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The potential of using climate indices as powerful tools to explain mortality anomalies: An application to mainland Spain

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ABSTRACT

Changes in the frequency and magnitude of extreme weather events represent one of the key indicators of climate change and variability. These events can have an important impact on mortality rates, especially in the ageing population. This study assessed the spatial and seasonal distributions of mortality rates in mainland Spain and their association with climatic conditions over the period 1979–2016. The analysis was done on a seasonal and annual basis using 79 climatic indices and regional natural deaths data. Results indicate large spatial variability of natural deaths, which is mostly related to how the share of the elderly in the population varied across the studied regions. Spatially, both the highest mortality rates and the largest percentage of elders were found in the northwest areas of the study domain, where an extreme climate prevails, with very cold winters and hot summers. A strong seasonality effect was observed, winter shows more than 10% of natural deaths compared to the rest of the seasons. Also, results suggest a strong relation between climatic indices and natural deaths, albeit with a high spatial and seasonal variability. Climatic indices and natural deaths show a stronger correlation in winter and summer than in spring and autumn.

1. Introduction

Although climate conditions affect human health, physiology, and mortality (McMichael and Lindgren, 2011), understanding the impacts of climate change and variability on human health is challenging. In the context of climate change, a higher frequency of extreme events (e.g. heatwaves, droughts, etc) has been reported in numerous studies at different spatial scales (e.g. Luber and McGeehin, 2008, Sheffield and Wood 2008; IPCC, 2013; Allan et al., 2020). Several studies have been conducted in the past to understand the relationships between human mortality and heatwaves (e.g. Basu and Samet, 2002; D'Ippoliti et al., 2010; Åström et al., 2011; Yin et al., 2018). Most of these studies indicate that heatwaves increase human mortality. A representative example of this is the 2003 heatwave which led to 44,000 excess fatalities in Europe as reported by the World Health Organization (WHO) (Trigoet al., 2009; Tobias et al., 2012). However, it is not only heatwaves that can have a high impact on mortality. Also cold waves (Analitiset al., 2008; Montero et al., 2010) and drought events (Stankeet al., 2013; Yusa et al., 2015; Berman et al., 2017; Salvador et al., 2020a) can have a major impact on mortality. Epidemiological evidences indicate that part of the deaths caused by cold waves are due to their infectious nature, while an increase in the number of deaths during heat waves is caused by the direct effects of heat stress on the individual metabolism (Montero et al., 2010). Drought, on the other hand, has also significant health impacts, including an increasing risk of morbidity and mortality (Stankeet al., 2013). Also, drought has indirect effects on human health and mortality, as deaths in this case may be caused by the reduction of water resources quantity and quality, crop and food production, or an increased risk of heat-waves and wildfires, among others (Salvador et al., 2020b).

The ways in which climate can impact mortality vary considerably between seasons and dominant climatic conditions (Ballester-Díezet al., 1997; Simón et al., 2005; López-Perea et al., 2011). Seasonally, the increased mortality during cold months compared to warm ones is

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well-established (Mackenbachet al., 1997; Sheridan and Kalkstein, 2004; Simón et al., 2005). Causes of death, which are more associated with temperature changes, are circulatory and respiratory diseases (Ballester-Díezet al., 1997). Furthermore, it is important to note that seasonal and annual flu epidemics involve a high level of hospitalizations and winter mortality (Fleming, 2000).

Numerous studies have evaluated the relationship between climatic variability and mortality (e.g.). Most of these studies use thermal data to evaluate this relationship (e.g. Carmona et al., 2016), and very few studies include other climatic variables. Kalkstein and Davis (1989) described the impact of weather on human mortality in numerous locations around the United States. Díaz et al. (2002) found that very hot weather is associated with high levels of mortality, especially in people over 65 years of age. Curriero et al. (2002) found associations between extremely high or low air temperatures and mortality in 11 cities in the eastern regions of the United States. Davis et al. (2003) calculated the annual excess mortality on days when apparent temperatures exceeded a threshold value for 28 in the largest metropolitan areas in the United States. Davis et al. (2004) found that mortality is higher on extremely hot and humid summer days, although mortality rates are higher in winter. McGregor (2005) studied the relationship between ischemic heart disease mortality and the North Atlantic Oscillation (NAO) in winter. Analitis et al. (2008) studied the effects of cold weather on mortality in 15 European cities. Miron et al. (2008) found that the drop in comfort temperature in Castilla-La Mancha (Spain) is attributable to the increase in the effects of heat on mortality due to the increase in the elderly population. Andrade et al. (2011) have investigated the relationship between people declared bioclimatic comfort, their personal characteristics and the atmospheric conditions in Lisbon (Portugal). Some studies have used the general circulation of the atmosphere, such as the classification of weather types, to understand better the climate-mortality relationship. Recently, a study by Fdez-Arróyabe et al. (2021) found out a link between atmospheric circulation and the number of influenza-related hospital admissions in the Spanish Iberian Peninsula during 2003–2013.

Although mortality is conditioned by climatic conditions, other socio-demographic characteristic, such as age, socioeconomic status, and number of inhabitants, can affect this association (Schwartz et al., 1995; Hummer et al., 1998). There is evidence that climate conditions have a particularly relevant impact on elderly population (D'Ippoliti et al., 2010), mainly due to the decreased physiological capacity to regulate body core temperature (Kenney and Munce 2003). In this regard, the spatial distribution of the elderly population allows to define which regions are more sensitive to the impact of climate changes on mortality.

Although most investigations about the relationship between climatic conditions and mortality take into account the effects of temperatures on mortality (Díaz et al., 2002; Achebak et al., 2018; Rasilla et al., 2019), other important climatic variables that can affect mortality (e.g. precipitation, wind, radiation, cloud cover, etc.) have received less attention. For example, lack in precipitation drives droughts; wind conditions influence pollution; and cloudiness affect precipitation. It is therefore important to have a catalog of comprehensive climate indices, which can be used to understand the impacts of different climatic factors on mortality rates. Many efforts have been made to develop climatic indices to understand the evolution and state of climate (e.g. Frich et al., 2002; (Klein Tank, 2003); Alexander et al., 2006; Moberg and Jones 2005; Klein Tank et al., 2009). These climatic indices have been employed in a number of previous studies to assess the impacts of climate on various sectors, such as the impact of drought on agriculture (e.g. Kuwayama et al., 2019) or water resources (e.g. Hui-Mean et al., 2018), among others. Recently, the database and cartographic viewer "INDECIS dataset" was published, including the highest range of climatic indices (N=125) for Europe. These indices were published with the aim of serving as a tool to evaluate the impact of climate on different socioeconomic sectors (Domínguez-Castro et al., 2020; https://indecis.csic.es/). This database contains the largest set of climatic indices, provided at a high spatial resolution and for a continuous and updated period of time. Also, the "ECTACI database" has been published recently by Peña-Angulo et al. (2020) (https://ectaci.csic.es/), allowing the characterization of the climatology, variability and trends of the 125 indices of the INDECIS database.

This study employs the INDECIS climatic dataset to assess the impacts of climate on natural deaths. The study is based on data from mainland Spain, which has interesting socio-demographic and climatic characteristics. Specifically, like the whole Spanish territory, mainland Spain is characterized by high rates of elderly populations and low birth rates (Leasure, 1963; Åström et al., 2011; Pueyo et al., 2014). Also, Spain is characterized by a strong spatial and temporal variability of its climate, with several configurations driving this variability (e.g. Atlantic, Mediterranean, sub-tropical, etc.). In addition, mainland Spain has witnessed frequent extreme heat events, which can induce high mortality rates. Overall, these demographic and climatic features make mainland Spain a good base region to assess the spatial and temporal variability of mortality in relation to climate change and variability, This study aims to: i) assess the spatial and seasonal distribution of mortality in mainland Spain; and ii) analyze the relationship between climatic indices and mortality taking into account spatial, seasonal, and inter-index differences.

2. Materials and methods

Mortality was estimated from the daily records of human deaths by natural causes, provided by the Spanish National Statistics Institute (INE). This includes data from 47 provinces in mainland Spain (Fig. 1) for the period 1979–2016. Additionally, the total population in mainland Spain (Fig. 1) and the population distribution by age in each province in 2015 were obtained from the INE.

Regarding climate data, we used seasonal and annual records from 79 climate indices for mainland Spain spanning the period 1979–2016 and with a spatial resolution of 0.25°. The climate indices were calculated using daily data from different climate variables. Data of these indices are available on the INDECIS project website (http://www.indecis.eu/). Further details about the main characteristics of this dataset are documented in Domínguez-Castro et al. (2020). Mainly, climate indices were grouped into seven broad categories: temperature (42), precipitation (21), bioclimatic (21), aridity/continentality (10), cloud/radiation (5), wind (6), and snow (12). A list of these selected indices is given in Fig. 2.

In this study, data of climatic indices and natural deaths for each province were considered for the period 1979–2016. Data were analyzed on seasonal and annual scales. Seasons were defined as: winter (DJF), spring (MAM), summer (JJA), and autumn (SON). A composite regional series for mainland Spain was also constructed using an arithmetic average of all province series. Importantly, to limit the possible impact of trends presented in population data in the number of deaths, we detrended the series of number of deaths using the ordinary least squares regression method, in which time was considered the independent variable, while the number of deaths was the dependent variable.

In mainland Spain, we examined the spatial distribution of natural deaths and the elderly population. The ageing index is the most commonly used method to measure aging in a given population. This index is simply defined as the proportion of the number of people over 65 years old relative to the number of people under 16 years old (INE, 2020). The ageing index was calculated for each province in mainland Spain in 2015. Also, we estimated the total number of natural deaths during the study period with respect to the total population in each province in 2015. Herein, we assumed that the population of each province in 2015 is representative of the population for the whole study period. This assumption was verified using the coefficient of variation (CV) in years with available information through the INE database (https://www.ine.es/jaxiT3/Tabla.htm?t=2852&L=0). The CV did not

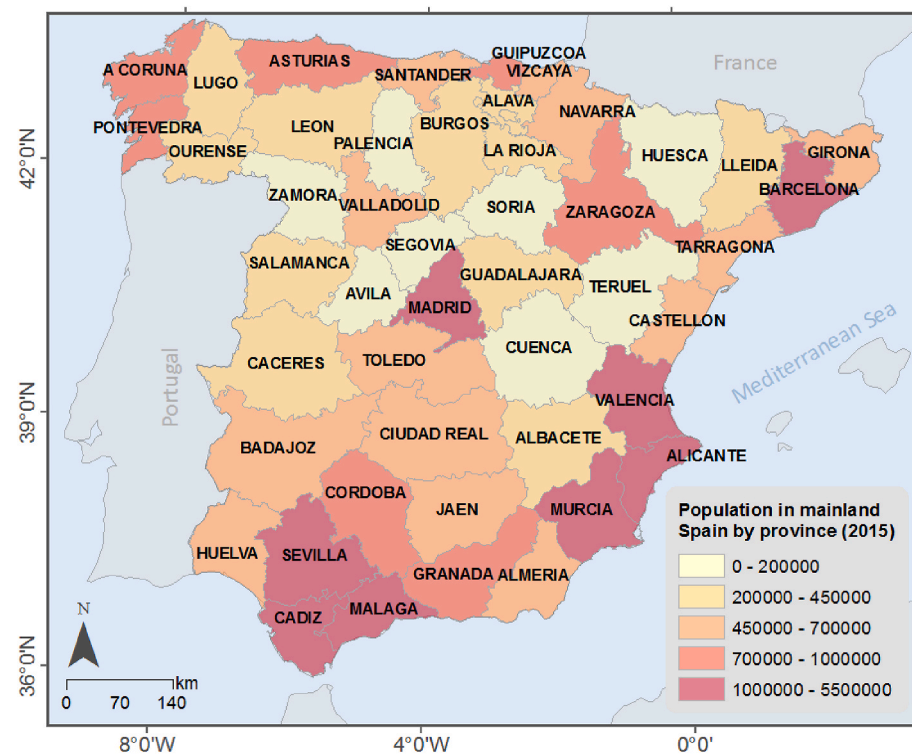

Fig. 1. Study area and total population by province in mainland Spain.

Temperature

CFD	Maximum consecutive frost days
CSD	Maximum number of consecutive summer days
CSDI	Cold spell duration
D32	Days with maximum temperature > 32°C
DD17	Difference days above/below with TXx 17°C
DTR	Diurnal temperature range
ETR	Extreme temperature range
FD	Frost days
GD4	Growing degree days
GTG	Mean average temperature
GTN	Mean minimum temperature
GTX	Mean maximum temperature
HD17	Heating degree days
ID	Ice days
NTG	Minimum mean temperature
TNn	Minimum minimum temperature
TXn	Minimum maximum temperature
OGS6	Onset of growing season 6 days
OGS10	Onset of growing season 10 days
SU	Summer days
TN10p	Cold nights
TN90p	Warm nights
TR	Tropical nights
TX10p	Cold days
TX90p	Warm days
VCD	Very cold days
vDTR	Mean daily difference DTR
VWD	Very warm days
WSDI	Warm spell duration
XTG	Maximum mean temperature
TNx	Maximum minimum temperature
TXx	Maximum maximum temperature
ZCD	Zero crossing days

Precipitation

CDD	Longest dry period
CWD	Longest wet period
D50mm	Heavy precipitation days
D95p	Very wet days
DD	Dry days
DR1mm	Wet days 1mm
DR3mm	Wet days 3mm
EP	Effective precipitation
R10mm	Days precipitation ≥ 10mm
R20mm	Days precipitation ≥ 20mm
R95tot	Precipitation fraction very wet days
R99tot	Precipitation fraction extremely wet days
RTI	Total precipitation
PRCPTOT	Total precipitation wet days
RX1day	Maximun precipitation
Rx5day	Maximum 5 days precipitation
SDII	Simple daily intensity index

Aridity/Continentality

CMD	Climatic moisture deficit
ETo	Reference evapotranspiration
UAI	UNEP aridity index

Cloud/Radiation

ACI	Atmospheric Clarity Index
CC	Mean daily cloud cover
FOD	Foggy days
SND	Sunny days
SSD	Sum of sunshine duration
SSp	Sunshine duration fraction

Bioclimatic

AT	Apparent temperature
BIO20	Mean radiation
HI	Heat index
MI	Mould index
UTCI	Universal thermal climate index
WCI	Wind chill index

Wind

DFx21	Days wind gusts above 21 m/s
FG	Mean of daily mean wind strength
FG6Bft	Days daily averaged wind above 10.8m/s
fgcalm	Calm days
FXx	Daily maximum wind gust

Snow

ASD	Average snow depth
FSD	Frequency of snow days
HSD	Heavy snowy days
MS	Maximum snow depth
MSD	Mild snowy days
SCD	Amount of snow covered days
SD0_10	Snow days depth 1-10
SD10_20	Snow days depth 10-20
SS	Snowfall sum

Fig. 2. A list of climate indices used in this study, and their definitions.

exceed 0.2 in any provinces, indicating that the population is almost homogenous, with low dispersion over time.

Finally, we looked at the climate-mortality association using Pearson's r correlation analysis. Correlations were computed between climate indices and seasonal records of natural deaths. The correlation analysis allowed us to define indices with stronger (positive or negative) relationship with natural deaths. Also, the correlation analysis was made at the province level to define spatial variability in the relationship between climate and mortality. For |r| values less than 0.320, a non-significant correlation was defined. Accordingly, significant correlations with p-levels below 0.05 and 0.01 were detected when |r| values exceeding 0.320 and 0.512, respectively.

3. Results

3.1. Spatial and seasonal distribution of natural deaths in mainland Spain

Results indicate large spatial differences in natural deaths, which are linked to the way in which the percentage of elderly population varies across the study domain. Fig. 3 shows the spatial distribution of the ageing index and the number of natural deaths, compared to the total population in mainland Spain in 2015. As illustrated, the northwest

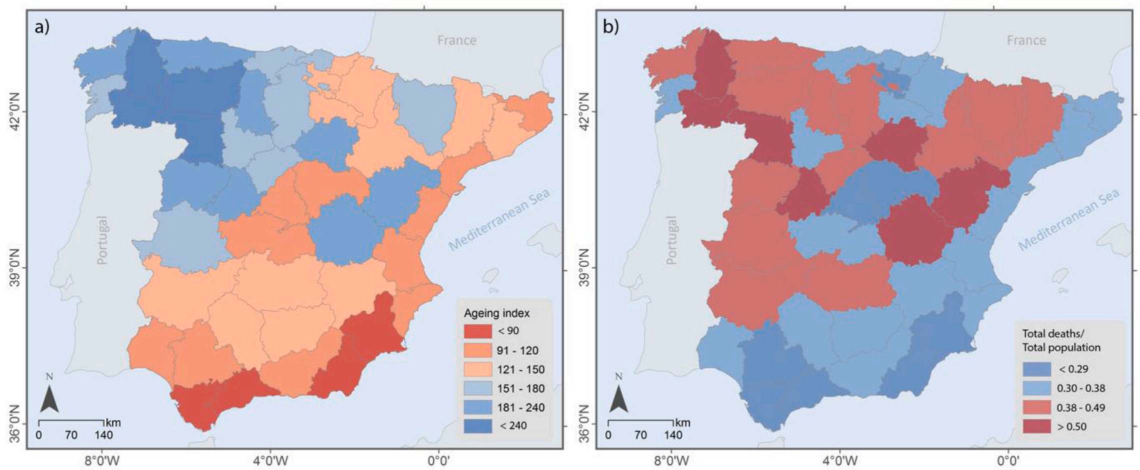

Fig. 3. a) Ageing index in 2015. b) The number of natural deaths relative to the total population in 2015. Results are presented for each province in mainland Spain.

territory had a higher ageing index and natural deaths, while the eastern and southern regions had lower ageing indices and natural deaths. As expected, there wass a high spatial agreement between provinces exhibiting the largest percentage of elders and those with the highest number of deaths (e.g. Ourense, Lugo, Zamora, Teruel, Soria, Cuenca, Ávila, and Palencia). In contrast, provinces with lower percentages of elders witnessed the lowest number of deaths (e.g. Madrid, Alava, Cadiz, Almeria, Murcia, Sevilla, and Guadalajara).

Spatially, we defined two main patterns summarizing the links between the number of natural deaths and climatic conditions dominating in the study domain. First, the provinces with the higher mortality and aging were found mainly in the northwestern provinces characterized by low winter temperatures. Second, younger populations and lower death rates were found in the southern provinces, with high summer temperatures and moderate winter temperatures.

Temporarily, results suggest a strong seasonal variability of the number of natural deaths. The lowest mortality rates were found during summertime, while the highest rates were recorded in winter. Fig. 4 shows the regional series of natural deaths, calculated for each season independently. As illustrated, a higher number of deaths was observed in winter, followed by spring. The lowest numbers of death cases were recorded in summer and autumn. Unsurprisingly, a marked peak of natural deaths was noted in the summer of 2003, which corresponds to an anomalous heatwave that affected most of Europe (Trigoet al., 2009; Tobias et al., 2012). On the other hand, winter exhibited higher temporal variability of natural deaths than other seasons.

3.2. Dependency between climatic indices and mortality rates in mainland Spain

Results reveal strong seasonal differences in the relationship between climate and mortality. Fig. 5 shows the correlation coefficients computed between regional time series of natural deaths and 79 climate indices for each season. As illustrated, correlations were higher and statistically significant in winter and summer. Conversely, Pearson's r coefficients were much lower and mostly non-significant in spring and autumn. In winter, many climate indices exhibited strong negative correlations with natural deaths, while correlations were mostly positive in summer. For cold-day indices (e.g. CFD, CSDI, AT, and WCI), as well as radiation indices (e.g. SND, SSD, and SSP), a positive correlation with the number of natural deaths was found during wintertime. Contrarily, negative correlations were found for temperature indices associated with warm days (e.g. XTG, XTN, HI, and UTCI), cloudiness indies (e.g. CC, FOD), wind indices (e.g. FG, FG6Bft, and FXX), and most precipitation indices (e.g. RTI, PRCPTOT). In summer, most indices were positively correlated with the number of natural deaths, except DTR and FOD. Typically, this was the case for indices related to mean, minimum, and maximum temperatures like CSD, D32, DD17, TN90p, TX90p, VWD,

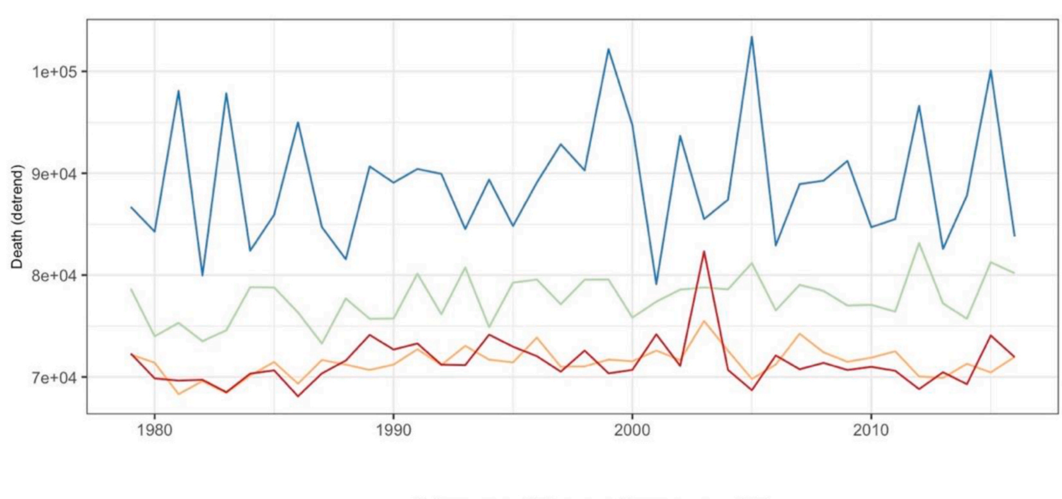

Fig. 4. Seasonal number of natural deaths in the averaged series of mainland Spain for the period 1979–2016.

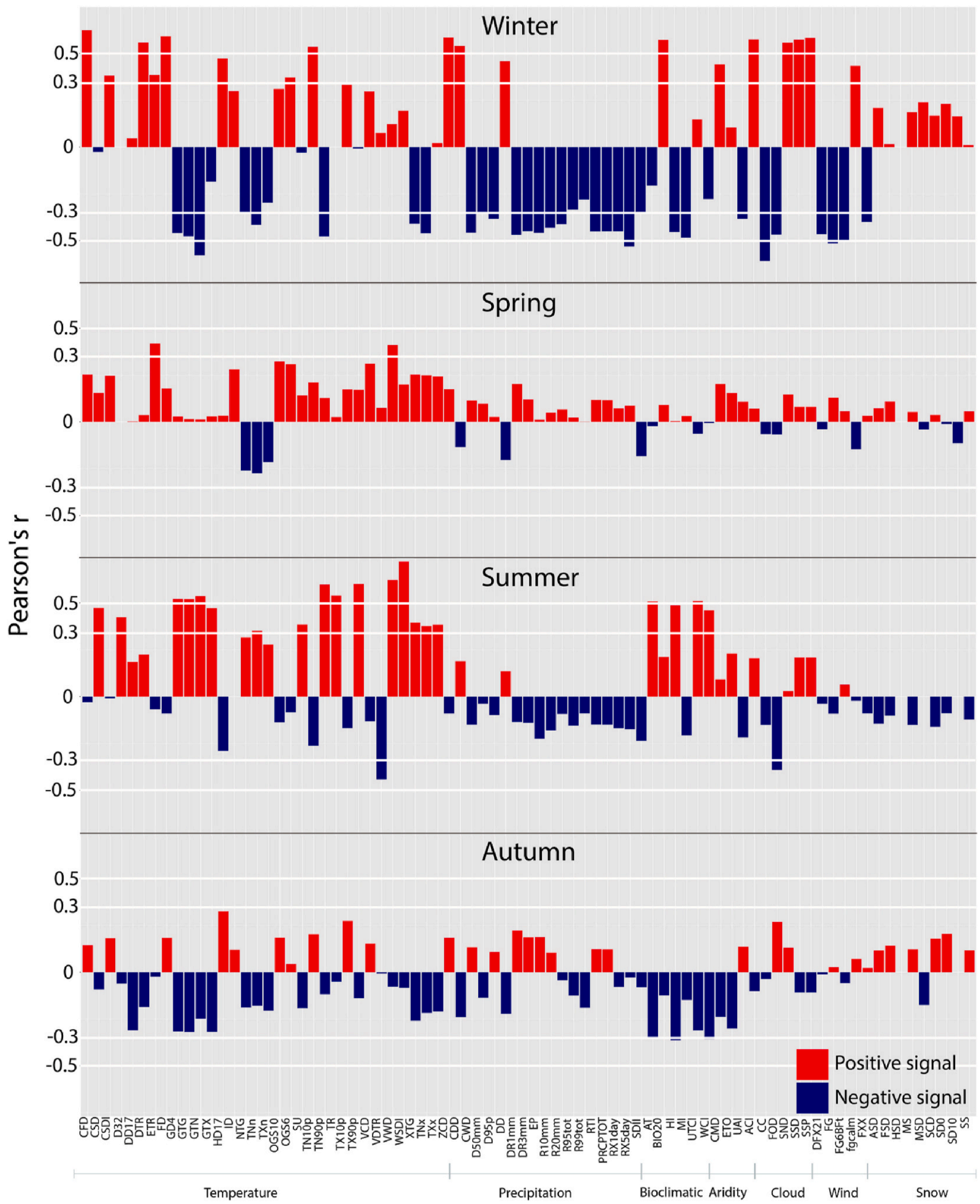

Fig. 5. Correlation coefficients between natural deaths and the 79 climate indices for the period 1979–2016 using the arithematically averaged regional series. The horizontal white lines indicate correlation values corresponding to the 95% and 99% significance levels.

and WSDI.

Overall, results indicated that the frequency of cold days was associated with an increase in mortality during wintertime. On the contrary, high frequency of warm days during winter was associated to a decrease of mortality. Most climate indices, especially thermal indices, showed positive correlations with the number of natural deaths during summer. Specifically, VDTR, CC, VWD, and WSDI showed the highest correlations with natural deaths. In winter, indices showing the highest correlations were CFD, FD, SND, SSD, SSP, CC, and FOD. Notably, in both cases, precipitation indices exhibited remarkably negative correlations with the number of natural deaths, being much stronger in winter than in summer.

The above-described relationships were supported by a spatial analysis that considered these associations at the province level (Fig. 6). At the province level, it was confirmed that correlations between climate indices and natural deaths were stronger in winter and summer, compared to spring and autumn. However, the sign of the correlations and the corresponding spatial distributions were different between these two seasons. Warm indices showed strong correlations with natural deaths, especially for WCI, UTCI, HI, AT, WSDI, TR, TX90p, and TN90p during summer. However, consistent spatial patterns cannot be identified. In the western provinces, precipitation indices showed higher correlations than other provinces.

Fig. 7 illustrates the spatial distribution of the correlation coefficients calculated between the number of natural deaths and a set of significant temperature (FD, WSDI), precipitation (RTI), and cloud/radiation (CC, SSP) indices for winter and summer. The FD index, defined as the total number of days with minimum temperature lower than 0 °C, showed higher positive correlations with natural deaths during wintertime, mainly in the western provinces. The WSDI index, which counts periods

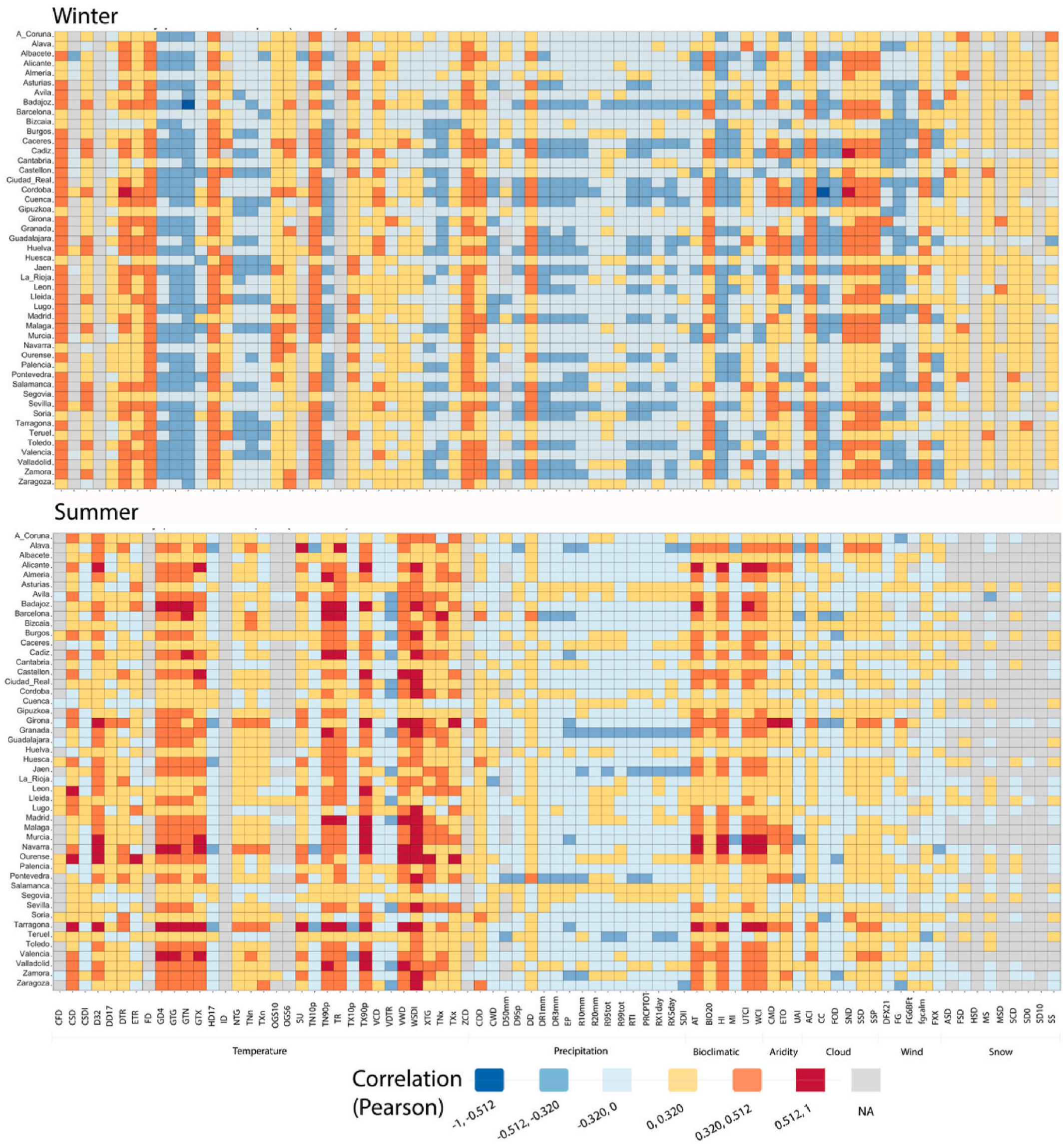

Fig. 6. Correlation coefficients between natural deaths and the 79 climate indices for the period 1979–2016.

with at least 6 consecutive days with maximum air temperatures exceeding the 90th percentile of maximum air temperature distribution, correlated significantly and positively with natural deaths during summer. This strong link was evident for the whole study domain. On the contrary, correlations were not statistically significant in winter, but with marked differences between maritime and continental provinces. Both RTI (total precipitation) and CC indices (daily mean cloud cover) revealed consistent seasonal and spatial patterns. Specifically, they showed strong negative correlations with natural deaths during wintertime, especially in the western provinces. In contrast, this dependency was statistically non-significant during summer, with no clear spatial patterns. Similarly, the SSP index (sunshine duration fraction) and CC (daily mean cloud cover) exhibited consistent spatial patterns in their relations with natural deaths, albeit with opposite correlation signs.

4. Discussion

4.1. Spatial and seasonal distribution of natural deaths in mainland Spain

The highest rate of natural deaths was found mainly in northwestern provinces of mainland Spain, where elderly populations and colder climate conditions are predominant. Overall, as compared to other European countries, Spain is characterized demographically by having a high percentage of elders, with an increasing trend of life expectancy and lower birth rates (Gutiérrez Posada et al. 2018). Indeed, there are important social and economic implications of these demographic characteristics, especially for healthcare services. Furthermore, the spatial distribution of the aging population is highly heterogeneous, given that more innovative regions (large urban areas) attract young people from rural areas. Historically, the differences between urban and rural regions in terms of innovation and aging population have grown rapidly (Gutiérrez Posada et al. 2018). In Spain, there are higher ageing rates over northern and northwestern regions, while lower ageing population rates is a characteristic of Madrid and southern regions (Blasco, 2008). From a climatic perspective, northern and northwestern portions of mainland Spain are characterized by colder but seasonally dependent climate. Several studies have reported that elderly populations are mostly impacted by extreme weather events like heat and cold waves (Hajatet al., 2007; Åström et al., 2011; Abrahamson et al., 2009; Achebak et al., 2019). This is typically the case in mainland Spain, where regions of elderly populations are subjected to frequent and more severe extreme events (Jiménez, 1989).

Hot and cold events are a risk factor for the health of the vulnerable

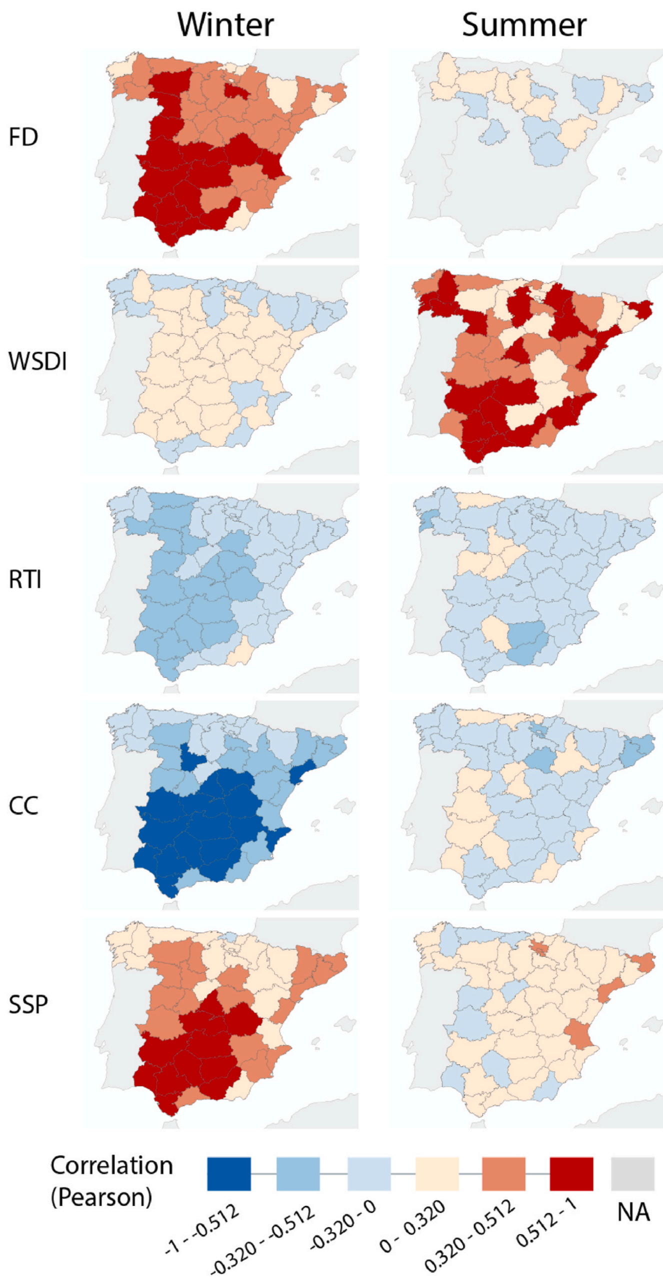

Fig. 7. Spatial distribution of correlation coefficients between natural deaths and some significant indices (FD, WSDI, RTI, CC, and SSP) in each province in mainland Spain during winter (left) and summer (right) for the period 1979–2016.

population, such as the elderly. Elders have a limited thermoregulatory capacity and high cholesterol levels (Keatinge et al., 1986), which increase cardiovascular stress and the probability of acute coronary events (Bunker et al., 2016). Exposure of this population to high temperatures can cause inflammatory processes, increase ventilation and exacerbate chronic obstructive pulmonary disease (Anderson et al., 2013). In winter, on the other hand, low temperatures make that elders spend more time in indoor areas with reduced ventilation, which increases viral transmission (Hajat and Haines, 2002). Cold exposure has effects on human health as it can increased blood pressure, blood viscosity, systemic inflammation and thrombosis (Keatinge et al., 1984). In addition, the inspiration of cold air can cause bronchoconstriction and airway congestion, triggering asthma (Giesbrecht, 1995), and it can also increase the susceptibility to infection by reducing mucosal clearing (Eccles, 2002). Due to the great sensitivity of the elderly population to hot and cold events, it is advisable to deepen the study of the relationship between climate and human health, and to include management and planning for the available climate change scenarios.

According to our data, a higher number of deaths occurred in winter periods, mainly due to below-normal temperatures. Earlier studies has presented similar results (e.g. Carson et al., 2006; Gasparrini et al., 2015; Analitis et al., 2008). Several studies (e.g. Fleming et al., 1993; Fleming, 2000) have examined the methods by which falling temperatures can affect the physiological mechanisms of the human body (e.g vascular disease, high blood pressure, cholesterol levels). The seasonal patterns observed in mortality in relation to climatic factors may also be affected by other socio-economic variables such as housing characteristics such as fuel poverty (Gemmellet al., 2000). The U-shaped relationship between temperature and mortality is well-know (Pan et al., 1995), both hot and cold events have adverse effects on human health. Our study indicates that despite the great importance of heat events in human health, cold waves can cause a greater number of deaths. In the Spanish case, larger ratios of elders in the population are found in the coldest regions, with increased environmental vulnerability to extreme cold (Cony and Hernández 2008).

4.2. Dependency between climatic indices and mortality in mainland Spain

The findings of this study indicate seasonal differences in the association of mortality rates with climatic conditions in mainland Spain. Natural deaths increase in summer and winter compared to spring and autumn. This is expected because extreme events that affect natural deaths occur both in winter and summer. Nonetheless, climate indices have an opposed relationship with natural deaths in winter and summer. Specifically, climate indices related to high winter temperatures correlate negatively with natural deaths, while they have positive correlations during summertime. In winter, the indices that indicate low temperatures have a high correlation with the number of natural deaths, which suggests that the greater the frequency of cold waves, the greater the number of natural deaths. Many studies have indicated that summer heatwaves increase natural deaths (e.g. D'Ippoliti et al., 2010, Tobias et al., 2012; Achebak et al., 2018; Yin et al., 2018; Rasilla et al., 2019), although studies analyzing the effect of cold waves on mortality are more limited (Díazet al., 2005; Carmona et al., 2016). Our findings stress that cold waves should not be underestimated by public health authorities in the mainland Spain (Analitiset al., 2008).

From a spatial perspective, considerable seasonal differences in the relationship between mortality rates and climatic indices can be found. In general, indices of extremely warm temperatures show a significant positive correlation with natural deaths across the entire territory, especially in summer. In winter, indices related to extreme cold temperature events exhibit a significant positive correlation with natural deaths. This was the case in the study domain and especially in western provinces. On the other hand, precipitation and cloudiness indices showed negative correlations with natural deaths, mainly in winter and in western provinces. In agreement with this, Salvador et al. (2020) noted that western portions of mainland Spain have the highest daily mortality risks associated with drought related conditions. This finding is confirmed in this study, particularly in the western provinces, where there has been an increase in natural deaths during periods of drought, while natural deaths decreased during wet periods.

Numerous studies have focused on the relationship between temperature and mortality (e.g. Díaz et al., 2002; Cheng et al., 2014; Pantavou et al., 2011; Xiong et al., 2015; Achebak et al., 2018; Rasilla et al., 2019). However, few investigations have studied the relation between precipitation and mortality (e.g. Burkart and Kinney, 2016). Most work about precipitation-mortality associations have indicated that there can be an increase in the number of fatal accidents due to flood or water contamination (Wu et al., 2014). In this study, precipitation indices correlate negatively with natural deaths during winter and summer, albeit with much stronger correlation during wintertime. This relationship can be explained by the notion that, during rainy days, there is an increase in air temperature due to latent heat released when atmospheric water vapor condenses (Schneider et al., 2010). The reduction of air pollution levels during wet events is another factor that can explain the decrease of natural deaths in winter (Renet al., 2008; Burkart et al., 2013). Cloudiness indices have correlations with natural deaths that are similar to those of precipitation indices during summer and winter (i.e. negative signal). On the contrary, radiation indices show a positive correlation with mortality rates. In summer, more radiation with higher temperatures means an increase in the number of natural deaths. This situation is completely different during winter, as more radiation implies higher daytime temperatures, and conversely clear-sky nights induce a large radiative deficit and accordingly a strong decline of nighttime temperatures (Cellier, 1993) with an associated impact on mortality.

This study provides useful information for health prevention plans in mainland Spain, given that it indicates that the highest number of natural deaths occur in winter, mainly in the northwestern provinces of the study domain. Elderly populations and colder air temperatures in the northwest. Furthermore, climatic indices indicate that cold winter extremes, combined with precipitation deficits, and a reduction of cloudiness can increase mortality.

This study uses, for the first time, a large database of climate indices for a relatively long period (1979–2016) and for a wide domain (mainland Spain) to assess the possible impacts of climate on mortality rates. This study has demonstrated the importance of using a great variety of climatic indices based on different climatic variables. This variety of indices has made it possible to delve into the relationship between the number of natural deaths and climatic conditions, as well as to find which are the indices that best express this relationship.

Finally, this study offers a useful tool for demographic studies. It also highlights the need to know the spatial distribution of the number of natural deaths, the rate of elders in the population, and the climatic conditions across the space and time. Moreover, the study shows the usefulness of the climatic indices to know the climate factors of the increase in natural deaths. However, the study has limitations that must be addressed in future studies. For example, future works should aim to improve the spatial resolution of the variables subject of study. Indeed, the relationships between climatic conditions and mortality rates can be strengthened by improving the spatial resolution of climatic data. Also, higher temporal resolution can be of particular importance, as it would allow assessing the delay in mortality effects of heat and cold waves.

5. Conclusions

This study analyzes the spatial and seasonal distribution of natural deaths in mainland Spain and their links to climatic conditions. This dependency was assessed using a newly developed high-resolution climate indices database spanning the period from 1979 to 2017. The key findings of this study can be summarized, as follows:

- The study indicates that, as expected, the highest natural deaths in mainland Spain is located in the northwestern regions, where the percentage of the elderly population is highest and the climate is much colder.
- There is a clear seasonality, with more deaths in winter than in the rest of the seasons.
- The increase in the number of natural deaths is mainly linked to thermal indices (e.g. frequency of cold days in winter and very warm days in summer).
- In addition to the thermal indices, other climatic indices such as precipitation, cloudiness or radiation indices are closely associated with natural deaths.
- Precipitation indices also have a remarkably strong negative correlation with natural deaths, which is stronger in winter than in summer. The same relationship is observed between indices of cloudiness and mortality. On the contrary, radiation indices show an opposite correlation sign with mortality rates.
- There are large spatial differences in the relation between climatic indices and natural deaths, especially during summer and winter periods. Extreme warm temperature indices show positive correlations with natural deaths throughout the territory, especially in summer. In contrast, indices related to extremely cold temperatures exhibit positive correlations with natural deaths in winter, mainly over western provinces. Similarly, there is a negative correlation between precipitation and cloudiness indices and natural deaths, especially in the western provinces during wintertime.
- The association between climatic conditions and mortality rates is season-dependent, with higher correlations found for CFD, FD, SND, SSD, SSP, CC, and FOD indices in winter, and VDTR, CC, VWD, and WSDI indices in summer.

Author statement

Dhais Peña-Angulo: Conceptualization, Methodology and writing-original draft preparation. Sergio M. Vicente-Serrano: Data curation and supervision. Fernando Domínguez-Castro: Visualization and investigation. Fergus Reig-Gracia: Visualization and software. Ahmed El-Kenawy: writing-reviewing and 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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