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Mortality attributable to high temperatures over the 2021-2050 and 2051-2100 time horizons in Spain: adaptation and economic estimate.

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Abstract

Background: In recent years, a number of studies have been conducted with the aim of analysing the impact that high temperatures will have on mortality over different time horizons under different climate scenarios. Very few of these studies take into account the fact that the threshold temperature used to define a heat wave will vary over time, and there are practically none which calculate this threshold temperature for each geographical area on the assumption that there will be variations at a country level.

Objective: To analyse the impact that high temperatures will have on mortality across the periods 2021-2050 and 2051-2100 under a high-emission climate scenario (RCP8.5), in a case: (a) where adaptation processes are not taken into account; and (b) where complete adaptation processes are taken into account.

Material and methods: Based on heat-wave definition temperature ($T_{threshold}$) values previously calculated for the reference period, 2000-2009, for each Spanish provincial capital, and their impact on daily mortality as measured by population attributable risk (PAR), the impact of high temperatures on mortality will be calculated for the above-mentioned future periods. Two hypotheses will be considered, namely: (a) that $T_{threshold}$ does not vary over time (scenario without adaptation to heat); and, (b) that $T_{threshold}$ does vary over time, with the percentile to which said $T_{threshold}$ corresponds being assumed to remain constant (complete adaptation to heat). The temperature data were sourced from projections generated by Coupled Model Intercomparison Project (CMIP5) climate models adapted to each region's local characteristics by the State Meteorological Agency (*Agencia Estatal de Meteorología/AEMET*). Population-growth projections were obtained from the National Statistics Institute (*Instituto Nacional de Estadística/INE*). In addition, an economic estimate of the resulting impact will be drawn up.

Results: The mean value of maximum daily temperatures will rise, in relation to those of the reference period (2000-2009), by 1.6ºC across the period 2021-2050 and by 3.3ºC across the period 2051-2100. In a case where there is no heat-adaptation process, overall annual mortality attributable to high temperatures in Spain would amount to 1,414 deaths/year (95% CI: 1,089 – 1,771) in the period 2021-2050, rising to 12,896 deaths/year

(95% CI: 9,852 – 15,976) in the period 2051-2100. In a case where there is a heat-adaptation process, annual mortality would be 651 deaths/year (95% CI: 500 - 807) in the period 2021-2050, and 931 deaths per year (95% CI: 770 - 1081) in the period 2051-2100. These results display a high degree of heterogeneity. The savings between a situation that does envisage and one that does not envisage an adaptive process is €49,100 million/year over the 2051-2100 time horizon.

Conclusion: A non-linear increase in maximum daily temperatures was observed, which varies widely from some regions to others, with an increase in mean values for Spain as a whole that is not linear over time. The high degree of heterogeneity found in heat-related mortality by region and the great differences observed on considering an adaptive versus a non-adaptive process render it necessary for adaptation plans to be implemented at a regional level.

Key Words. Heat Wave; Climate Change; Adaptation; Mortality

Introduction

In recent years, a number of studies have been conducted with the aim of analysing the impact that heat waves will have on mortality over different time horizons under different emission scenarios, using different climate modelling approaches and different socio-economic scenarios (Sellers&Ebi, 2018). The initial studies undertaken in the field of assessment of the possible impact of heat on future mortality considered that the threshold temperature at which heat waves are currently triggered would not vary with time and would thus have the same impact on mortality as that calculated at present. Under this hypothesis, and as a consequence of the increase in temperatures associated with climate change (IPCC, 2013), important increases in heat-related mortality are obtained (Ciscar et al., 2014; Hajat et al., 2014; Wu et al., 2014; Petkova et al., 2014; Roldan et al., 2016; Martínez et al., 2016). Viewed from the current demographic and socio-economic context, however, this preliminary assumption is somewhat unrealistic in that there are a number of factors which come together and, in their different ways, influence the impact that high temperatures have on mortality.

In addition to the above-mentioned rise in temperatures, lending impetus to a greater increase in this impact over future time horizons are factors such as population ageing, quantified by reference to the higher number of persons over the age of 65 years, i.e., the target population in terms of heat impact (Montero et al., 2012; Díaz et al., 2015ª), energy poverty, and the age of buildings (López-Bueno et al., 2018). Against this, there are factors that should result in the impact of heat being reduced in future. Preeminent among these is the existence of an active heat-adaptation process on the part of the population, due to multiple factors, ranging, *inter alia*, from the so-called heat culture (Bobb et al., 2014) and implementation of prevention plans (Tan et al., 2007; Schifano et al., 2012; Van Loenhout et al., 2016), to improvements in health-care services (Ha & Kim., 2013), socio-economic conditions and home infrastructures (Vandentorren et al., 2006), along with things such as an increase in the number of air-conditioning units (Díaz et al., 2018a).

The vulnerability of the population to heat is strongly influenced by both physical and social environmental factors, which cause its impact to vary in accordance with local conditions, from some geographical places to others (Montero et al., 2012; Guo et al., 2017). Despite such local variation, there are general behaviours that are observed everywhere, such as the clear overall decrease in heat-related mortality, both in studies at a single-country level in Europe (Schifano et al., 2012; de 'Donato et al.,2015; Astrom et al., 2016; Díaz et al., 2018) Asia (Lee et al., 2018), Australia (Coaetes et al., 2014) and America (Konkel et al., 2014; Barreca et al., 2016), and in multicountry-type studies around the world (Gasparrini et al., 2015; Guo et al., 2017; Vicedo-Cabrera 2018).

Population heat-adaptation processes and, by extension, decreases in the impact of heat, can be observed either through temporal variations in mortality threshold temperatures or through variations in the impact of heat as measured by relative risk (RR) or population attributable risk (PAR). There are many studies that have reported such variations in heat-related mortality threshold temperatures in recent years (Mirón et al., 2015; Linares et al., 2014; Gasparrini et al., 2017; Weinberger et al., 2017; Chung et al., 2018), with regional characteristics having a marked influence on these patterns (Montero et al., 2012; Gasparrini et al., 2017). Furthermore, there is a clear relationship between the percentile of the temperatures series to which the threshold temperature corresponds and the PAR of heat-related mortality, determined via this percentile (Díaz et al., 2015b, Yang et al., 2019). Threshold temperatures which correspond to high percentiles have a greater impact on mortality than those which correspond to lower percentiles and are associated with lower risks (Díaz et al., 2015b; Yang et al., 2019).

It is known that the temperature series percentiles to which heat-related mortality threshold temperatures correspond cannot be the same for all geographical areas, since local-type factors, at both a physical and social level, are of great importance when it comes to ascertaining these temperatures and their corresponding percentiles (Montero et al., 2012; Díaz et al., 2015b; Guo et al., 2017). An important contribution to this current line of research will consist of including the value of this specific percentile for each place analysed, instead of maintaining it constant for all places and all countries, as has been the practice in multicountry studies until now (Guo et al., 2018).

Accordingly, the designated objective of this study is to quantify mortality attributable to high temperatures in Spain over the 2021-2050 and 2051-2100 time horizons, under a scenario of elevated emissions (RCP8.5), by performing specific analyses at a local level under two assumptions, namely: (a) that there is no heat-adaptation process; and, (b) that such an adaptation process does indeed occur. An estimate, based on the Value of a Statistical Life (VoSL) concept, will also be made to quantify the benefit of adaptation in economic terms.

Material and methods

The statistical analysis was organised in the following four stages:

1. Retrospective study

The values of the heat-wave threshold definition temperatures ($T_{threshold}$) and PARs for each Spanish provincial capital used as the basis for this study are those that were obtained in a previous analysis (Díaz et al 2015b). The analysis was performed for the summer months (June-September) across the period 2000-2009. The reason for using maximum daily temperature (T_{max}) is that this provides the best pattern for linking the impact of heat to daily mortality (Guo et al., 2017).

Based on these data, the heat-wave threshold temperature was calculated using scatterplot diagrams. For study purposes, a heat wave was deemed to exist in any case where the maximum daily temperature was exceeded on one or more days. Based on the values of the maximum daily temperature (T_{max}) and threshold temperature ($T_{threshold}$), we calculated a new variable T_{heat}, defined as follows (Díaz et al., 2006):

$$T_{heat} = 0 \qquad \text{if } T_{max} < T_{threshold}$$

$$T_{heat} = T_{max} - T_{threshold} \qquad \text{if } T_{max} > T_{threshold}$$

Variables lagged up to five days were created to take into account the lagged effect of heat over time (Alberdi et al., 1998).

Generalised linear models (GLMs) with the Poisson link were used to calculate the relative risks. Based on these, the corresponding PARs were then calculated via the equation PAR = (RR-1)*100/RR (Coste&Spira,1991). In these models, we controlled for trend, seasonalities and the autoregressive nature of the series, as well as mean daily relative humidity.

Table 1 shows the values of the threshold temperatures for each province, the percentile to which this temperature corresponds in relation to the maximum daily temperature series for the summer months across the period 2000-2009, and the corresponding PARs.

2. Projections

2.1 Obtaining the maximum daily temperature data at each observatory over the 2021-2050 and 2051-2100 time horizons.

Climate scenarios for the 21st century were obtained by applying statistical regionalisation methods to the outputs of the Coupled Model Intercomparison Project (CMIP5) climate models used by the IPCC in its Fifth Assessment Report (IPCC, 2013). For the most part, the new generation of global climate models belong to the category of so-called Earth System Models (ESMs) which, in their standard version, include carbon cycle, aerosol, chemistry and dynamic vegetation simulations.

We used new emission scenarios corresponding to Representative Concentration Pathways (RCPs), defined as scenarios which encompass time series of emissions and concentrations of the complete range of greenhouse gases, aerosols and chemically active gases, along with land use and land cover (Moss et al., 2010). These are identified by total approximate radiative forcing for the year 2100 relative to 1750: 8.5 Wm^{-2} (RCP8.5). For the RCP8.5 scenario, radiative forcing does not peak in 2100 but continues to rise, thus representing a more pessimistic scenario insofar as implementation of greenhouse gas reduction policies are concerned. Empirical/statistical regionalisation methods are based on the development of statistical relationships that link large-scale atmospheric variables (predictors) with local/regional-scale climate variables (predictands), relationships that are assumed to be invariable in the face of climate change. The statistical techniques used by AEMET are based on a method of multiple linear regression between variables yielded by the climate model and the climate variable of interest in the study area (Amblar et al., 2017). The temperature fields are smoother and their statistical pattern is closer to normality, thereby rendering regionalisation based on regression models reasonably feasible.

To calculate statistical regionalisation, we used three datasets grouped into two types, i.e., reference data and output yielded by climate models. Reference data are the result of observation at meteorological stations and furnish information on the predictands or local variables. The third group of data is made up of data from global climate-model simulations, both for the period 1961-1990, corresponding to simulations of what is termed "current or reference climate", and for the 21st century. Based on these data, future projections of the predictands at the observation points will be estimated using empirical regionalisation techniques.

The downscaling method used in AEMET is the multiple linear regression between variables yielded by the climate models (global scenarios) and the climate variable of interest, that is, the temperature at 374 observation points distributed around Spain. As we stated in the paper, the temperature field is smooth and correspond to normality in a statistical sense, thereby using statistical downscaling based on regression models is reasonably feasible. For this study, we used the information for the meteorological observatories situated in the 49 provincial capitals in order to evaluate the possible change in the values of the heat-wave threshold definition temperatures and PARs for each Spanish provincial capital in climate change conditions.

Maximum daily temperatures were chosen as the predictands. The historical maximum daily temperature data considered in this study corresponding to the provincial capitals, as sourced from the AEMET data bank for the period 1951-2005. These observation points were selected after their time series, for the period of interest, had been undergone rigorous quality control (Brunet et al., 2008). The large-scale predictor variables for current climate were obtained as follows: from NCEP-NCAR Reanalysis daily average data (National Centre for Environmental Prediction & National Centre for Atmospheric Research) (Kalnay et al., 1996) for the period 1951-2005; and from global climate models sourced from the CMIP5 data portal (Taylor et al., 2012) for future climate projections.

2.2 Mortality, population data and calculation of mortality rates.

Annual data on mortality and population projections at a provincial level were obtained from the National Statistics Institute for the period 2021-2030 (INE, 2018), with these remaining constant from 2030 onwards. Based on these data, mortality rates per thousand population were then calculated.

3. Adaptation and no adaptation processes. Attributable Mortality.

To calculate attributable mortality for each period and province, it is necessary to ascertain the $T_{threshold}$ and daily T_{max} values, along with the corresponding PARs with their 95% CIs and the mortality rates.

Two hypotheses will be considered, namely: (a) that $T_{threshold}$ does not vary over time (scenario without adaptation to heat); and, (b) that $T_{threshold}$ does vary over time, with the percentile to which said $T_{threshold}$ corresponds being assumed to remain constant (complete adaptation to heat).

Hence, on the percentile not varying, the number of heat waves will remain constant, despite the fact that temperatures may increase, since the increase in temperatures will be offset by the adaptation of the population to heat. This would assume a process of “complete adaptation” to heat. Obviously, the real impact on mortality will occur somewhere between these two options, i.e., no heat adaptation on the one hand (the threshold temperature remains constant over time), and complete heat adaptation on the other (the percentile to which the current threshold temperature corresponds remains constant) (Sánchez-Martínez et al.,2018 a,b; Guo et al., 2018).

For each province, $T_{threshold}$ will therefore be assumed to be: the same as that in Table 1, if no heat adaptation is envisaged; or alternatively, the percentile shown in this Table, if complete heat adaptation is envisaged. For study purposes, it will further be assumed that PARs do not to vary over time and are those shown in Table 1.

For each day on and place at which the Tmax predictions indicate that $T_{threshold}$ will be exceeded, taking into account the fact that PAR expresses the increase in mortality in percentage terms for each degree whereby $T_{threshold}$ is exceeded, the percentage increase in mortality can be calculated and, along with it, how much of this increase is due to heat (Carmona et al., 2017).

4. Economic estimate

We used the Value of a Statistical Life (VoSL) in Euros, concept to arrive at an economic estimate of attributable mortality. The VoSL corresponds to the monetary value a society would be willing to pay to prevent the death of one of its members (Martínez-Pérez *et al.,* 2007). To obtain an estimator of the VoSL, we used 13 estimates made by four papers using Spanish populations resident in Spain (Martínez-Pérez *et al.,* 2007; Martínez-Pérez and Méndez-Martínez, 2009; Corbacho *et al.*, 2010; Abellán-Perpiñán *et al.*, 2011): two used the contingent valuation method (Martínez-Pérez *et al.,* 2007; Abellán-Perpiñán *et al.*, 2011) and two a hedonic wage model (Martínez-Pérez and Méndez-Martínez, 2009; Corbacho *et al.*, 2010).

Specifically, we first updated the monetary values of these 13 estimators to euros in the year 2018. We then performed a meta-regression and, based on a random effects meta-analysis, controlled for the estimation method used (contingent valuation or hedonic wage). As the estimator obtained corresponded to the VoSL, the cost of attributable mortality was obtained by aggregating this.

We performed the analysis for both scenarios, namely, with and without heat adaptation, for the two time horizons considered, 2021-2050 and 2051-2100.

All analyses were performed using the R free software environment (version 3.5.1).

Results

Tables 2 and 3 show the mean daily maximum temperature values for the summer months for each provincial capital over the 2021-2050 and 2051-2100 time horizons, under an RCP 8.5. emission scenario. The following are also shown: the $T_{threshold}$ for each provincial capital during the reference period, which serves to a define a heat wave in a non-adaptation process; and the percentile to which this $T_{threshold}$ corresponds, along with the corresponding T_{max} for said percentile, which becomes the $T_{threshold}$ in a complete adaptation process, as explained under Methods above. In line with these two $T_{threshold}$ values (with and without adaptation), the average number of heat waves per year are shown for each province over the two time horizons analysed, under the two adaptation assumptions.

As can be seen from Table 2, mean overall temperatures in Spain went from 28.7ºC in the reference period 2000-2009 to 30.3ºC, i.e., an increase of 1.6ºC, which amounts to a mean rate of increase in maximum daily temperatures of 0.053 degrees/year. Over the 2051-2100 time horizon (Table 3), the mean maximum temperature for Spain as a whole is 33.6ºC, amounting to an increase of 3.3ºC over the reference value, at a mean rate of 0.066ºC/year. This rise in mean maximum temperatures is not uniform, however: in some cases, such as Corunna (*A Coruña*), this increase is 0.2ºC across the 2020-2050 time horizon and 2.3ºC across the 2051-2100 time horizon, whereas in others, such as Guipúzcoa (capital city, San Sebastián), it is 4.8ºC across the 2020-2050 time horizon and 7.8ºC across the 2051-2100 time horizon.

In terms of the mean number of days with temperatures in excess of the threshold which will occur in Spain over the different time horizons, this will logically vary depending on whether or not heat adaptation is taken into account: in other words, whether $T_{threshold}$ is kept constant, or alternatively, whether it is allowed to vary and it is the percentile that is kept constant. If $T_{threshold}$ is assumed to be constant over the 2021-2050 time horizon, there will be 557 heat waves per year on average (Table 2), with temperatures exceeding this threshold on as many as 2269 days/year over the 2051-2100 time horizon (Table 3). These values refer to the sum of heat waves occurring in all provinces, taking into account that many of the heat waves occurred in parallel at the same provinces.

In the first case, there are 1.3 times more heat waves with respect to the baseline period (Table 1), whereas there are 5.2 times more with respect to the current number of heat waves shown in Table 1. Taking the adaptation process into account by keeping the percentile constant obviously means that the annual number of heat waves will remain constant, regardless of the time horizon analysed.

The analysis at a provincial level once again highlights the heterogeneity of the results. For instance, if adaptation is not considered in the case of Alicante, there would be a mean of 78 heat waves per year over the first time horizon, which would then rise to 111 over the 2050-2100 time horizon versus the current figure of 19, while in other places such as Cantabria or Malaga, there would not be one day on which the heat-wave definition threshold temperature, $T_{threshold}$, is exceeded.

The results of calculating annual attributable mortality with the above-described methodology for the different time horizons, 2021-2050 and 2051-2100, assuming processes without and with adaptation respectively, are shown in Figures 1-2.

(a) Without adaptation

Annual heat-related mortality in a process without adaptation across Spain as a whole is 1,414 deaths/year (95% CI: 1,091 – 1,823) for the period 2021-2050, rising to 12,917 deaths/year (95% CI: 9,853 – 15,890) for the period 2051-2100.

Figure 1 highlights the wide geographical heterogeneity over the 2021-2050 time horizon, in which mention must be made of provinces such as Alicante with as many as 463 deaths/year (95% CI: 343 - 582) versus places where there is not a single day with temperatures above $T_{threshold}$ and which thus register no heat-related mortality in the province in this period.

Over the 2051-2100 time horizon depicted in Figure 1, the peak values for annual heat-related mortality are registered by the provinces of Madrid and Barcelona, with 2,249 deaths/year (95% CI:1894, 2601) and 1,465 deaths/year (95% CI: 1239, 1687) respectively, versus places such as Cantabria and Tarragona with no annual heat-related mortality.

(b) With adaptation

Considering the adaptation process assumed in this study, annual heat-related mortality in the period 2021-2050 would be 647 deaths/year (95% CI: 498 - 793), a decrease of 50.4% over the mortality figure of 1,310 deaths/year in the reference period. Furthermore, a complete heat-adaptation process would mean that annual mortality in the period 2051-2100 would be 997 deaths/year (95% CI : 770 – 1,218), i.e., a decrease of 23.9% with respect to mortality in the reference period (Fig. 2).

Economic estimate of the impact of heat waves on mortality

In terms of the annual cost of attributable mortality under a scenario without adaptation, this is estimated at €6,021 million (in 2018 euro values) (95% CI: 5,773 - 6,269) over the 2021-2050 time horizon, and €53,217 million (95% CI: 51,022 - 55,413) for the 58 provinces over the 2051-2100 time horizon.

In terms of the annual cost of attributable mortality under a scenario with adaptation, this is estimated at €2,667 million (95% CI: 2,557.39-2,777.52) for Spain as a whole over the 2021-2050 time horizon, and €4,108 million (95% CI: 3,938 - 4,277) over the 2051-2100 time horizon.

Discussion

Temperature Projections

The mean increases in maximum temperatures observed by this study in each period highlight the high impact had by climate change on the increase in heat-wave frequency and intensity (IPCC, 2013). The mean increases of 1.6ºC over the nearest time horizon and 3.3ºC over the more distant time horizon, 2051-2100, are in line with estimates made for Southern Europe by other multicountry studies (Gasparrini et al., 2017), which estimated increases of 4.5ºC (3.0-5.1) in mean temperature across the 2090-2099 time horizon in comparison with the decade 2010-2019. The fact of using a reference period of 50 years in our study versus one of 10 years, and moreover at the end of the period, in that by Gasparrini et al may account for the smaller increase found by us, since the rise in temperatures will be greater, the closer one draws to the year 2100 (IPCC., 2013). Indeed, this is precisely what is seen in our results, where mean increases go from 0.053ºC/year in the period 2021-2050 to 0.066ºC/year in the period 2051-2100.

A recent study conducted in different countries, including Spain (Guo et al., 2018), establishes an increase of 3ºC in the value of the mean temperature, corresponding to the 95th percentile of the mean temperature series for the summer months across the period 2031-2080 in comparison with the period 1971-2020, i.e., values practically similar to those observed by us.

Another of our study's relevant results is the high degree of heterogeneity found in temperature projections by province. These differences, which in some cases rise to as much as 5.5ºC if the cities with the lowest expected temperature increase, such as Corunna, are compared to those with the highest expected increase, such as San Sebastián, may be a consequence of the statistical regionalisation used by AEMET in these predictions, which include local regionalisation factors (even vegetation) incorporated into global models (Amblar et al., 2017), as explained under Methods.

Adaptation and no adaptation processes. Attributable Mortality.

This variability in expected maximum daily temperatures is one of the factors that could account for the difference between the expected number of heat waves according to the province concerned in a process without adaptation to heat, as seen in Tables 2 and 3. However, the other key factor is the percentile to which the $T_{threshold}$ corresponds. If the percentiles are very high, as in the case of Malaga or Cantabria where the threshold percentile is the 99th, this would indicate that, even with increases in the maximum daily temperature of 2.7ºC over the 2051-2100 time horizon in the case of Cantabria and 2ºC in that of Malaga, heat waves in these provinces are going to be extremely infrequent even in 2100. In these provinces, even the current $T_{threshold}$ is higher than that projected over the 2021-2100 time horizons.

Furthermore, places with low percentiles, such as Alicante (83rd percentile) with important increases envisaged in mean maximum daily temperatures (6.1ºC), would explain the high number of heat waves expected in this city in 2100.

Overall in Spain, the number of days with temperatures above this threshold will be 1.3 times higher over the first climate horizon considered and 5.2 times higher over the 2051-2100 time horizon. This value is higher than that found for the city of Vilnius in Northern Europe, where the number of heat-wave days over the 2095-2100 time horizons will be 4.4 times the current number (Sánchez-Martínez et al., 2018b). In contrast, in Antwerp, without taking acclimatisation into consideration, the number of days with maximum daily temperatures above $T_{threshold}$ will be 8.3-fold higher across the period 2096-2100 as compared to 2009-2013 (Sánchez-Martínez et al., 2018a). Similar values in terms of the number of heat-wave days per year were found in studies undertaken in cities in the eastern United States, with increases of 6.4 times the current values as compared to those for 2057-2059 (Wu et al., 2014).

Changes in population is another factors to be considered when it comes to calculating attributable mortality over different time horizons (Lee et al., 2016). Although there are studies in which the population is assumed constant (United Nations, 2015) and there are others in which different high, medium or low population-change scenarios are considered (Guo et al., 2018), the ideal situation is to have different projections adjusted for each city (Roldan et al., 2016; Weinberger et al 2017; Sánchez-Martínez et al., 2018a,b). In our case, there was no mortality or population projection for each province for the entire period of analysis but these did exist for part of the period (INE, 2018), which would amount to a slight bias in results. At a national level, according to these National Statistics Institute population data, there will be a 11.6% decrease in the population in Spain between 2016 and 2066, which would explain the increase in mortality rates observed in Tables 2 and 3 in relation to Table 1.

The value of annual heat-related mortality, without taking adaptation into consideration, across the period 2021-2050 is a value very similar to the 1,310 deaths/year (Carmona et al., 2016) which occur in the reference period 2000-2009, i.e., an increase of 7.9%. However, over the 2051-2100 time horizon this annual mortality in Spain rises to 12,896 deaths/year (95% CI: 9,852 – 15,976), which is 9.8 times the annual mortality of the reference period, i.e., an increase of 884%. In other words, annual heat-related mortality experiences non-linear growth, as a consequence, fundamentally, of the increase in expected temperatures and, by extension, of the increase in the number and intensity of heat waves.

This value is higher than but of the same order of magnitude as that obtained for Spain in a multicountry study (Guo et al., 2018), which establishes an increase of close on 400% in the period 2031-2080 in relation to the period 1971-2020. These differences in estimates may be for a number of reasons: firstly, due to the differences in the reference periods for the calculation of increases in mortality; secondly, while the 95th percentile of the mean daily temperature series is considered in Guo et al's study, the percentile specifically pertaining to each province is used in ours; and lastly, the percentage population change estimated for 2080 is an increase of 21% under a high population growth scenario when, in reality, National Statistics Institute projections indicate a decrease of 11.6% (INE, 2018). Increases in the same range of values have been found in different places. Hence, in Vilnius the increase in annual heat-related mortality in a process without adaptation across the period 2085-2100 was 6.2-fold that of the reference period 2009-2015 (Sanchez-Martínez et al., 2018b), and in Antwerp annual heat-related mortality in the period 2081-2100 will be multiplied by 6.6 in relation to the period 2009-2013 (Sánchez-Martínez et al., 2018a). Another study conducted for 10 large USA cities, considering population projections under an RCP8.5 scenario, shows that in the year 2050, heat-related mortality will be 1.7-fold that of 1997, and will be 2.9-fold that of 1997 over the 2090 time horizon (Weinberger et al., 2017). An increment on population is associated with an increment in the impact and the number of vulnerable people will increase. In this sense, the ageing of population is important too. The main population groups affected by heat waves are people older than 65, so the demographic structure plays an important role. It is foreseeable that, even if the population decreases, if the number of people older than 65 increases, the impact of heat will increase (Lee et al., 2016).

In Spain, few studies have been conducted with reference to mortality projections under different climate scenarios. Those of most relevance were the study undertaken in Zaragoza (Roldan et al., 2016), which reported increases in annual heat-related mortality of 0.4% when annual mortality in the reference period 1987-2006 was compared to that in the period 2014-2020, and the study carried out by Ostro et al., (Ostro et al., 2012), which reported increases in annual attributable mortality of 2% for Barcelona and 0.8 % for the whole of Catalonia over time horizons similar to those of Zaragoza. The different time horizons used by these other studies and ours mean that the results are not comparable.

The different geographical patterns of the temperature-prediction models, the different heat-wave and daily-mortality definition thresholds, account for the heterogeneity shown in Figure 1. If one focuses on annual heat-related mortality by province (Figure 2), it will be noted that places with the highest annual heat-related mortality correspond, on the one hand, to the most densely populated cities and, thus, to higher mortality, as is the case of Madrid, Barcelona and Seville over the 2051-2100 time horizon. Yet on the other hand, there are also cities which have a lower population density but which, according to the projections, are destined to have a high number of heat waves. This, as can be seen from Table 3, is the case of Alicante and Zaragoza with 111 and 99 heat-wave days per year out of the 122 days between June and September.

Given that the number of heat-wave days remains practically constant under these $T_{threshold}$ and PAR defining conditions, the only variable that can account for this decrease in impact must be that linked to the expected population decline in Spain. Similar results in terms of reduced impacts with complete adaptation processes were found by Guo et al's multicountry study (Guo et al., 2018) for Moldova, Japan and Italy, precisely those countries which displayed a decline in expected population according to the projections used.

Although this study used the $T_{threshold}$ determined for each province in accordance with its population pyramid, the prevailing socio-economic and local conditions that mark this value, and the percentile to which it corresponds in the maximum daily temperature series for the summer months (Montero et al., 2012; Roldán et al 2015; Díaz et al., 2015b), there can be no doubt that a series of assumptions were made that must necessarily influence the results obtained.

Limitations

1. Firstly, a single observatory at a provincial level was deemed to be representative of the entire province, something that could induce problems of the representativeness of exposure of the entire population (Carmona et al., 2017). Por otro lado el period del estudio retrospective de solo 10 años puede considerarse corto.
2. Though there is a relationship between the percentile to which the $T_{threshold}$ corresponds and the PAR value (Díaz et al., 2015b; Yang et al., 2019), as mentioned above, in this study the PAR value was assumed to be constant. In practice, this implies that account was not taken of changes in infrastructures, green areas, and the age of housing, which affect PAR values and will inevitably vary over time (Oleson et al., 2018; López-Bueno et al., 2018).
3. Population projections were taken into account but not variations in the number of persons over the age of 65 years, the target group when it comes to the effects of heat (Díaz et al., 2015a; Montero et al., 2012).
4. Similarly, account was not taken of the existence of other environmental factors whose health effects are enhanced in heat wave periods, such as air pollution caused by particulate material (Ortiz et al., 2017) and ozone (Díaz et al., 2018b).

5. The VoSL concept has been used in the sphere of road safety and traffic accidents (Jones-Lee *et al.*, 1985, 1993; Mon *et al.*, 2018), in assessment of environmental risks (Carson and Mitchell, 2000; Jaafar *et al.*, 2018), including assessment of the impact of heat waves (Chiabai *et al.*, 2018), and in economic assessment of health-care policies (Johannesson *et al.*, 1991; Almagro *et al.*, 2017). In our case, the papers that we meta-analysed in order to estimate the VoSL relied on general population samples (Martínez-Pérez *et al.,* 2007; Abellán-Perpiñán *et al.*, 2011) and on gainfully-employed population samples (Martínez-Pérez and Méndez-Martínez, 2009; Corbacho *et al.*, 2010). Given that deaths attributable to high temperatures will correspond to the most vulnerable subjects, and that these, whether due to their age or health status, will not participate in the labour market, particularly under a non-adaptation scenario, estimators obtained from gainfully-employed population samples might over-estimate the attributable cost. It has to be said, however, that in our case, the lower value of the 95% confidence interval proved very similar to the mean of the VoSL estimators of studies which used general population samples, and the upper value proved slightly lower than the mean of the estimators of studies which used samples of gainfully employed persons.

Relevance in public health policies

From a qualitative point of view, the principal outcome of our study is the high degree of heterogeneity in the results obtained according to the different geographical regions involved. The same heterogeneity is found on the map, which defines these thresholds and is caused by the different socioeconomic and demographic conditions that vary from one province to another despite their geographical proximity (Díaz et al., 2015b). This clear influence of local factors has highlighted the expected increases both in temperatures and in the mortality attributable to such temperatures under different scenarios and over different time horizons. This geographical heterogeneity, in terms of temperature as well as mortality, is present in studies conducted both at a multicountry (Gasparrini et al., 2017; Guo et al., 2018; Martínez et al; 2016) and at single-country level (Oleson et al., 2018; Weinberger et al., 2018). While it is clear that studies on a global scale can mark out adaptive strategies to be followed at a macro level, real adaptation should nonetheless be carried out at a local level (López-Bueno et al., 2018; Díaz et al., 2018c). To this end, it is essential to have studies which take into account these regional differences in the various parameters that will define the impact of heat waves on mortality over different time horizons, not only with respect to determination of threshold temperatures and the impact of heat on mortality, which should factor in geographical factors and local socio-economic and demographic characteristics (Montero et al., 2012; Díaz et al., 2015b; Carmona et al., 2016; Oleson et al., 2018), but also with respect to the temperature-projection models which have to be constructed with greater accuracy, both temporal and geographical (Amblar et al., 2017). From the standpoint of estimating the health impacts of temperature under different climate change scenarios, there is no sense in using climate models having extremely high spatio-temporal resolution, accompanied by health-impact estimates obtained on the basis of heat-related mortality threshold temperatures that are constant over time, without taking possible adaptive processes and population changes into consideration (Linares et al., 2014).

Considering a heat-adaptation process based on keeping the percentile to which $T_{threshold}$ corresponds constant in relation to the maximum temperature series of the summer months means that the number of heat-wave days under the different time horizons will remain constant over time. Given that maximum daily temperatures tend to rise, what this assumption means in practice is that $T_{threshold}$ should rise at the same pace as temperatures do. Maintaining the number of heat waves constant, and bearing in mind that the PAR is also being kept constant, variations in mortality will be exclusively due to changes in the population. This would be a way of ensuring that, despite global warming, the impact of heat waves remains practically similar or even declines in relation to current values, something that converts this hypothesis into a tool for monitoring adaptation to high temperatures (Sanchez-Martínez et al., 2018a,b).

Conclusions

These adaptation processes are showing themselves to be effective because the impact of heat is decreasing in many countries (Gasparrini et al., 2015; Guo et al., 2017; Vicedo-Cabrera 2018; Díaz et al., 2018), and they should factor in individual, interpersonal, community, institutional, environmental and public policy processes (Mc Gregor et al., 2015; Guo et al., 2018). Different analysis conducted recently in Stockholm (Astrom et al., 2016) and Japan (Chung et al., 2017), have focused in the increment of the temperature of minimum mortality along the time. In Stockholm, indicates that the temperature of minimum mortality has increased by 0.8ºC per decade and in Japan 1.4 ºC per decade. The values proposed for a total adaptation process are theoretically assumable in Spain, since the rate of adaptation observed previously (0.8ºC/decade or 1.4 ºC/decade) were higher than the rate found in Spain in the future horizons 2051-2100 corresponding to 3.3 ºC, this means, 0.66ºC/decade.

The cost in human lives, coupled with the economic cost reflected in a savings of €49,100 million/year between a situation that does envisage and one that does not envisage an adaptive process over the 2051-2100 time horizon, should serve as an important incentive to efforts targeted at ensuring, as far as possible, that the goal of heat adaptation is successfully achieved.

DISCLAIMER

The authors declare they have no actual or potential competing financial interests. This article presents independent research. The views expressed are those of the authors and not necessarily those of the Carlos III Institute of Health.

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