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Will there be cold-related mortality in Spain over the 2021-2050 and 2051-2100 time horizons despite the increase in temperatures as a consequence of climate change?

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Abstract

Introduction: Global warming is resulting in an increase in temperatures which is set to become more marked by the end of the century and depends on the accelerating pace of greenhouse gas emissions into the atmosphere. Yet even in this scenario, so-called “cold waves” will continue to be generated and have an impact on health.

Objectives: This study sought to analyse the impact of cold waves on daily mortality at a provincial level in Spain over the 2021-2050 and 2051-2100 time horizons under RCP4.5 and RCP 8.5 emission scenarios, on the basis of two hypotheses: (1) that the cold-wave definition temperature ($T_{\text{threshold}}$) would not vary over time; and, (2) that there would be a variation in $T_{\text{threshold}}$.

Material and methods: The results of a retrospective study undertaken for Spain as a whole across the period 2000-2009 enabled us to ascertain the cold-wave definition temperature at a provincial level and its impact on health, measured by reference to population attributable risk (PAR). The minimum daily temperatures projected for each provincial capital considering the above time horizons and emission scenarios were provided by the State Meteorological Agency. On the basis of the $T_{\text{threshold}}$ definition values and minimum daily temperatures projected for each province, we calculated the expected impact of low temperatures on mortality under the above two hypotheses. Keeping the PAR values constant, it was assumed that the mortality rate would vary in accordance with the available data.

Results: If $T_{\text{threshold}}$ remained constant over the above time horizons under both emission scenarios, there would be no cold-related mortality. If $T_{\text{threshold}}$ were assumed to vary over time, however, then cold-related mortality would not disappear: it would instead remain practically constant over time and give rise to an estimated overall figure of around 250 deaths per year, equivalent to close on a quarter of Spain’s current annual cold-related mortality and entailing a cost of approximately €1000 million per year.

Conclusion: Given that cold waves are not going to disappear and that their impact on mortality is far from negligible and is likely to remain so, public health prevention measures must be implemented to minimise these effects as far as possible.

1. **Introduction**

All climate models, regardless of the emission scenarios used -ranging from the most conservative (RCP2.5, RCP4.5) to those which envisage elevated emission levels over future time horizons (RCP8.5)- have indicated that temperatures are going to rise in Europe over the course of the 21st century (IPCC 2013; Kendrovski et al., 2017; Gasparrini et al., 2017). In the case of Spain specifically, maximum daily temperatures are going to rise from a mean of 28.7ºC in the summer months across the period 2000-2009 to 30.3ºC across the period 2021-2050 and 33.6ºC across the period 2051-2100 (Díaz et al., 2019a) under an RCP8.5 emission scenario. In other words, by the end of the 21st century, maximum daily temperature values will, on average, be almost 5ºC higher than those that existed at the outset of the century.

However, this rise in temperature does not signify an end to what are known as “cold waves” (Díaz et al., 2005; Kysely et al., 2009; Montero et al.,2010; Ebi and Mills, 2013; Gasparrini et al., 2015) or days on which the minimum daily temperature falls below the so-called cold-related mortality threshold temperature (Carmona et al., 2016). The reason for this is twofold. Firstly, meteorologically speaking, there are still going to be days with very low temperatures (Kodra et al., 2011): excessive warming of the Arctic region has led to a weakening of the thermal gradient between the Arctic and middle latitudes and an ensuing slowing of the jet stream, thereby spilling pockets of very cold air (“cold drop”) which may affect middle latitudes more frequently (Cohen et al., 2014).

From a health standpoint part of the aetiology of the excess mortality observed after exceptionally cold days is known to be of an infectious nature (Kysely et al. 2009), due to the presence or absence of a pathogenic agent, whose ability to spread is, in turn, favoured by this selfsame drop in temperatures (Hajat and Haines 2002). Specifically, influenza is the main infectious agent that is associated with winter mortality (Glezen 1982). Cold waves tend to be associated with mortality over a prolonged period (Alberdi et al 1998; Braga et al 2001), thereby making it more complicated to establish cause-effect relationships. A systematic review conducted until 2013 (Ryti et al 2015) indicated that in most studies cold waves were statistically defined on the basis of a frequency distribution (e.g., 1st-3rd percentiles) as a set of consecutive days with extreme temperatures, and found a positive association between cold waves and mortality due to all and non-accidental causes, cardiovascular diseases and respiratory diseases, as well as increased morbidity. Cold temperatures are associated with increased occurrence of respiratory tract infections (Makinen et al 2009), respiratory diseases (Monteiro et al 2013), excess cardiovascular-disease mortality and morbidity (Urban et al 2014; Davidkovova et al 2014), and cardiac arrest deaths (Medina-Ramón et al 2006). Cold exposure is a trigger factor for certain diseases and can contribute to aggravation of prevailing chronic diseases (Rytkönen et al 2005).

The minimum mortality temperature is changing over time (Mirón et al., 2008). Two studies recently undertaken in Stockholm (Åström et al., 2016) and Japan (Chung et al., 2018) respectively, reported that the minimum mortality temperature is rising over time, i.e., 9.7^{o}C over the period 1901-2009 in the case of Stockholm, and 5.5 ^{o}C over the period 1972-2012 in the case of Japan. This increase in the value of the minimum mortality temperature brings with it a resulting shift towards higher values in the heat- and cold-wave definition temperatures. In the case of heat, one of the methods used to model this shift in the heat-wave definition temperature is to assume that it is the percentile to which this temperature corresponds rather than the temperature itself which is going to remain constant over time. This would mean that the number of heat waves is not going to increase over time (Sánchez-Martínez et al., 2018a,b; Guo et al., 2018; Díaz et al., 2019a). In other words, if there was a way of ensuring that the different population heat-adaptation processes (Sheridan et al., 2018) could succeed in keeping the rate of increase in the heat-wave definition temperature equal to or higher than the rate at which temperatures increased as a consequence of climate change, then the health impact of heat waves could be guaranteed not to increase.

It is thus a matter of transferring this same hypothesis to the case of cold waves: as a consequence of this progressive adaptation to heat, there is going to be a process of disadaptation to cold, i.e., cold-wave definition temperatures are going to increase with time, and a temperature which is not currently indicative of a cold wave, will be so in future. This increase can be modelled over future time horizons, assuming that it is the percentile corresponding to the current cold-wave definition temperature which is going to remain constant over time. This methodology was recently used in a study conducted in the city of Vilnius (Sánchez-Martínez et al., 2018a), which showed that, under this hypothesis, cold-related mortality was not going to disappear.

Hence, in terms of their effect on mortality, cold waves are not about to disappear; unlike what happens in the case of heat, their impact is not declining (Wang et al., 2016; Vicedo-Cabrera et al., 2018; Lee et al., 2018; Åström et al., 2018; Díaz et al., 2019b). Moreover, in Spain, daily cold-related mortality exceeds that due to heat (Carmona et al., 2016b). Accordingly, the aim of this study was to analyse what cold-related estimations of mortality would be for each Spanish province over the 2021-2050 and 2051-2100 time horizons under RCP4.5 and RCP 8.5 emission scenarios, on the basis of two hypotheses:

1. Whithout adaptation processes: the cold-wave threshold definition temperature would not vary over time.

2. Whith Adapatation processes: the percentile to which the current cold-wave definition temperature corresponds would remain constant over time.

In addition, an economic estimate was made of the cost of such cold-wave-related mortality.

2. Material and methods

The findings from Carmona et al., 2016a were used for each Spanish provincial capital as the basis for this analysis.

2.1. Retrospective study data

In this previous study, a cold-wave is defined any day when the daily minimum temperature is below $T_{threshold}$. To calculate the value of $T_{threshold}$, we first fitted a univariate autoregressive integrated moving average (ARIMA) model (Box GE et al 1994) for daily mortality in each of the 52 provincial capitals, which allowed us to obtain the residuals of the mortality series; based on daily natural-cause mortality (International Classification of Diseases, 10th Revision (ICD-10) codes: A00-R99) in each Spanish province across the period 2000-2009 (known as reference period onwards).

From the ARIMA models we obtained the fit and the (upper and lower) confidence intervals corresponding to this fit. Mortality residuals are the difference between the raw mortality and the fit. We then proceeded to plot the following on a scatterplot diagram: the mean value of the mortality series residuals on the same day (vertical axis); the minimum daily temperatures at 2^{o}C intervals (horizontal axis), and their corresponding 95% confidence intervals (CIs) (upper and lower limits of the CI: UL and LL respectively); and the 95% CIs of the mean of the residuals for the entire study period (shown by parallel broken lines). When mortality residuals are shown on a scatterplot diagram with the minimum temperature data, the deviations detected correspond to real mortality anomalies. The temperature from which the mortality residuals increased significantly vis-à-vis the mean would thus be the threshold temperature.

The impact of extreme cold temperature on mortality was quantified, using generalised linear model (GLM) methodology, with the Poisson regression link. This methodology allows for calculation of the relative risks (RRs) associated with increases in the environmental variable, in this case temperature. Based on the RR, we then calculated the proportional attributable risk (PAR) associated with this increase via the following equation: $AR = [(RR—1)/RR]x100$ (Coste and Spira 1991).

To consider the effect of a cold wave through minimum daily temperatures (Tmin), we respectively created the variables Tcold, defined on the basis of the previously calculated mortality threshold temperatures ($T_{threshold}$) as those on which the minimum daily temperature failed to exceed $T_{threshold}$ (Díaz et al 2005):

$Tcold = 0$ if $Tmin > T_{threshold}$

$Tcold = T_{threshold} - Tmin$ if $Tmin \leq T_{threshold}$

The intensity of a cold wave is defined by the value of T_{cold}. This value extends to those days in which are different from 0. Variables lagged up to fourteen days were created to take into account the lagged effect of cold over time (Alberdi et al., 1998). The analysis was performed for the winter months (November-March).

On fitting the model, we controlled: firstly, for mean daily relative humidity. Secondly, for seasonalities of an annual, six-monthly and quarterly nature, using the sine and cosine functions with these same periodicities. The trend was controlled through a variable in the database that counts along the period: this variable starts on the first day of the series and continues to the end of the series, such that it is 1 on 1st January 2000 and 2963 on 31st December 2009. The possible autoregressive nature of the series was controlled through the calculate of a lag 1 of natural causes, which takes into account the effect of the mortality due to natural causes, one day later.

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

2.2. Projections

2.2.1 Estimating the minimum 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: 4.5 and 8.5 Wm^{-2} (RCP 4.5 and 8.5). 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 is 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 the State Meteorological Agency (*Agencia Estatal de Meteorología/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, namely, 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, 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 were estimated using empirical regionalisation techniques. Minimum daily temperatures were chosen as the predictands. The historical minimum daily temperature data considered in this study corresponded to 374 observation points, 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 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.

2.2.2. 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 (*Instituto Nacional de Estadística /INE*) 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.

2.3. Calculation of mortality attributable to low temperatures in each period.

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

We calculated cold-related mortality under two hypothesis:

Firstly, that the cold-wave definition, $T_{\text{threshold}}$, is not going to vary over time (hereafter referred to as "without adaptation").

Secondly, that, as explained in the Introduction, it is the percentile to which this $T_{\text{threshold}}$ corresponds which remains constant over time ("with adaptation"), i.e., that there is adaptation to the ever-higher temperatures corresponding to global warming.

For each province, the $T_{\text{threshold}}$ is therefore assumed to be: the same as that in Table 1, in a case where no adaptation to new temperaturas is envisaged; or alternatively, the percentile shown in this Table, in a case where adaptation to new temperatures is envisaged. For study purposes, it is further assumed that the PAR values do not to vary over time and are those shown in Table 1.

For each day on and place at which the daily mean T_{min} predictions indicate that $T_{\text{threshold}}$ will not be exceeded, taking into account the fact that PAR expresses the percentage increase in mortality for each degree whereby the minimum daily temperature lies below the $T_{\text{threshold}}$, the percentage increase in mortality can be calculated and, along with it, how much of this increase is due to cold (Carmona et al., 2016b).

2.4. Economic estimate

We used the concept of Value of a Statistical Life (VoSL) 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 adaptation, for the two time horizons considered, 2021-2050 and 2051-2100, under the RCP4.5 and RCP8.5 emission scenarios.

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

3. Results

Temperatures, Thresholds and Cold-waves stimations obtained for RCP4.5

Tables 2 and 3 show the mean daily minimum temperature values according to the climate model projections under an RCP4.5 emission scenario for each of the provincial capitals and for Spain as a whole, over the 2021-2050 and 2051-2100 time horizons respectively.

For Spain overall, it should be noted that there will be a clear rise in minimum daily temperatures in the winter months, going from 5.1 ^{o}C in the reference period 2000- 2009 to 6.1 ^{o}C in the period 2021-2050 and 6.5 ^{o}C in the period 2051-2100. This increase in temperature of only 1^{o}C in the first period is very much higher at the extremes, as can be seen in the $T_{threshold}$ definition values which correspond to the same percentile. In the case of Avila, for instance, the mean minimum temperature went from 0.5^{o}C in the reference period to 2.7^{o}C in the period 2021-2050 and 3.2^{o}C in the period 2051-2100, while the 70th percentile went from corresponding to a current temperature of -10^{o}C to values of 0.2^{o}C in the first period and 0.5^{o}C in the second, i.e., variations of 10.2^{o}C and 10.5^{o}C respectively.

Without adaptation, the daily minimum temperature stimations results in no cold-waves in any case. With adaptation, $T_{threshold}$ remaining constant (without statiscally significant differences), as can be seen in Table 2 and 3.

In the period 2001-2009 there are 301 days per year with temperatures below the threshold temperature, 313 days in the period 2021-2050 and 309 days in the period 2051-2100 under an RCP4.5 scenario.

Temperatures, Thresholds and Cold-waves stimations obtained for RCP8.5

The same comments are applicable to the RCP8.5 emission model, the results of which are shown in Tables 4 and 5. In these cases, the average value for Spain as a whole under the 2021-2050 time horizon is 6.3°C, i.e., 1.2°C more than the reference period (2000-2009), whereas for the 2051-2100 time horizon the increase in the mean minimum daily temperature for Spain as a whole rises by 2.8°C more than the reference period (2000-2009). As occurs in the case of RCP4.5, at extreme values this increase is much greater. For instance, if one focuses again on the case of Avila, the 70th percentile which in the period 2000-2009 corresponded to -10°C in the minimum daily temperature series for the winter months projected under an RCP8.5 emission scenario corresponds to 0.2 °C in the period 2021-2050 and 1.6 °C in the period 2051-2100.

Without adaptation, the daily minimum temperature stimations results in no cold-waves in any case. With adaptation, T threshold remaining constant, as can be seen in Table 4 and 5. About cold-waves stimations, under a RCP 8.5 emission scenario will be 318 cold-waves in the period 2021-2050 and 316 cold-vawes in the period 2051-2100.

Mortality stimations obtained for RCP 4.5

Figure 1, shows annual attributable mortality due to cold-waves at province level in Spain over the 2021-2050 and 2051-2100 time horizon. From the standpoint of overall annual attributable mortality for Spain under an RCP4.5 scenario, cold-related mortality would be 230 deaths per year (95%CI: 175, 286) over the 2021-2050 time horizon and 212 deaths per year (95%CI: 155, 269) over the 2051-2100 time horizon.

Mortality stimations obtained for RCP 8.5

Figure 2 shows annual attributable mortality due to cold-waves at province level in Spain over the 2021-2050 and 2051-2100 time horizon in RCP 8.5. In this figure, annual cold-related mortality for Spain as a whole would be 229 deaths per year (95%CI: 94, 364) over the 2021-2050 horizon and 242 deaths per year (95%CI: 104, 380) over the 2051-2100 time horizon.

Annual attributable mortality remains practically constant or with statistically non-significant differences, regardless of the emission scenario and time horizon.

Economic quantification

In terms of economic quantification, the cost of annual cold-related mortality over the 2100 time horizon would be €873 million per year under the RCP4.5 emission scenario and €997 million per year under the more unfavourable RCP8.5 emission scenario.

4. **Discussion**

The first relevant finding of this study is that, without adaptation processes, if the cold-wave threshold definition temperature in Spain is assumed to be constant, then cold waves will disappear over the 2021-2050 and 2051-2100 time horizons under both emission scenarios, RCP4.5 and RCP8.5, as a consequence of global warming (IPCC, 2013).

Findings about minimum temperatures predicted

The values of the predicted increase in mean minimum temperatures may be relatively small when compared to those for the reference period, but this does not apply if this same comparison is made in the case of the extremes, as is highlighted by the concrete case of Avila reported in the Results section. The important increase in these minimum daily temperatures, especially at low percentiles, may account for the fact that no cold waves are detected over any time horizon or scenario in a case where the cold wave definition temperature is assumed to remain constant over time. This different behaviour pattern in extreme with respect to mean temperature values was also detected in earlier studies in the case of heat (Carmona et al., 2017).

As can be seen from the Results section, the envisaged increases in minimum daily temperature over the different time horizons for the two emission scenarios considered are appreciably smaller than those projected for maximum daily temperature. Hence, under an RCP8.5 scenario, the mean maximum daily temperature for Spain as a whole went from 28.7ºC in the reference period 2000-2009 to 30.3ºC over the 2021-2050 horizon, i.e., an increase of 1.6ºC, whereas for minimum temperature the equivalent increase was 1.2ºC; and the same occurred over the 2051-2100 time horizon, with the mean maximum daily temperature rising by 4.9ºC versus only 2.8ºC in the case of the minimum daily temperature (Díaz et al., 2019a).

A large amount of evidence continues to support the conclusion that most global land areas analyzed have experienced significant warming of both maximum and minimum temperature extremes since about 1950 (IPPC, 2013). All datasets examined in the IPCC report indicate a faster increase in minimum temperature extremes than maximum temperature extremes. But in absolute value, recent warming (last30 years) has been characterized by larger increases in warm anomalies relative to cold anomalies (Robeson et al., 2014). For summer and winter months, the local temperature increase is smaller for minimum temperature than for maximum temperature, yielding enhanced temperature amplitude in both seasons.

Findings about the predicted mortality impact of cold waves

Although few studies have focused on the mortality impact of cold waves, almost all agree on the foreseeable decrease in the number of cold waves per year and, by extension, in expected annual cold-wave-related mortality, particularly in urban environments. A large-scale study undertaken in the USA thus envisages that in the period 2061-2080, cold waves will fall from their current rate of 2 per year to one every 5 years under an RCP4.5 emission scenario and one every 10 years under an RCP8.5 scenario (Oleson et al., 2018). Similarly, another study conducted in 10 US cities shows that cold-related mortality will undergo a significant decline in 8 of these (Weinberger et al., 2017). A further study conducted in the city of Vilnius (Sánchez-Martínez et al., 2018a) reports that the current rate of 10.1 cold wave days per year will fall to 4.4 in the period 2030-2045 and then practically disappear over the 2085-2100 time horizon (a drop of 93%) under an RCP8.5 emission scenario. However, the most complete study of this type undertaken to date was undoubtedly that by Gasparrini et al. (Gasparrini et al., 2017): it covered 451 cities across 23 countries and established that the effect of cold waves on mortality would be nil over the 2090-2099 time horizon.

The adaptation processes

Just as it is unrealistic to assume that the heat-wave definition temperature will remain constant over time (Guo et al., 2018; Sánchez-Martínez et al., 2018b; Díaz et al., 2019a), it is equally unrealistic to assume that the cold-wave definition temperature will do so.

The hypothesis used for the Vilnius study (Sánchez-Martínez et al., 2018a) is similar to that used here, i.e., the current percentile of the cold-wave definition temperature being assumed to remain constant over time. In practice, this leads to a situation where the cold-wave threshold temperature will rise over time, something that is in line with the increase in minimum mortality temperatures detected both in Stockholm (Åström et al., 2016) and Japan (Chung et al., 2018). Most studies assessing temporal variations have focused on heat mortality associations, reporting a substantial attenuation in risk in several countries. But, more complex mechanisms are involved in the cold effects; indeed mechanisms driving cold-related mortality still remain largely unknown (Ebi and Mills, 2013). Maintaining a constant cold wave definition percentile over time implies maintaining an invariable number -*but not an invariable intensity*- of any cold waves that may occur. That is to say, the same number of cold waves may occur but the difference (T_{cold}) between the minimum daily temperature and the cold-wave threshold definition temperature may be smaller than what is seen at present. This would account for the clear decrease in projected mortality, ranging from 212 deaths per year under an RCP4.5 emission scenario to 242 deaths per year under an RCP8.5 emission scenario across the period 2051-2100, as compared to the figure of 1,046 deaths per year for the reference period (Carmona et al., 2016b).

Another noteworthy finding is that cold-related mortality remains without statistically non-significant differences, regardless of time horizons and emission scenarios. This is logical, given that the following are all assumed to be constant, namely, the impact of cold over time as measured by reference to PAR, the population from 2030 onwards, and the number of cold waves which occur each year, so that any differences can be assumed to be exclusively due to changes in the intensity of the projected cold waves. This same finding was reported by the Vilnius study (Sánchez-Martínez et al., 2018a).

Limitations

Furthermore, it must be borne in mind that the modelling process used to project minimum daily temperatures by reference to time horizons and emission scenarios is based on climate variables (Amblar et al., 2017). Hence, synoptic-scale meteorological situations, which may account for inflows of cold air masses into the Iberian Peninsula and thereby give rise to a great proportion of the cold waves detected in Spain, were not taken into consideration (Prieto et al., 2004). These meteorological situations could increase the number of cold waves which really occur in future but are not contemplated in climate models.

Apart from this limitation, there are others that may introduce biases into the results obtained in this study. Firstly, at a provincial level a single observatory was considered to be representative of the entire province, something that could induce problems of representativeness of exposure of the whole population (Carmona et al., 2017). Although there is a relationship between the percentile to which $T_{threshold}$ corresponds and the PAR value (Carmona et al.,2106a), for study purposes the PAR value was assumed to be constant. This limitation is not excessively important, since this PAR value has frequently been seen not to vary significantly over time in retrospective studies in which cold time trends have been analysed (Díaz et al., 2019b; Åström et al., 2018). Furthermore, no account was taken of the possible changes which may, at an urban level, take place in cities. While such changes have been shown to be effective in the case of heat, they do not seem to have been so clearly effective in the case of cold (Milojevic et al., 2016). Another limitation concern to capacity to human thermal adjustment (physiologically), though this is assumed to be quite limited until reaching “peak heat/cold stress” (Sherwood and Huber, 2010).

Although we took into account population projections until 2030, no account was taken of the variations experienced in the distribution of the population pyramid, something that is crucial when it comes to projecting the impact of extreme temperatures on mortality over future time horizons (Lee et al., 2016). What this therefore means is that, in our case, no account was taken of the respective proportions of children under the age of 5 years and adults over the age of 65 years, i.e., the target groups insofar as the effects of cold are concerned. The over-65 age group in particular is that in which the impact of cold has most clearly increased in Spain in recent years (Díaz et al., 2015). Likewise, no account was taken of the existence of other environmental factors whose health impact is seen to increase during cold wave periods, e.g., air pollution caused by particulate matter (Ortiz et al., 2017) or NO_2 (Linares et al., 2018). Although the existence or absence of influenza epidemics was taken into account in the retrospective study performed to ascertain the PARs, this factor was not considered for the purpose of drawing up the projections.

Conclusions

The economic estimate of close on €1000 million per year attributable to cold waves over the 2100 time horizon indicates the sheer dimension of the problem. Needless to say, data associated with cold-related mortality in a global warming environment are not of the same order as those expected for heat (Díaz et al., 2019a; Guo et al., 2018). Nonetheless, the fact that retrospective studies conducted in different places around the world have shown that the impact of cold has not decreased (Wang et al., 2016; Vicedo-Cabrera et al., 2018; Lee et al., 2018; Åström et al., 2018; Díaz et al., 2019b), that in other places -as well as in retrospective studies- daily cold-related mortality has been shown to exceed that due to heat (Carmona et al., 2016b), that acclimatisation measures in cities are not working properly in the case of cold (Milojevic et al., 2016), that social inequalities such as energy poverty mean that there is no guarantee of homes being suitably insulated from the cold (Sanz et al., 2016). The regional approach of the analyses is likely to be highly useful in implement regional prevention plans against cold-waves in Spain. Cold Health Action Plans could tap into the large untapped potential in local structures, community capacity and in-depth knowledge of local needs.

Global warming may actually favour occasional inflows of extremely cold air from the Arctic (Cohen et al., 2014) make it necessary to adopt public health measures, such as the implementation of prevention plans similar to those which are already in place for heat, in order to protect the population, even in a scenario of a clear rise in mean global temperatures (IPCC, 2013).

Disclaimer

This paper reports independent results and research. The views expressed are those of the authors and not necessarily those of the Carlos III Institute of Health (*Instituto de Salud Carlos III*).

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PROVINCE (capital)	Mean T_{min} (^{o}C) 2000 2009	Percentile	T_{min} threshold (^{o}C)	Cold waves (every year)	PAR (%)
Álava (Vitoria)	2.2	*	*	*	*
Albacete	1.8	8	-4	12	1.7
Alicante	8.1	*	*	*	*
Almería	10.2	4.7	6	6	17.8
Asturias (Oviedo)	5.5	7.0	0	9	9.0
Avila	0.5	0.7	-10	1	25.2
Badajoz	5.2	11.8	0	16	10.3
Balearic Isles (Palma M)	2.9	7.3	0	10	14.9
Barcelona	6.7	2.4	0	3	6.9
Burgos	0.6	*	*	*	*
Caceres	5.3	2.4	-2	4	7.4
Cadiz	11.2	5.1	6	6	11.9
Cantabria (Santander)	6.8	10.4	2	14	7.2
Castellón	8.1	2.4	2	3	20.6
Ciudad Real	3.4	2.6	-4	3	25.9
Cordoba	5.8	1.6	-2	3	18.7
Corunna (*Coruña A*)	9.1	4.8	4	7	10.6
Cuenca	1.4	7.1	-4	10	3.9
Gerona	2.6	*	*	*	*
Granada	3.1	1.7	-4	2	20.5
Guadalajara	0.3	6.5	-6	8	7.2
Guipúzcoa (San Sebastián)	6.9	*	*	*	*
Huelva	7.7	5.2	2	7	16.5
Huesca	2.8	1.3	*	*	*
Jaén	7.1	2.2	0	3	7.4
León	0.5	12.6	-4	17	4.1
Lleida	2.6	12.5	-2	17	5.2
La Rioja (Logroño)	3.3	19.5	0	28	3.2
Lugo	2.8	2.2	-6	3	13.6
Madrid	4.5	2.3	-2	3	10.5
Malaga	9.4	4.1	4	5	25.7
Murcia	11.4	0.5	4	0	21.6
Navarre (Pamplona)	2.9	1.7	-6	2	6.2
Ourense	4.3	1.7	-2	11	7.8
Palencia	**	*	*	*	*
Las Palmas	16.0	*	*	*	*

Pontevedra	7.1	6.7	2	9	14.1
Salamanca	0.2	16.6	-4	23	4.3
SC Tenerife	16.4	*	*	*	*
Segovia	1.7	3.5	-6	4	13.2
Seville	8.3	4.4	2	6	16.4
Soria	-0.1	7.1	-6	9	4.3
Tarragona	7.0	3.1	0	4	6.9
Teruel	-0.9	5.3	-8	7	*
Toledo	4.0	0.5	-6	1	20.2
Valencia	8.9	1.5	2	2	20.6
Valladolid	1.8	5.8	-4	8	5.2
Vizcaya (Bilbao)	6.4	1.5	-2	2	13.7
Zamora	2.0	2.4	-6	3	6.0
Zaragoza	4.2	6.1	-2	9	1.6
SPAIN	**5.1**			301	

Table 1. Values corresponding to the period 2000-2009.

* Without cold-wave threshold temperature

** Without T_{min} data at the observatory

PAR**:** population attributable risk

		T_{min} threshold (^{O}C)		Cold waves (every year)	
PROVINCE (capital)	**Mean T_{min} (^{O}C) 2021 2050**	**With adaptation**	**Without adaptation**	**With adaptation**	**Without adaptation**
Álava(Vitoria)	3.5	*	*	*	*
Albacete	3.3	1.4	-4	12	0
Alicante	8.4	*	*	*	*
Almería	10.8	9.1	6	7	0
Asturias (Oviedo)	6.7	5.3	0	11	0
Avila	2.7	0.2	-10	1	0
Badajoz	7.1	5.8	0	18	0
Balearic Isles (Palma M)	9.4	7.8	0	11	0
Barcelona	8.8	6.6	0	4	0
Burgos	**	*	*	*	*
Caceres	7.5	5.5	-2	4	0
Cadiz	12.6	11.1	6	8	0
Cantabria (Santander)	7.9	6.8	2	15	0
Castellón	6.6	4.5	2	4	0
Ciudad Real	4.3	1.8	-4	4	0
Cordoba	4.8	2.9	-2	2	0
Corunna (*Coruña A*)	9.7	8.4	4	7	0
Cuenca	2.4	0.6	-4	11	0
Gerona	**	*	*	*	*
Granada	5.7	3.6	-4	3	0
Guadalajara	3.1	1.16	-6	10	0
Guipúzcoa (San Sebastián)	**	*	*	*	*
Huelva	10.5	8.8	2	8	0
Huesca	**	*	*	*	*
Jaén	6.1	4	0	3	0
León	2.1	0.7	-4	19	0
Lleida	3.1	1.6	-2	19	0
La Rioja (Logroño)	4.8	3.8	0	29	0
Lugo	5.2	3.2	-6	3	0
Madrid	5.7	3.4	-2	4	0
Malaga	8.2	6.6	4	6	0

Murcia	8.6	6.2	4	1	0
Navarre	5.1	2.9	-6	3	0
Ourense	6.5	4.2	-2	3	0
Palencia	**	*	*	*	*
Las Palmas	**	*	*	*	*
Pontevedra	7.5	6.1	2	10	0
Salamanca	2.5	1.2	-4	25	0
SC Tenerife	**	*	*	*	*
Segovia	2.6	0.6	-6	5	0
Seville			2		
Soria	0.3	-1.1	-6	11	0
Tarragona	10.9	9.0	0	5	0
Teruel			-8		
Toledo	5.8	2.9	-6	1	0
Valencia	10.1	7.9	2	2	0
Valladolid	2.3	0.5	-4	9	0
Vizcaya (Bilbao)	3.9	1.6	-2	2	0
Zamora	2.4	0.3	-6	4	0
Zaragoza	3.8	1.92	-2	9	0
SPAIN	**6.1**			0	

Table 2. Values corresponding to the RCP 4.5 scenario over the 2021-2050 time horizon.

* Without cold-wave threshold temperature

** Without T_{min} data in the projection

		T_{min} threshold		Cold waves (every year)	
PROVINCE (capital)	**Mean T_{min} (^{o}C) 2051 2100**	**With adaptation**	**Without adaptation**	**With adaptation**	**Without adaptation**
Álava(Vitoria)	4.0	*	*	*	*
Albacete	3.9	1.9	-4	12	0
Alicante	9.1	*	*	*	*
Almería	11.3	9.5	6	7	0
Asturias (Oviedo)	7.2	5.7	0	10	0
Avila	3.2	0.5	-10	1	0
Badajoz	7.7	6.2	0	18	0
Balearic Isles	10.1	8.2	0	11	0
Barcelona	9.4	6.9	0	4	0
Burgos	**	*	*	*	*
Caceres	8.1	5.9	-2	4	0
Cadiz	13.1	11.5	6	8	0
Cantabria (Santander)	8.3	7	2	16	0
Castellón	7.2	4.9	2	4	0
Ciudad Real	5.0	2.4	-4	4	0
Cordoba	5.3	3.2	-2	2	0
Corunna (*Coruña A*)	10.1	8.7	4	7	0
Cuenca	3.1	1.1	-4	11	0
Gerona	**	*	*	*	*
Granada	6.3	4.0	-4	3	0
Guadalajara	3.8	1.7	-6	10	0
Guipúzcoa (San Sebastián)	**	*	*	*	*
Huelva	11.1	9.3	2	5	0
Huesca	**	*	*	*	*
Jaén	6.7	4.4	0	3	0
León	2.5	1.2	-4	19	0
Lleida	3.7	2.0	-2	19	0
La Rioja (Logroño)	5.4	4.2	0	29	0
Lugo	5.7	3.5	-6	3	0
Madrid	6.3	3.9	-2	3	0
Malaga	8.6	6.9	4	6	0
Murcia	9.3	6.6	4	1	0
Navarre	5.6	3.2	-6	3	0
Ourense	7.0	4.4	-2	3	0

Palencia	**	*	*	*	*
Las Palmas	**	*	*	*	*
Pontevedra	7.9	6.5	2	10	0
Salamanca	3.1	1.8	-4	25	0
SC Tenerife	**	*	*	*	*
Segovia	3.2	1.1	-6	5	0
Seville	**	*	2	0	*
Soria	0.9	- 0.8	-6	11	0
Tarragona	11.5	9.4	0	5	0
Teruel	**	*	-8	0	*
Toledo	6.4	3.2	-6	1	0
Valencia	10.7	8.3	2	2	0
Valladolid	2.8	0.9	-4	9	0
Vizcaya (Bilbao)	4.4	2.2	-2	2	0
Zamora	2.9	0.6	-6	4	0
Zaragoza	4.3	2.3	-2	9	0
SPAIN	**6.5**				

Table 3. Values corresponding to the RCP 4.5 scenario over the 2051-2100 time horizon.

* Without cold-wave threshold temperature

** Without T_{min} data in the projection

		T_{min} threshold (^{o}C)		**Cold waves (every year)**	
PROVINCE (capital)	**Mean T_{min} (^{o}C) 2020 2050**	**With adaptation**	**Without adaptation**	**With adaptation**	**Without adaptation**
Álava (Vitoria)	3.6	*	*	*	*
Albacete	3.3	1.4	-4	12	0
Alicante	8.7	*	*	*	*
Almería	11.0	9.1	6	7	0
Asturias (Oviedo)	6.8	5.3	0	11	0
Avila	2.8	0.2	-10	1	0
Badajoz	7.2	5.8	0	18	0
Balearic Isles (Palma M.)		7.8	0	12	0
Barcelona	8.9	6.6	0	4	0
Burgos	**	*	*	*	*
Caceres	7.7	5.6	-2	4	0
Cadiz	12.7	11.1	6	8	0
Cantabria (Santander)	8.0	6.8	2	16	0
Castellón	6.8	4.5	2	4	0
Ciudad Real	4.5	1.8	-4	4	0
Cordoba	5.0	2.9	-2	2	0
Corunna (*Coruña A*)	9.8	8.4	4	7	0
Cuenca	2.6	0.6	-4	11	0
Gerona	**	*	*	*	*
Granada	5.9	3.6	-4	3	0
Guadalajara	3.2	1.2	-6	10	0
Guipúzcoa (San Sebastian)	**	*	*	0	*
Huelva	10.6	8.8	2	8	0
Huesca	3.1	0.2	-6	2	0
Jaén	6.4	4	0	3	0
La Rioja (Logroño)	4.9	3.8	0	29	0
Las Palmas	**	*	*	*	*
León	2.2	0.7	-4	19	0
Lleida	3.2	1.6	-2	19	0
Lugo	5.4	3.3	-6	3	0
Madrid	5.8	3.4	-2	4	0
Malaga	8.3	6.6	4	6	0
Murcia	8.9	6.2	4	1	0
Navarre	5.1	2.9	-6	3	0

Ourense	6.6	4.2	-2	3	0
Pontevedra	7.6	6.2	2	10	0
Palencia	**	*	*	*	*
Salamanca	2.6	1.2	-4	25	0
SC Tenerife	**	*	*	*	*
Segovia	2.8	0.65	-6	5	0
Seville	**	*	2	*	*
Soria	0.5	-1.1	-6	11	0
Tarragona	11.1	9.0	0	5	0
Teruel	**	*	-8	*	*
Toledo	6.0	2.9	-6	1	0
Valencia	10.3	7.9	2	2	0
Valladolid	2.4	0.5	-4	9	0
Vizcaya (Bilbao)	4.0	1.6	-2	2	0
Zamora	2.5	0.3	-6	4	0
Zaragoza	3.9	1.9	-2	10	0
SPAIN	**6.3**				

Table 4. Values corresponding to the RCP 8.5 scenario over the 2021-2050 time horizon.

* Without cold-wave threshold temperature

** Without T_{min} data in the projection.

		T_{min} threshold		**Cold waves (every year)**	
PROVINCE (capital)	**Mean Tmin (^{o}C) 2051 2100**	**With adaptation**	**Without adaptation**	**With adaptation**	**Without adaptation**
Álava (Vitoria)	5.2	*	*	*	*
Albacete	5.3	3.0	-4	12	0
Alicante	10.6	*	*	*	*
Almería	12.5	10.4	6	7	0
Asturias (Oviedo)	8.4	6.6	0	11	0
Avila	4.6	1.6	-10	1	0
Badajoz	8.8	7.2	0	18	0
Balearic Isles (Palma M.)	11.7	9.3	0	11	0
Barcelona	10.8	8.1	0	4	0
Burgos	**	*	*	*	*
Caceres	9.3	6.7	-2	4	0
Cadiz	14.2	12.3	6	8	0
Cantabria (Santander)	9.3	7.8	2	16	0
Castellón	8.6	5.9	2	4	0
Ciudad Real	6.4	3.4	-4	4	0
Cordoba	6.4	4.0	-2	2	0
Corunna (*Coruña A*)	11.1	9.4	4	7	0
Cuenca	4.4	2.1	-4	11	0
Gerona	**	*	*	*	*
Granada	7.6	4.8	-4	3	0
Guadalajara	5.1	2.7	-6	10	0
Guipúzcoa (San Sebastian)	**	*	*	*	*
Huelva	12.2	10.1	2	8	0
Huesca	5.1	1.7	-6	2	0
Jaén	8.3	5.4	0	3	0
La Rioja (Logroño)	6.6	5.3	0	29	0
Las Palmas	**	*	*	*	*
León	3.7	1.2	-4	19	0
Lleida	5.0	3.1	-2	19	0
Lugo	6.9	4.5	-6	3	0
Madrid	7.6	4.7	-2	4	0
Malaga	9.7	7.6	4	6	0

Murcia	11.0	7.5	4	1	0
Navarre	6.8	4.2	-6	3	0
Ourense	8.3	5.6	-2	3	0
Pontevedra	9.0	7.3	2	10	0
Palencia	**	*	*	*	*
Salamanca	4.2	1.78	-4	25	0
SC Tenerife	**				
Segovia	4.4	2.0	-6	5	0
Seville	**		2		
Soria	2.1	0.2	-6	11	0
Tarragona	12.9	10.3	0	5	0
Teruel	**	*	-8	*	*
Toledo	7.8	4.3	-6	1	0
Valencia	12.0	9.2	2	2	0
Valladolid	4.2	2.0	-4	9	0
Vizcaya (Bilbao)	5.5	2.2	-2	2	0
Zamora	4.2	1.6	-6	4	0
Zaragoza	5.7	3.4	-2	9	0
Spain	**7.9**				

Table 5. Values corresponding to the RCP 8.5 scenario over the 2051-2100 time horizon.

* Without cold-wave threshold temperature

** Without T_{min} data in the projection

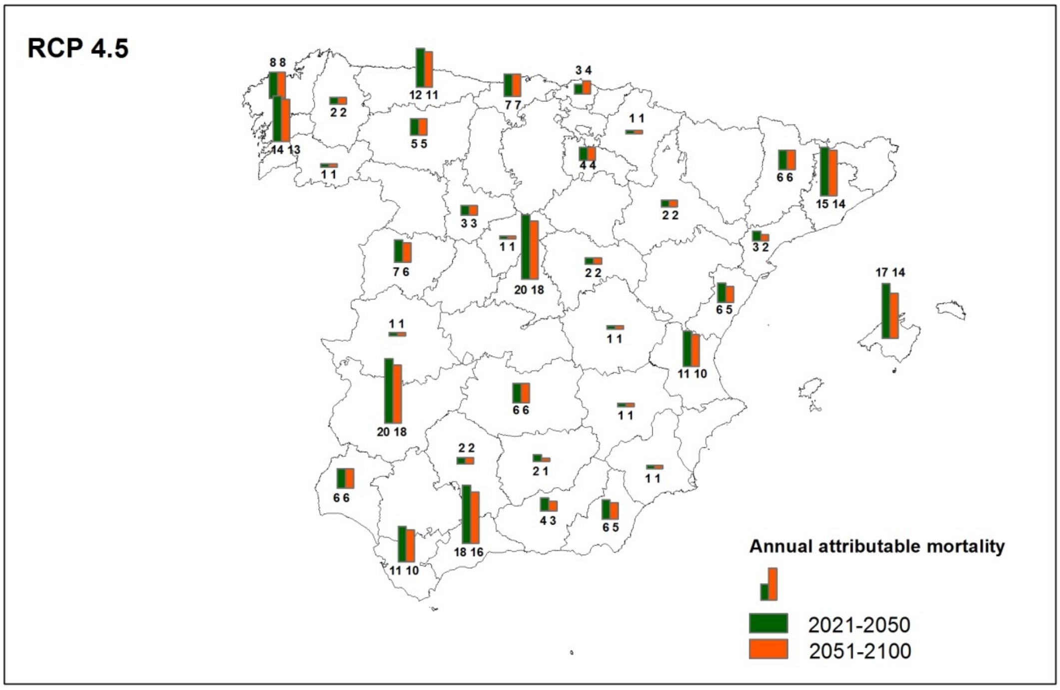

Figure 1. Annual attributable mortality due to cold-waves. **Values corresponding to the RCP 4.5 scenario over the 2021-2050 and 2051-2100 time horizon.**

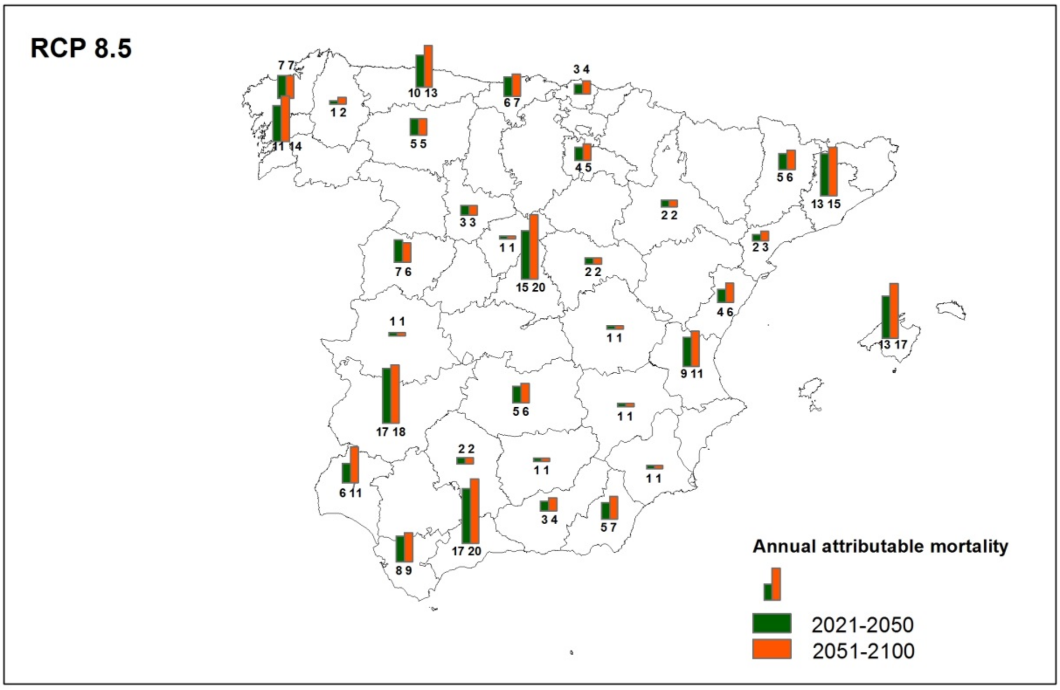

Figure 2. Annual attributable mortality due to cold waves. **Values corresponding to the RCP 8.5 scenario over the 2021-2050 and 2051-2100 time horizon.**