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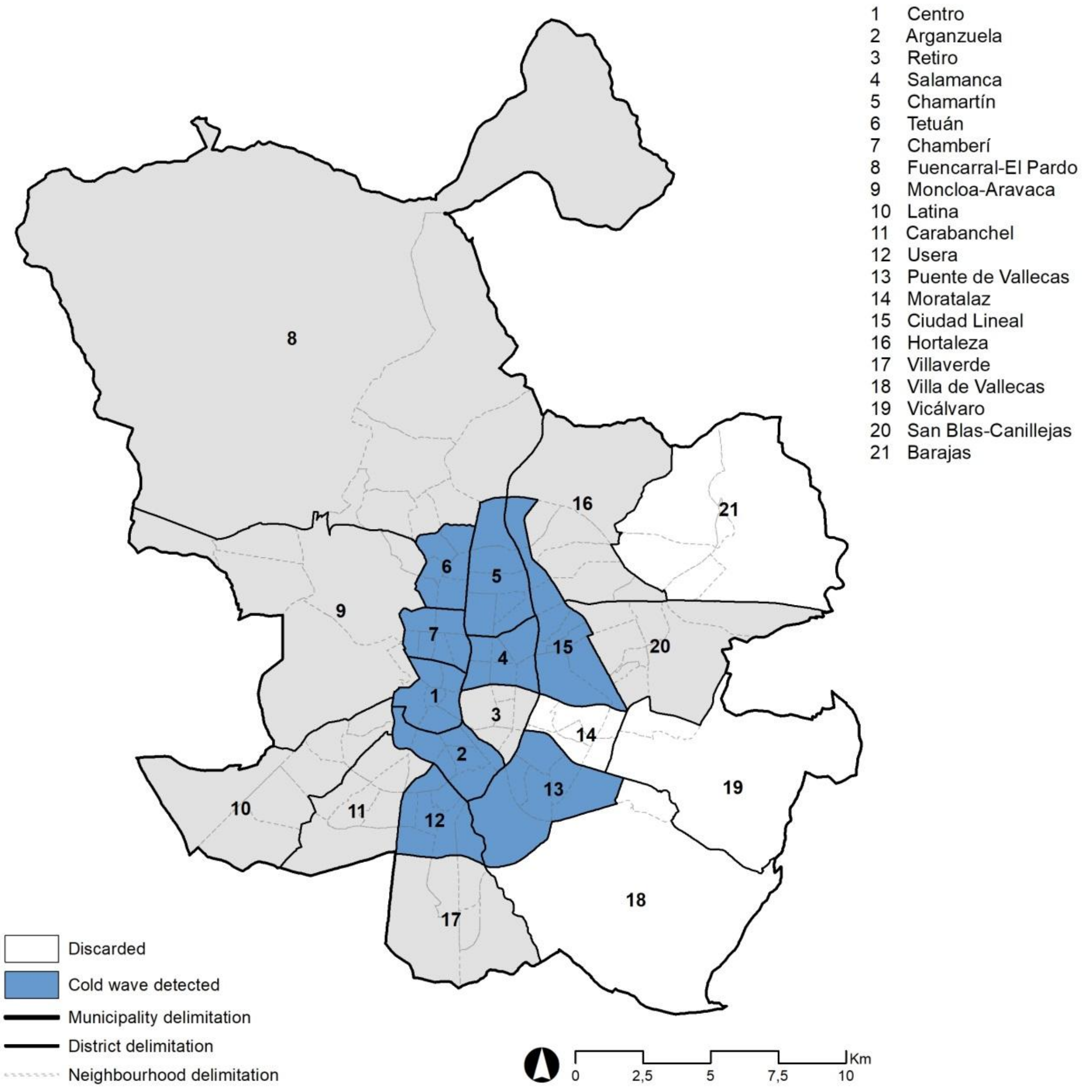
Graphical Abstract



Highlights.

- The impact of cold on mortality was detected in 9 of the 17 districts analyzed.
- The probability of detecting an impact increases with a higher percentage of homes without heating systems.
- The probability of detecting an impact in a district increases with a of population over age 65.
- The results obtained identify the factors that should be considered to reduce the impact of cold waves.

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Abstract:

While there is much research that focuses on the association between cold waves and their impacts on daily mortality at the city level, few analyze the impact related to social context and demographic variables at levels lower than the municipal. The objective of this study was to determine the role of the percentage of people over age 65, income level and percentage of homes without heating in the analysis of the impact of cold waves on daily mortality between January 1, 2010 and December 31, 2013 in different districts of the municipality of Madrid. We calculated Relative Risks (RR) and Attributable Risks (RA) for each of 17 districts to determine correlations between the effect of cold waves and daily mortality due to natural causes (CIEX: A00-R99) using Generalized Linear Models (GLM) of the Poisson family (link log). The pattern of risks obtained by district was analyzed using binomial family models (link logit), considering socioeconomic and demographic variables. In terms of results, an impact of cold on mortality was detected in 9 of the 17 districts analyzed. The analysis of risk patterns revealed that the probability of detecting an impact in a district increases in a statistically significant way (p-value <0.05) with a higher percentage of homes without heating systems and a higher percentage of population over age 65. The results obtained identify the factors that should be considered in public health policies that target the district level to reduce the impact of cold waves.

Key words: Cold wave; energy poverty; aging population; heating; district.

1. Introduction

Global warming of the planet is one of the phenomena associated with climate change and is currently accelerating (WHO, 2019). However, although earlier health research pointed to an increase in temperatures accompanied by reduced winter mortality, recent studies show that this is not occuring (Ebi and Mills, 2013; Gasparrini et al., 2015). There is ample evidence that confirms a greater risk to health due to cold than due to heat in places such as North America (Allen et al., 2016 & 2018), Kenya (Egondi et al., 2015), France (Goix et al., 2019), Brazil (Son et al. 2016), China (Wang et al., 2017) and Spain (Díaz et al., 2015a).

In the case of Madrid, there is an established trend in greater risks linked to extreme cold than to heat waves (Díaz et al., 2015a). If specific measures are not taken to address this trend, a decrease in mortality attributable to cold is unlikely in the future, with accompanying health costs that could reach 1 billion euros per year by the year 2100 (Díaz et al., 2019).

There are various causes that seem to be related to this phenomenon. On one hand, from a climatological perspective, changes in ocean and atmospheric currents due to climate change could give rise to an intensification in cold waves in some regions in the middle latitudes (Cohen et al., 2014). On the other hand, in populations adapted to more temperate climes, cold tends to have a greater effect on health, although without temperatures that are as low as in cold climates (Linares et al. 2017). The growing trend in minimum mortality temperatures (MMT) found in countries like Spain (Follos et al., 2020), Sweden (Åström et al. 2016 & 2018) and Japan (Chung et al. 2017) shows how populations are adapting to the increase in temperatures produced by global warming. This possible population adaptation to heat could entail a maladjustment to cold (Díaz et al, 2019); that is to say, in the future, there could be an increase in the temperature at which mortality due to low temperatures spikes, more so than the complete disappearance of excess mortality due to cold (Díaz et al., 2015a).

From the perspective of the effects on health, cold waves are related to complications with respiratory diseases (Mäkinen et al., 2009; Monteiro et al., 2013) and circulatory diseases (Urban et al., 2014; Davidkovova et al., 2014, Medina-Ramón et al., 2006), including worsening of other chronic diseases (Rytkönen at al., 2005). However, cold is primarily related to infectious diseases, becuase low temperatures favor their spread (Hajat and Haines, 2002). Specifically, the flu is the primary etiological agent responsible for excess mortality in the winter (Glezen, 1982). In terms of the type of response, the negative effects of cold on health tend to become manifest over the medium and long-term (Alberdi et al., 1998; Braga et al., 2001). These circumstances tend to co-occur in people over age 65 (Linares et al., 2017), and among those whose physiological systems have lost the efficiency of their thermo-regulatory capacity with age (Guyton & hall., 2011). Therefore, the percentage of people in this age group seems to be a decisive demographic parameter that can limit the capacity of the population to adapt to the cold. Of course, social and economic factors also influence this process. Income level is a variable that has been shown to be related to the effects of cold, because those over age 65 who have fewer resources are more vulnerable to low temperatures (Nakajima et al., 2019; Timothy et al., 2014). Furthermore, low income is related to other factors that are linked to extreme temperature mitigation, such as energy efficiency and quality of housing (Sanz Fernández et al., 2016; Sánchez-Guevara et al., 2018), interior air conditioning (Barreca et al. 2016) and situations of loneliness (Lin et al., 2019; Zhang et al., 2017) and energy poverty in general (Sánhez-Guevara et al., 2018). However, there is a need to continue to delve more deeply into how these factors modify the vulnerability to the cold.

Finally, in specialized literature there is a clear absence of work that analyzes the effects of temperature extremes at a level below the municipal. However, at this level there are unequal variables of socioeconomic indicators that suppose different rates of exposure and vulnerability to cold. Thus, studies that analyze the effect of cold waves by neighborhood or district zones in a differentiated way can provide new evidence to support understanding of how the social, economic and demographic context is related to extreme cold waves.

The objective of this study was to calculate the impact that cold waves have had in districts in Madrid between 2010 and 2013, by analyzing whether the percentage of population over age 65, the number of homes without heating and income level explain the different behavior of the impact of cold waves on daily mortality.

2. Material and methods

We carried out an ecological, longitudinal retrospective time series study in 21 districts in Madrid for the daily period between January 1, 2010 and December 31, 2013.

2.1. Variables analyzed

The dependent variable used was the time series of aggregated daily mortality for natural causes (CIE X: A00 – R99), with one per district available. These data were provided by Madrid Health (Madrid City Council) based on raw data from the Statistics Institute of the Community of Madrid.

Of the 21 districts in Madrid - the map of which is shown in Figure 1 - the following were discarded due to having over 10 percent lost values: districts 14, 18, 19 and 21, which correspond to Moratalaz, Villa de Vallecas, Vicálvaro and Barajas, respectively.

The independent variable considered was heat waves. The minimum daily temperature of -2 ºC is the threshold temperature at which mortality due to cold begins to increase in the municipality of Madrid, according to prior studies (Carmona et al. 2016). This variable, Tcold was quantified based on the minimum daily mortality data registered by the reference observatory in Madrid-Retiro at the State Meteorological Agency (AEMET).

The variable Tcold was defined for all of the districts analyzed in the following way:

Tcold = -2ºC – Tmin when Tmin ≤ -2ºC

Tcold = 0 when Tmin > -2ºC

As the effect of cold on mortality manifests over the medium to long-term, lag variables were introduced for the Tcold variable to the 13th order (Carmona et al. 2016). Variables were also included for the values of relative daily humidity, control variables for the series trend, seasonal components and the autoregressive character of mortality.

2.2. Calculation of relative risks and risks attributable to the Impact of cold waves

Using Poisson regression modeling allowed us to obtain the Relative Risks (RR) associated with the variable Tcold and with the lags that were statistically significant in each district. Based on the values of RR, population Attributable Risks (AR) were calculated using the equation:RA = (RR-1/RR)* 100 % (Coste y Spira, 1991). This process was repeated for each district. The models were adjusted using a backward stepwise modeling process, eliminating those variables that did not reach statistical significance with a p-value ≤ 0.05. The following equation represents the models analyzed:

$$Ln(y_i) = b + \beta_j Tcold_{ij} + \omega_k C_{ik} + \gamma_z hr_{iz}$$

Where i represents each observation; *y,* the mortality data used; *b,* the intercept; *β,* represents the coefficient calculated for Tcold and its lags *j*; *Ѡ,* represents the coefficient for each of the *k* control variables (C_i); and γ, represents the coefficient calculated for each of the lags z of relative humidity (hr_i). A different model was designed for each district.

2.3. **Analysis of the pattern of risks and daily percentage of attributable mortality**

Based on the risks calculated above, a second phase of the study created new variables to analyze the association with the social context and demographic variables shown here.

First, a “pattern of risks” variable was created, which was a dichotomous variable termed Rcold. This variable adopts the value described in the following equation:

If RA > 0 then Rcold = 1

If RA = 0 then Rcold = 0

The social context and demographic variables considered in this work are described here:

- Income by household: for each district, this value was expressed in thousands of euros per year. The data were extracted from Sanz Fernández et al. 2016 with available data between the years 2011 and 2013 from the Urban Audit project (INE 2015). Based on this, a categorical variable was created, called “income group”. This variable adopts the value “high” in those districts with income that is above average, and “low” in those districts that are below average.
- Population over age 65: considers the percentage of population in this age group that lives in each district, for each year included in the time series.
- Homes without heating: This value was expressed as a percentage for each district. These data were extracted from Sanz Fernández et al. 2016 based on the data from the Urban Audit project (INE, 2015).

Maintaining the observations in the database that correspond to values of Tcold > 0, the relationship between the pattern of risk and the social context and demographic variables was analyzed. We used a GLM model from the binomial family that uses the logit function link.

In this model the dependent variable was Rcold, and the socioeconomic context variables were added as independent variables. The equation of the analyzed model is defined as follows:

$$ln\ ln\left(\frac{p}{p-1}\right) = b + \beta_{1z}GR_z + \beta_2E_j + \beta_3NC_j$$

Where p represents the probability of detecting impact; b, the model intercept; β represents the coefficient calculated for the context variable indicated in the district *j.* These context variables were the z income groups (R), percentage of those over age 65 (E), and homes without access to heating (NC).

The next variable calculated was the daily percentage of mortality attributable to the cold wave. In the case of this variable, its value was defined in terms of the following equation:

$\%Ddead_i = Tcold_i * RA_j$

Where Tcold is a cold wave for observation i, the calculation of which has already been described; and RA the attributable risks for district j, calculated in the first phase of the study.

Finally, the association between this last variable and the context variables already described was analyzed. Thus, retaining the observations corresponding to $Tcold_i > 0$, we constructed a GLM model of the Poisson family.

For the construction and cleaning of the database we used the free software R 3.6, and STATA 14.2 was used to later calculate the models.

3. Results

Table 1 shows the descriptive statistics for daily mortality in districts in Madrid. The table shows that daily mortality was of the same order of magnitude in all of the districts, with maximums in Latina and Carabancel, whose average values doubled those of districts with lesser mortality such as Moncloa-Aravaca, Usera or Villaverde.

Table 2 shows descriptive data for the social context and demographic variables shown. In Table 2 we observed that on average, around 3 percent of homes in the districts do not have heating. However, there is elevated dispersion, and therefore there are observations quite far from the average. Also, there is a wide range of incomes in the districts, such that the income level in the wealthiest district was more than double that of the district with the lowest income per household.

Table 2 shows the districts where a cold wave impact was detected, and the RA are shown in Table 3. It can be observed that there was a cold wave impact detected in 9 of the 17 districts included in the study. In quantitative terms, the RA calculated range from 22.1 percent in Chamberi to 32.3 percent in Ciudad Lineal, though these were not statistically significant differences. On the other hand, the cold wave lag effect tends to occur in the medium-long term, that is to say, in lags 4 through 13.

Table 4 shows the results of the binomial model of the pattern of risks. In the table, the percentage of people over age 65 was statistically significant (p-valor < 0.05) along with the number of households without heating, although income has been displaced in the model. Thus, the probability of detecting risks in a district increases with the number of households without heating and the percentage of the population over age 65.

Finally, Table 5 shows the model that analyzed the percentages of daily mortality attributable to cold waves (%Ddead). All of the variables considered were statistically significant. Also, in addition to prior models, this model indicates that the percentage of daily mortality attributable to cold waves tends to be greater in the districts with lower than average incomes.

4. Discussion

One of the first results worth noting is that there was different behavior by Madrid's districts in terms of cold waves, given that not all of them showed an impact for low temperatures. On the other hand, when comparing these results with those found for the case of heat by López-Bueno et al. 2020 –in which a similar study was carried out for heat waves- we find that the effect of cold waves is greater and found in more districts than in the case of extremely high temperatures. Specifically, in the case of heat an effect was found for only three districts, compared to the nine districts with an impact in the case of cold. Furthermore, the risks quantified for heat were all lower than those observed for low temperatures. In particular, the RA calculated in Tetuan was 13.2 percent (4,6 21,1) for extremely high temperatures, compared to 26.1 percent (5,8 42,1) in the case of cold waves. On the other hand, in the case of Puente de Vallecas, the RA associated with heat was 10 percent (1,7 17,5) compared with 31.5 percent (17,6 43,1) detected for the cold. Therefore, it seems that the impact of cold waves on mortality tends to be greater than the impact of heat, as has been observed in other studies (Wang et al., 2017; Vicedo-Cabrera et al., 2018; lee et al., 2018; Amstrom et al, 2018; Díaz et al, 2016). In terms of the lags, it was found in the case of heat that, at the district level, an effect is produced immediately and in a short time frame. In contrast, the risks of cold detected in this study are related to medium and long-term effect. These lagged effects behave in a way that corresponds with what has been described in other literature, which describes how in the case of heat the short term effect dominates the circulatory system, while the effects of cold tend to manifest over the longer term and have an impact on pathologies related to the respiratory system (Linares et al., 2017).

If we analyze the way in which the risks are distributed (Table 1), it is important to note that Vallecas is among the zones that suffers greater risks due to cold waves, despite being a district with a younger population. In contrast, in Retiro and Moncloa-Aravaca there was no effect found even though these areas have a higher percentage of population over age 65. In this way, some of the most reduced risks are found in Chamartin (RA = 22,3% (1,8 38,6)) or Chamberi (RA = 22,1% (5,2 36,0)), despite a greater percentage of the population being among the older ages, compared to other districts with greater associated risks. Thus, if we consider the variables in an isolated way, the risks we found are not well explained by the percentage of people over age 65 who live in a district, despite the fact that this is the age group that is most affected by low temperatures (Linares et al., 2017).

What is described in the above paragraph coincides with the results described in Table 4, which shows the binomial model that relates the pattern of risks and context variables. This model aims to determine which variables are related to the probability of detecting a cold wave's impact on mortality. According to the results found, the percentage of the population over age 65 and the percentage of households without heating are statistically significant (p-valor < 0.05). This means that knowing the distribution of the observed risks requires considering the percentage of households without heating, in addition to the percentage of elderly population. Thus, according to the model, detecting an impact is more likely in districts where there is a greater percentage of households without heating. Furthermore, when comparing districts with the same percentage of households without heating, detecting an impact is more likely in those areas where there is a greater percentage of people over age 65. The relationship between both variables can be understood, considering the fact that the interior temperature in homes is more related to air conditioning and building structure than to exterior temperatures (Loughnan et al.,2015; Lundgren et al., 2019); or, described in another way, if the population has the possibility to remain at a comfortable temperature, there is no effective exposure to a cold wave, and therefore its effects can be more attenuated, even when the population risk is higher. This hypothesis explains why we find districts with greater risks than other districts with a higher percentage of people over age 65.

The final model (Table 5) aims to analyze whether the social context and demographic variables allow for explaining the percentages calculated for daily mortality attributable to cold waves (%Ddead). In this case, all of the variables are statistically significant, such that the impact is greater in those districts with incomes lower than average and grows with greater population over age 65 and the percentage of households without heating. It is important to point out that given the fact that income level and the percentage of households without heating are simultaneously statistically significant (p-valor < 0.05), both variables represent different realities. The results of this final model agree with other studies in which greater risks due to cold are related to unfavorable economic situations (Nakajima et al. 2019; Carter et al. 2016). Furthermore, it has been shown that people with low incomes tend not to climatize their homes, even when they have the apparatus available to do so (Gao et al., 2020; Sanchez-Guevara et al., 2015), which is intimately related to energy poverty. In terms of the inability to confront energy consumption, in temperate climes in Europe, low incomes levels are related to inefficient heating systems (Bouzarovski & Petrova, 2015). Spain is one of the countries in which there are more households with inefficient heating systems. (Lelkes & Zolyomi, 2010). In fact, in 2014, 10 percent of families were unable to maintain their homes in adequate temperature conditions during the winter (Martin-Consuegra et al., 2016). In Madrid, it has been shown that the average energy consumption per household is lower than what would be expected given general standards of comfort. It is likely that this is a sign of energy poverty (Martin-Consuegra et al., 2019). In summary, the association between income level and the percentage of mortality attributable to cold that is observed in this section could be interpreted as one more manifestation of this phenomenon.

With respect to housing quality, available scientific evidence shows the role in mitigating the impact of extreme temperatures on health (Fisk, 2015; Sanché-Guevara et al., 2018). It has been shown that the age of building construction is related with the pattern of risks associated with temperature extremes (López-Bueno et al. 2018). The importance of the quality of the insulation lies in the fact that, along with low income levels and inefficient heating systems, it is one of the determining factors of energy poverty. Along these lines, Spain is one of the countries in Europe with more households with insulation that is sub-optimal in terms of energy efficiency (Martin-Consuegra et al., 2016). At the same time, the energy quality and efficiency of the home are aspects that are intimately related to income level.

In any case, low income levels can also underlie other circumstances that increase vulnerability to cold waves. For example, elderly people who are lonely are even more vulnerable to temperature extremes (Lin et al., 2019; Zhang et al., 2017; Timothy et al., 2014), a circumstance which could be related to income and access to personal services that guarantee an adequate level of care for eldergy people (Sanz Fernández et al., 2016). Other aspects that could be hidden behind reduced income levels are low levels of job qualifications and occupational posts carried out in exterior environments, which have also been shown to be related to greater vulnerability to extreme temperatures (Ingole et al. 2017; Kysely et al., 2009).

In comparing the results found for the case of cold in this study to what has been previously discovered for the case of heat (López-Bueno et al., 2020), is it important to highlight that in both cases the percentage of the population over age 65 does not explain on its own the observed risks. In contrast, income level and climatization systems play a determinant role, without which it would be impossible to understand how extreme temperatures affect districts. In terms of public policy, addressing energy poverty is a problem with solutions that are complex in practice. For example, there is no clear evidence that policies implemented at the national level and promoted by the European Union are of benefit to the target groups. In this sense, the strong integration of the role of local authorities and the third sector (NGOs and non-profit organizations) could be a key to addressing the phenomenon of energy poverty = (Creutzfeldt, Gill, McPherson, & Cornelis, 2020).

Finally, it should be noted that there are limitations to this study that are common to ecological studies. On one hand, the results of this type of study are only applicable to the population as a whole and not at the individual level. Another limitation present in all ecological studies is that methodological variables are measured in a way that is delocalized from the place in which exposure takes place, such that the whole population is not necessarily truly exposed to the temperatures assigned to them. In this sense it is important to signal that the environment where measurement stations are located is very different from that of the urban environment (Núñez-Peiró et al., 2019). However, these problems are common to all studies of this type (Samet et al. 2000), and they are minimized by including control variables in the models used to calculate risks (Ingebrigtsen et al., 2015). On the other hand, the analysis of the effect of cold waves on mortality did not control for air pollution, given that there were no available data with an adequate level of disaggregation. It is considered that this limitation is minimal, given that there was compensation through controlling for periodicity, and also, the effect of air pollution in relation to the impact of temperatures is relatively low (Díaz et al., 2015b). In relation to the social context variables, the data on households without heating systems are from 2001, outside of the time period of the series and much prior to the date of the start of the series. However, there are currently no recent data available.

5. Conclusions

The first conclusion that stands out from this study is that the cold impacts the districts of Madrid differently. The variable that is most determinant in the detection of risks is the number of households without heating systems, followed by the percent of population over age 65. Once the effect of cold waves on health has been found, there is a tendency to find greater percentages of daily mortality in those districts with lower than average incomes. In a comparison of districts with equivalent socioeconomic situations, the percentage of the population over age 65 is determinant, with greater risks as this percentage increases.

The risks associated with cold make it necessary to develop and implement new measures and prevention plans to address low temperatures (Díaz et al., 2015a; Montero et al.; 2010). In the same way that a culture of heat has supposed a positive prognosis for health in Spain (Díaz et al., 2015b), information campaigns aimed at promoting a culture of cold could suppose great advances in mitigating the impact of extremely low temperatures on morbidity and mortality. In any case, it is important to highlight the need for public policies related to urban development that passively ensure minimal conditions of temperature habitability, in addition to guaranteeing energy efficient climatization systems. Policies of this type, together with other policies aimed at addressing energy poverty, could contribute to a significant reduction in mortality attributable to the cold.

6. Disclaimer

The researchers declare having no conflicts of interest that compromise the independence of this work of research. The points of view expressed here by the authors do not necessarily coincide with those of their institutions of affiliation.

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Table 1. Descriptive Statistics of daily mortality from 01-01-2010 to 12-31-2013

District (number)	Mean	SD	Min	Max
Centro (1)	3.4	1.8	1	11
Arganzuela (2)	3.2	1.7	1	12
Retiro (3)	3.2	1.7	1	11
Salamanca (4)	3,9	1.9	1	11
Chamartín (5)	3.5	1.8	1	13
Tetuán (6)	3.7	1.9	1	13
Chamberí(7)	4.1	2.0	1	13
Fuenc.-El Pardo (8)	4.2	2.0	1	13
Moncloa-Aravaca (9)	3.0	1.6	1	9
Latina (10)	5.6	2.4	1	15
Carabanchel (11)	5.6	2.4	1	15
Usera (12)	3.1	1.6	1	10
Puente Vallecas(13)	5.3	2.3	1	13
Ciudad Lineal (15)	5.1	2.3	1	14
Hortaleza (16)	3.0	1.6	1	13
Villaverde (17)	2.9	1.6	1	10
S. Blás-Canillejas (20)	3.2	1.7	1	14

Table 2. Descriptive statistic for the social context and demographic variables

Variable	Mean	SD	Min	Max
Income by household (1000 €/year)	38.77	11.65	23.91	58.69
>65 years (%)	19.50	2.66	15.46	24.24
Homes without heating systems (%)	2.99	2.03	0.84	9.78

Table3. Cold wave impact for districts . * Without impact.

Distrito	Lag	AR
Centro	Tcold (lag 11)	24.4% (7.0 38.6)
Arganzuela	Tcold (lag 6)	29.5% (12.6 43.1)
Retiro	*	
Salamanca	Tcold (lag4)	26.6% (10.3 39.9)
Chamartín	Tcold (lag 12)	22.3% (1.8 38.6)
Tetuán	Tcold (lag 10)	26.1% (5.8 42.1)
Chamberí	Tcold (lag 6)	22.1% (5.2 36.0)
Fuencarral-El Pardo	*	
Moncloa-Aravaca	*	
Latina	*	
Carabanchel	*	
Usera	Tcold (lag 4)	22.7% (2.6 38.7)
Tcold	Tcold	31.5% (17.6 43.1)
Ciudad Lineal	Tcold (lag 6 + lag 13)	32.3% (18.9 43.5)
Hortaleza	*	
Villaverde	*	
San Blás-Canillejas	*	

Table 4 Results of the binomial model of the pattern of risks.

Variable	**Coef**	**Std.err**	**z**	**P >|z|**
Low income	0.1753	0.3452	0.50	0.612
% > 65	0.2318	0.0578	4.01	0.000
% Households without heating	0.5329	0.1347	3.96	0.000
Constant	-5.9468	1.2809	-4.4	0.000

Table 5. Model that analyzed the percentages of daily mortality attributable to cold waves (%Dead).

Variable	**Coef**	**Std.err**	**z**	**P >|z|**
Low income	0,4360	0,0446	9,77	0,000
% > 65	0,1014	0,0083	12,19	0,000
% Households without heating	0,1186	0,0095	12,54	0,000
Constant	-0,2003	0,1864	-1,08	0,282

Figure 1. Districts in Madrid City

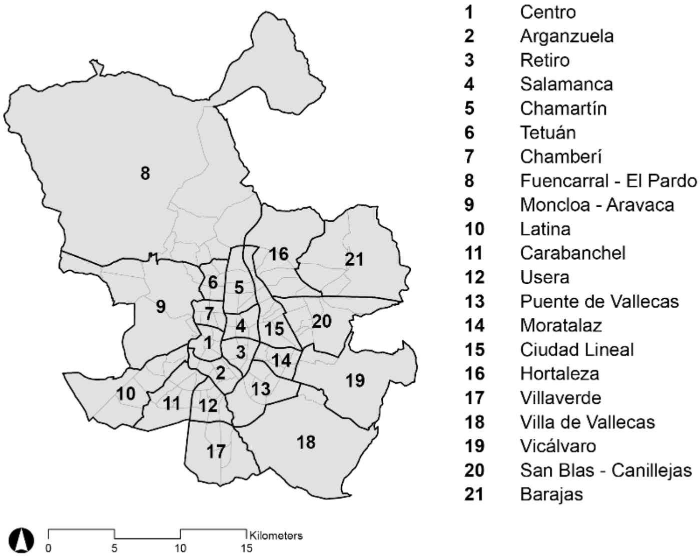

Figure 2. In blue districts in Madrid with cold wave impact. In white districts discarded