influenced by both SPEI and ozone levels. In addition, the mortality in the male age subgroups was associated with the highest number of pollutants. These differences could contribute to a higher risk in elderly male groups compared to elderly female groups.

Table 6. As Table 5 but for the exposed population separated by gender and age groups.

DISTRICT OF LISBON						
SPEI-1/SPI-1 + THWAVE + POLLUTION						
Population	**Causes of mortality**	**Age range**	**Type of drought Index**	**p-value**	**Coefficients (95% CI)**	**RR (95% CI)**
TOTAL	Natural	**65-74**	**SPEI-1**	SPEI-1 (p=0.017) Thwave-2 (p=0.013) O_3a-3 (p=0.023)	-0.013 (-0.023, -0.002) 0.035 (0.007, 0.063) 0.0020 (0.0003, 0.0037)	1.013 (1.002, 1.023) 1.036 (1.007, 1.065) 1.002 (1.003, 1.038)
			SPI-1			
		≥75	**SPEI-1**	Thwave-1 (p=0.000) Thwave-2 (p=0.001) Thwave-4 (p=0.000) NO_2-0 (p=0.002) NO_2-3 (p=0.002) O_3a-2 (p=0.0[illegible]9)	0.046 (0.029, 0.062) 0.029 (0.012, 0.047) 0.026 (0.012, 0.041) 0.0007 (0.0003, 0.0012) 0.0007 (0.0003, 0.0012) 0.0009 (0.0000, 0.0018)	1.047 (1.029, 1.064) 1.029 (1.012, 1.048) 1.026 (1.012, 1.042) 1.0007 (1.0003, 1.0012) 1.0007 (1.0003, 1.0012) 1.0009 (1.0000, 1.0018)
			SPI-1			
	Circulatory	**65-74**	**SPEI-1**	SPEI-1 (p=0.047) Thwave-2 (p=0.027)	-0.020 (-0.040, -0.0003) 0.059 (0.007, 0.111)	1.020 (1.0003, 1.041) 1.061 (1.007, 1.117)
			SPI-1			
		≥75	**SPEI-1**	Thwave-1 (p=0.000) Thwave-2 (p=0.006) Thwave-4 (p=0.000) NO_2-3 (p=0.001)	0.057 (0.031, 0.083) 0.037 (0.011, 0.064) 0.047 (0.025, 0.070) 0.0011 (0.0004, 0.002)	1.059 (1.031, 1.087) 1.038 (1.011, 1.066) 1.048 (1.025, 1.073) 1.0011 (1.0004, 1.002)
			SPI-1			
	Respiratory	**≥75**	**SPEI-1**	Thwave-1 (p=0.002) Thwave-3 (p=0.032) PM_{10}-0 (p=0.033) O_3a-4 (p=0.002)	0.063 (0.023, 0.104) 0.044 (0.004, 0.085) 0.0015 (0.0001, 0.0028) 0.0039 (0.0014, 0.0063)	1.065 (1.023,1.110) 1.045 (1.004, 1.089) 1.0015 (1.0001, 1.0028) 1.0039 (1.0014, 1.0063)
			SPI-1	Thwave-1 (p=0.002) Thwave-3 (p=0.032) PM_{10}-0 (p=0.033) O_3a-4 (p=0.002)	0.063 (0.023, 0.104) 0.044 (0.004, 0.085) 0.0015 (0.0001, 0.0028) 0.0039 (0.0014, 0.0063)	1.065 (1.023, 1.110) 1.045 (1.004, 1.089) 1.0015 (1.0001, 1.0028) 1.0039 (1.0014, 1.0063)
	Causes of mortality	**Age range**	**Type of drought Index**	**p-value**	**Coefficients (95% CI)**	**RR (95% CI)**
MEN	Natural	**65-74**	**SPEI-1**	SPEI-1 (p=0.035) O_3a-3 (p=0.003)	-0.014 (-0.027, -0.001) 0.0032 (0.001, 0.005)	1.014 (1.001, 1.027) 1.0032 (1.001, 1.005)
			SPI-1			
		≥75	**SPEI-1**	Thwave-0 (p=0.019) Thwave-2 (p=0.000) PM_{10}-0 (p=0.003)	0.027 (0.005, 0.050) 0058 (0.036, 0.080) 0.001 (0.0004, 0.0019)	1.027 (1.005, 1.051) 1.060 (1.037, 1.083) 1.001 (1.0004, 1.0019)
			SPI-1			
	Circulatory	**65-74**	**SPEI-1**	SPEI-1 (p=0.018)	-0.030 (-0.055, -0.005)	1.030 (1.005, 1.057)
			SPI-1			
	Respiratory	**≥75**	**SPEI-1**	Thwave-0 (p=0.003) NO_2-0 (p=0.029) O_3a-4 (p=0.030)	0.084 (0.028, 0.140) 0.002 (0.0002, 0.004) 0.004 (0.0004, 0.007)	1.088 (1.028. 1.150) 1.002 (1.0002, 1.004) 1.004 (1,0004, 1,007)
			SPI-1	SPI-1 (p=0.026) Thwave-0 (p=0.001) O_3a-4 (p=0.028)	-0.030 (-0.056, -0.004) 0.096 (0.041, 0.150) 0.004 (0.000, 0.007)	1.030 (1.004, 1.058) 1.101 (1.042, 1.162) 1.004 (1.000, 1.007)
	Causes of mortality	**Age range**	**Type of drought Index**	**p-value**	**Coefficients (95% CI)**	**RR (95% CI)**
WOMEN	Natural	**≥75**	**SPEI-1**	Thwave-1 (p=0.000) Thwave-2 (p=0.007) Thwave-4 (p=0.000) NO_2-0 (p=0.019) NO_2-3 (p=0.002)	0.056 (0.034, 0.078) 0.031 (0.008, 0.053) 0.035 (0.017, 0.054) 0.0007 (0.0001, 0.0013) 0.0009 (0.0003, 0.0015)	1.058 (1.035, 1.081) 1.031 (1.008, 1.054) 1.036 (1.017, 1.055) 1.0007 (1.0001, 1.0013) 1.0009 (1.003, 1.0015)
			SPI-1			
	Circulatory	**≥75**	**SPEI-1**	Thwave-1 (p=0.000) Thwave-2 (p=0.024) Thwave-4 (p=0.000) NO_2-2 (p=0.000)	0.059 (0.027, 0.091) 0.038 (0.005, 0.071) 0.049 (0.022, 0.076) 0.0017 (0.0009, 0.0026)	1.061 (1.027, 1.095) 1.039 (1.005, 1.074) 1.050 (1.022, 1.079) 1.017 (1.0009, 1.0026)

			SPI-1			

4. DISCUSSION

This study reveals, for first time, the effects of different drought conditions on the daily natural, circulatory, and respiratory mortality in Lisbon district from 1983–2016 as measured by two meteorological indices of drought (SPEI and SPI) obtained at short and short-to-medium term. This work, which included analysis by gender and age, allowed us to compare the capability of different types of drought indices and timescales to reflect and quantify the impact of drought on daily mortality in the population of Lisbon and to determine which groups were the most vulnerable. Heatwaves and poor air quality (among other factors) were the mechanisms most associated with drought conditions. Therefore, a re-quantification of the impact of short-term droughts on daily mortality was considered across the last decade of the period studied (2007–2016), when pollution data were available, to include a control of the short-term effect of heatwaves and atmospheric pollution in the statistical models.

The main findings obtained in this study show that drought events were significantly associated with all causes of deaths analysed in the study, with higher RR values for daily respiratory mortality across the period 1983 to 2016. This is in agreement with Salvador et al. (2019; 2020b) for Spain and in accordance with other studies that have shown that drought conditions can exacerbate disorders of the respiratory tract (e.g. allergies, bronchitis, and pneumonia) (Bernstein and Rice, 2013; Yusa et al., 2015; Alpino et al., 2016; Grigoletto et al., 2016; Bifulco and Ranieri, 2017). This could result in respiratory mortality due to the accumulation of pollutants, dust, or allergens in the lungs, particularly in vulnerable individuals such as those with common chronic lung pathologies. A recent study revealed a significant increase in respiratory hospital admissions (excluding a decrease in asthma cases) during drought episodes from 2000 to 2016 (Machado-Silva et al., 2020). Smith et al. (2014) described an increase in hospital admissions for respiratory diseases in children linked to the occurrence of fires caused by droughts in the Amazon region. However, the deterioration of air quality associated with drought conditions could also contribute to an increased risk of cardiovascular problems and heart disease (Stanke et al., 2013; Bell et al., 2018; Salvador et al., 2020a).

The **oldest population groups were the most affected in terms of mortality**, confirming that the elderly are a particularly vulnerable subgroup. In terms of the climatic mechanisms that frequently link drought and health repercussions thereof, it has been noted that the elderly are one of the population groups most vulnerable to heatwaves, pollution, or extreme cold events, among others. The risk of adverse health impacts on them is higher than on younger adults due to their mobility constraints and weakened immune response to environmental stresses (Filiberto et al., 2008; IPCC, 2014; Berman et al., 2017). Moreover, the elderly have a reduced ability to restore homeostasis, including a decreased thermoregulatory capacity (Vida et al., 2014; Linares et al., 2017), and a higher prevalence of chronic heart and lung diseases (Yazdanyar and Newman, 2009; Akgün et al., 2012; EPA, 2019). A recent study noted an increase of 1.55% in the mortality risk for adults aged 65 years or above in the western USA during the high-severity drought conditions that worsened from 2000 to 2013 (Berman et al., 2017). Moreover, in Spain, those regions with the highest proportion of elderly people had the greatest risk of daily natural, circulatory and respiratory causes of deaths (Salvador et al., 2020c). However, there have also been indications that those 65 years old and above are at the greatest risk of mortality associated with the occurrence of heatwaves (Díaz et al., 2002; Linares and Díaz, 2008; deCastro et al., 2011; Linares et al., 2017) and with the effect of atmospheric pollution on natural, circulatory, and respiratory deaths (e.g., Gouveia and Fletcher, 2000). In addition, in Lisbon, the effects of extreme cold events in winter on these specific causes of death is particularly remarkable among the elderly (Antunes et al., 2017). Countries with higher mean temperatures and mild winter climates, such as Portugal, suffer the greatest winter deaths because homes in their cities tend to have poor domestic thermal efficiency, and their populations and infrastructures are less prepared than others to counteract the effects of cold temperatures (Healy, 2003). Other factors associated with economic and biological conditions, as well as the social behaviours (e.g. the ability to keep warm in indoor and outdoor environments) are strongly linked to a higher vulnerability to cold (Almendra et al., 2015). Moreover, evidence also indicates that elderly people are a high-risk subgroup in cases where circulatory and respiratory diseases are exacerbated and mortality associated with wildfire smoke (Bell et al., 2018; EPA, 2019; Machado-Silva et al., 2020). They are also more vulnerable than other groups to the impact of suspended particles from Saharan dust intrusions on circulatory mortality (Zhang et al., 2016).

According to the results obtained through an assessment by **gender and age**, some differences were observed between men and women regarding of the effects of drought conditions on specific causes of daily mortality. Previous studies have also indicated that both genders respond differently, in terms of mortality, to the effect of heatwaves (Díaz et al., 2002) and air pollution (Clougherty, 2000). The risks varied between the long and short study periods. From 1983 to 2016, the SPEI only reflected a significant influence of short-term droughts on circulatory mortality in women, whereas the use of SPI showed greater risk of respiratory and natural death among men. In addition, only men´s daily mortality in the population aged 65 to 74 years old was affected significantly by drought. For the more recent sub-period analysed, from 2007 to 2016, the results obtained for men and women of all ages were very similar. However, when an analysis by age was conducted, there were marked differences showing that men were more strongly affected by short-term droughts than women. In this regard, the risk and the magnitude of the effects associated with drought are defined by the product of the exposure to a specific event in a given region and the vulnerability of the population to this hazard (Wilhite, 2000; Quiring, 2015). Gender-based differences in population structure, social relationships, customs, and sensitivity and adaptation capability could influence the vulnerability and risks to men and women (Kallis, 2008; United Nations, 2019). The World Health Organization has indicated that men and women have different roles, behavioural attitudes, and means and strategies with which they respond to climatic phenomena (WHO, 2014). Moreover, as a possible explanatory hypothesis for the results obtained specifically for the period 2007 to 2016, men could have been more engaged in activities in which their health risk could have increased via a greater degree of exposure to drought (e.g., activities that involve more time outdoors). This could have resulted in a greater vulnerability and contributed to greater risks they faced (Yusa et al., 2015). In this context, a recent report from the United Nations indicates that differences in vulnerability of each gender to the effects of climate change depend principally on social factors, not biological sex. Conversely, other studies have shown that sex-linked differences (e.g., hormone levels) could influence the degree of susceptibility that men and women face from environmental hazards (Clougherty, 2010; Van Steen et al., 2019). However, this topic has not been studied sufficiently and more is not known. The relationship between gender and vulnerability is complex. Evidence shows that, generally, women face a greater risk of mortality associated with extreme events; however, regional variability results in men being more affected in specific parts of the world (IPCC, 2014). Though, a recent study conducted in the United States from 1983 to 2014 indicated systemic differences (heterogeneity) in association between drought severity and all-cause mortality rates based on climate region, race, and age, but not gender (Lynch et al., 2020). This highlights the need to carry out further assessments focused on the health effects of climate and environment by both gender and age. The differences observed in the mortality risks between the long and short periods could also be influenced by differences in the vulnerability of the population. These could change over time and increase or decrease as a function of the response to changes in the population numbers, rural to urban shifts (or vice-versa), demographic characteristics, or other social factors such as technology, policy, education, or other behaviours (Wilhite, 2000; Quiring, 2015).

This study also allowed a comparison of **the performance of SPEI and SPI calculated** in the short-term (one month of accumulation) and short-to-medium term (three months of accumulation) from 1983 to 2016 and for the short-term from 2007 to 2016 for identifying and quantifying daily natural, circulatory, and respiratory mortality in Lisbon district. The main findings revealed that, generally, SPEI was more capable than SPI of reflecting the different mortality risks attributable to the incidence of this type of hydrological extreme, especially in the short study period. Moreover, according to the timescale used, the results suggested that SPEI calculated for the short-term appeared to be more optimal than that used for the short-to-medium term in identifying a greater number of statistically significant associations between daily mortality and drought among the different population groups, which contrasts with what was found with the use of SPI. However, previous studies conducted in peninsular Spain indicated that, in general, both types of indices were equally valid for assessing the effects of daily natural, circulatory, and respiratory mortality attributable to drought because they produced similar results with some regional exceptions (Salvador et al., 2019; 2020b;c). It thus appears that in Lisbon district, the inclusion of the atmospheric evaporative demand in the calculation of the SPEI makes this index more optimal to reflect the mortality impact of short-term droughts. The SPEI is based on a climatic water balance that takes the influence of temperature into account. In contrast, the SPI, only requires precipitation data for its calculations. As the impact of drought depends largely on its severity (Stanke et al., 2013; Berman et al., 2017; Salvador et al., 2020a), the fact that SPEI can identify an increase in drought severity linked to higher water demand by the potential evapotranspiration (Vicente-Serrano et al., 2010; Spinoni et al., 2017) could make it more sensitive in detecting specific effects on health, especially for periods with high temperatures. This finding regarding the results of SPEI vs. SPI was also observed in other studies that were not health-related. For instance, Vicente-Serrano et al. (2012) indicated small differences in the comparative performance of the drought indices but noted that SPEI had a superior capability to predict the effects of drought on streamflow, soil moisture, forest growth, and crop yield (particularly in summer). This was also the case in another European study that evaluated the impact of drought on agriculture, energy and industry, public water supplies, and freshwater ecosystems (Stagge et al., 2015).

In the second part of this study, the short-term effects of heatwaves and atmospheric pollution on daily mortality were controlled. Both mechanisms are, in principle (but not limited to), the most influential in terms of health links to drought. Therefore, for cases in which there were significant associations between drought and daily mortality for the period from 2007 to 2016, the control of the short-term effects of heatwaves and atmospheric pollution was included along with the drought indices in the Poisson models. The three consecutive steps conducted revealed additional information of possible links between SPEI/SPI and heatwaves and atmospheric pollutants in terms of explaining their impact on daily mortality. First, only the influence of short-term droughts was assessed, then a control of the short-term effect of heatwaves was added, and finally pollution variables were included in the statistical models as the third environmental parameter.

Regarding the additional control of the effect of the heatwaves alone, the impact on daily mortality was mainly influenced by the effect of drought conditions measured in the short-term and the occurrence of heatwaves or only by the occurrence of extreme high temperatures. Thus, the impact of droughts was explained by the effect of heatwaves in some cases. When atmospheric pollution was also included in the analysis, the significant signal from drought indices previously observed disappeared in almost all cases among the population, leaving the effect of heatwaves and atmospheric pollutants to explain daily mortality. Otherwise, the drought indices explain largely the relationship with mortality through heatwave temperatures and pollution levels in Lisbon district. Similar results were obtained in Spain for the total population in many provinces (Salvador et al., 2019, 2020b). However, these mechanisms did not explain the impact in specific cases among the total and male populations (in particular, men 64 to 75 years old who died of circulatory-related and natural causes); therefore, there must be another drought-binding mechanism that elucidates the effect. Drought episodes are frequently linked to the occurrence of persistent blocking conditions (Hu et al., 2019; Vicente-Serrano et al., 2020) that are strongly associated with the occurrence of extreme cold events in winter (Sillmann et al., 2011) with serious repercussions on natural, cardiovascular, and respiratory mortality, as Carmona et al. (2016) and Antunes et al., (2017) showed for the Iberian Peninsula. In Lisbon in particular, there has been a marked excess of mortality due to circulatory diseases in winter (Almendra et al., 2015). In summary, the main findings obtained in this study suggest that drought indices were indirect indicators that reflected with a high level of confidence the impact of pollution and heatwaves on daily mortality. Both phenomena are often associated with drought, but the indices were able to account for more than these two environmental factors.

Heatwaves were the major environmental risk factors for daily natural, circulatory, and respiratory mortality among the population, corresponding to the highest RR of mortality. Several studies show a remarkable impact of extreme heat on specific-cause mortality via direct and/or indirect effects, as warmer temperatures are frequently linked to poor air quality and higher levels of pollutants such as ozone and PM_{10} (Trigo et al., 2009; IPCC, 2014; Peterson et al., 2014; Franchini and Mannucci, 2015; Díaz and Linares et al., 2018; Royé et al., 2020). Although extreme heat temperatures and atmospheric pollution can occur independently and without the presence of drought conditions, in many cases the impact on health is often the result of the occurrence of compound or cascading events (Seneviratne et al., 2012, Raymound et al., 2020). For instance, heatwaves, droughts and wildfires are closely associated phenomena characterised by common precursors (persistent decrease in precipitation and increase in temperature) (Peterson et al., 2014; Bell et al., 2018). Evidence indicates that in Southern Europe, in particular, drought has an important role in the occurrence of compound and cascading hazards (Sutanto et al., 2020) and several studies conducted in Portugal have evaluated the links between these phenomena (Parente et al., 2018; Parente et al., 2019; Turco et al., 2019). Drought can accelerate a heatwave via land–atmosphere feedback mechanisms and in turn high temperatures can lead to drier soils. Moreover, both climatic phenomena can promote the occurrence of wildfires (IPCC, 2014; Sutanto et al., 2020), which have a notable impact on natural, respiratory, and circulatory mortality owing to exposure to wildfire smoke (Collen et al., 2016; Black et al., 2017). In this context, drought is frequently associated with increased pollution (higher levels of dust, ozone, and other pollutants) not only because of its strong association with wildfires, but also through its direct effect on atmospheric chemistry (Wang et al., 2017; Vicente-Serrano et al., 2020). Moreover, the fact that drought events are often associated with a persistent upper-level high-pressure system or a ridge that produces an inversion layer aggravates the pollution generated under these conditions (Peterson et al., 2014). PM_{10}, NO_2, and O_3 have serious effects on health, –including natural, circulatory, and respiratory mortality, –with the highest effect on respiratory mortality, coming particularly from O_3. The inhalation of atmospheric pollutants is associated with a reduction in lung function and exacerbation of respiratory diseases because it leads to high inflammation, oxidative stress, and cytotoxicity. Poor air quality is also linked to a high risk of hypertension, ischaemic events, and heart failure (Du et al., 2016; Ortiz et al., 2017; Linares et al., 2018; Díaz and Linares, 2018).

Meanwhile, the effects of drought on daily mortality that remained statistically significant in specific groups of the total population and men independently of the control of the effect of heatwaves and pollution, could be linked to other impacts of drought that have not been considered in this analysis; such impacts include the extreme cold events previously mentioned. Moreover, other specific mechanisms associated with human physiology–such as the impact of breathing dry air into an otherwise moist lung and the potential influence of lung dryness on atmospheric pollutants entering therein and crossing into the blood stream to exert physiological effects, –could also influence health outcomes although they could not be measured in this study. In addition, serious mental health issues that could possibly be linked to drought events (e.g. chronic stress, anxiety, and depression) should also be taken into consideration (Magalhães, 2016). Such mental health issues have been linked to pathogenic processes and could result in a higher risk of mortality, especially in vulnerable populations such as farmers, farm workers, or those with pre-existing conditions (Edwards et al., 2014; IPCC, 2014; Berman et al., 2017; Salvador et al., 2020a). The World Health Organization has indicated that prolonged droughts can increase the suicide rate in male farmers (WHO, 2014). An Australian study described differences in the effects of droughts on mortality by suicide between men and women in New South Wales in the period from 1997 to 2007. That study found that there was an increase in suicide by 30 to 49 year-old rural male farmers and farm workers during droughts, whereas there was a decrease in suicide among rural women over 30 years old during similar conditions (Hanigan et al., 2012).

Finally, the present work has some limitations inherent to any ecological study. For instance, the results are not extrapolated to an individual level, and air pollutant data and maximum temperature do not represent individual exposure due to the heterogeneity of the measurements. In this context, the exposure levels used were based on averages of readings taken from outdoor air quality stations. Therefore, they do not represent entire individual exposures. Moreover, there was a problem of misalignment that has also been described in other studies evaluating the impact of air pollution on health (Gelfand, 2010; Barceló et al., 2016). Another limitation of this study was its inability to measure variables related to human physiology and examine others, such as the previous health conditions of the group being studied and race, which could affect vulnerability to drought in terms of impacts on mortality. According to the main findings of this study, seasonal analysis is therefore a necessity in future research to improve our knowledge of the impact of drought by accounting for cold waves and flu epidemiology as other controls. Moreover, an evaluation of the relationship between mental health and the occurrence of longer drought events as a possible causal factor for cardiorespiratory affectations is also required.

5. CONCLUSIONS

Effects of drought measured by two indices (SPEI and SPI) on specific-cause mortality, including an assessment by gender and adult age group, were evaluated in the Lisbon district. The main conclusions were the following:

- Droughts had a significant impact on daily natural, circulatory, and respiratory mortality across the population.
- Not all the study subgroups within the population were equally affected by the drought conditions in terms of daily mortality and the risks varied between the long and short studied periods.
- In terms of age-based assessments, there was no statistically significant association between drought events and mortality in people aged 45 to 64 years old. For the long study period, individuals 75 years old and above were the most vulnerable group; for the sub-period 2007 to 2016, there was a notable impact both in those 65 to 74 years old and those 75 years old and above, with the latter being the most affected.
- There were gender differences in the risks of mortality associated with the incidence of this hydroclimatic phenomenon. These differences were more evident for the last decade of the studied period when both gender and age were considered in the analysis; the male population was more affected than the female population.
- Short-term drought indices largely reflected the impact of heatwaves and atmospheric pollution, phenomena often associated with drought, with heatwaves presenting the highest risk. However, when an analysis by age group was conducted for specific cases in the total and male populations, none of

these mechanisms were able to explain the effect of droughts.

- The SPEI, which incorporates the influence of temperature in its calculations by including the effect of evapotranspiration, was a better indicator of the different risks of mortality attributable to the incidence of drought than the SPI, which accounted only for precipitation. The use of a drought index that incorporates the impact of heat and pollution and sensitive to global warming is particularly important considering future projections of climate change that indicate more frequent and intense extreme events.
- The integration of these results that consider the assessment by gender and age into public health are crucial to the enhancement of action plans and the development of more effective measures to address the risks of these climatic extremes on health (mitigate the effects and reduce the vulnerability among the population subgroups).

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Declaration of competing interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Credit Author Statement

Coral Salvador: Conceptualization, Writing-Original draft preparation, Writing-Reviewing and Editing, Raquel Nieto: Writing-Reviewing and Editing, Supervision, Cristina Linares: Writing-Reviewing and Editing, supervision, Julio Díaz: Writing-Reviewing and Editing, supervision Célia A. Alves: Writing-Reviewing and Editing, investigation, Luis Gimeno: Writing-Reviewing and Editing, supervision. All authors have read and agreed to the published version of the manuscript.

Graphical abstract

Highlights

Drought was associated with all analysed causes of daily mortality in Lisbon district

SPEI showed an improved capability to reflect mortality risks as compared with SPI

The oldest population groups had the highest risks of mortality linked to drought

There were differences in mortality risks linked to drought between men and women

Mortality was largely explained by pollution and heat, often linked to short droughts