Title Page

Does the meteorological origin of heat waves influence their impact on health? A 6-year morbidity and mortality study in Madrid (Spain)

Ruiz-Páez R[1], Díaz J*[2], López-Bueno JA[3], Navas MA[2], Mirón IJ[4], Martínez GS[5], Luna MY[6], Linares C[2].

(1) University Teaching Hospital Infanta Leonor. Madrid, Spain.

(2) Reference Unit on Climate Change, Health and Urban Environment. National Institute of Health Carlos III. Madrid, Spain.

(3) University Autonoma of Madrid. Madrid, Spain.

(4) Department of Health, Community Board of Castile La Mancha, Toledo, Spain.

(5) The UNEP DTU Partnership, Copenhagen, Denmark.

(6) State Meteorological Agency (AEMET), Madrid, Spain

Corresponding Author:

Dr. Julio Díaz Jiménez.

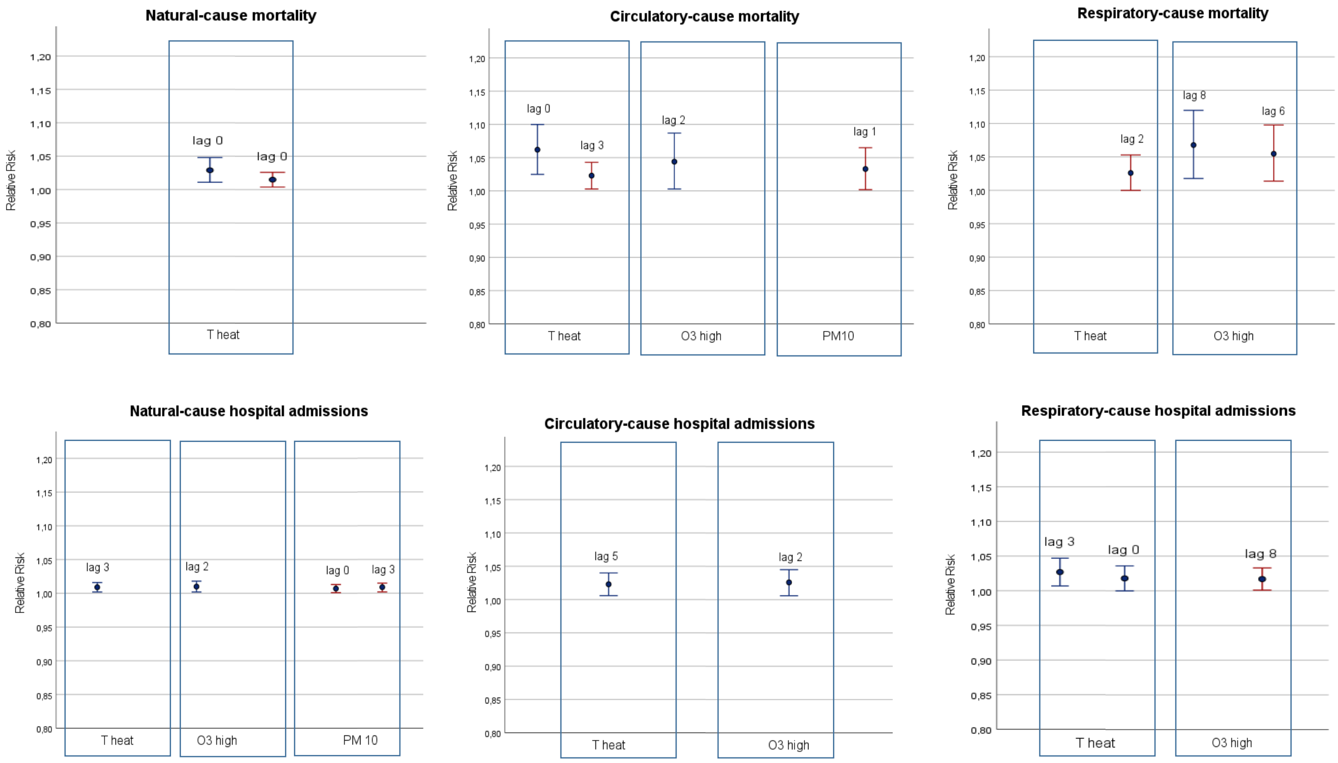
Carlos III Institute of Health. National Scholl of Public Health

Ava. Monforte de Lemos 5.

28029 Madrid.(Spain)

Email. J.diaz@isciii.es

Graphical Abstract



Highlights:

- The effect of heat waves on morbimortality depends on the synoptic situation.
- The impact of heat waves is greater under NAF= 0 conditions than under NAF= 1.
- The health impact of PM_{10} and O_3 varies according to the synoptic situation.

Does the meteorological origin of heat waves influence their impact on health? A 6-year morbidity and mortality study in Madrid (Spain)

Ruiz-Páez R[1], Díaz J*[2], López-Bueno JA[3], Navas MA[2], Mirón IJ[4], Martínez GS[5], Luna MY[6], Linares C[2].

(1) University Teaching Hospital Infanta Leonor. Madrid, Spain.

(2) Reference Unit on Climate Change, Health and Urban Environment. National Institute of Health Carlos III. Madrid, Spain.

(3) University Autonoma of Madrid. Madrid, Spain.

(4) Department of Health, Community Board of Castile La Mancha, Toledo, Spain.

(5) The UNEP DTU Partnership, Copenhagen, Denmark.

(6) State Meteorological Agency (AEMET), Madrid, Spain

Corresponding Author:

Dr. Julio Díaz Jiménez.

Carlos III Institute of Health. National Scholl of Public Health

Ava. Monforte de Lemos 5.

28029 Madrid.(Spain)

Email. J.diaz@isciii.es

Abstract.

US studies showed that synoptic-scale meteorological conditions characterizing a heat wave influenced its impact on mortality. Thus, those data were included in the corresponding prevention plans. In Spain, two synoptic-scale conditions influence heat wave formation. The first involves advection of warm and dry air masses carrying dust of Saharan origin (North African Dust (NAF) =1). The second entails anticyclonic stagnation with high insolation and stability (NAF) =0).

Our aim is to determine whether the impact of heat waves on health outcomes in Madrid (Spain) during 2013-2018 varied by synoptic-scale condition. Outcome data consist of daily mortality and daily hospital emergency admissions (morbidity) for natural, circulatory, and respiratory causes. Predictors include daily maximum and minimum temperatures and daily mean concentrations of NO_2, PM_{10}, $PM_{2.5}$, NO_2, and O_3. Analyses adjust for insolation, relative humidity, and wind speed.

Generalized linear models were performed with Poisson link between the variables controlling for trend, seasonality, and auto-regression in the series. Relative Risks (RR) and Attributable Risks (AR) were determined. The RRs for mortality attributable to high temperatures were similar regardless of NAF status. For hospital admissions, however, the RRs for hot days with NAF=0 are higher than for days with NAF=1. We also found that atmospheric pollutants worsen morbidity and mortality, especially PM_{10} concentrations when NAF=1 and O_3 concentrations when NAF=0.

The effect of heat waves on morbidity and mortality depends on the synoptic situation. The impact is greater under anticyclonic stagnation conditions than under Saharan dust advection. Further, the health impact of pollutants such as PM_{10} and O_3 varies according to the synoptic situation. Based on these findings, we strongly recommend prevention plans to include data on the meteorological situation originating the heat wave, on a synoptic-scale, as well as comprehensive preventive measures against the compounding effect of high temperatures and pollution.

1. Introduction

According to the latest Intergovernmental Panel on Climate Change (IPCC) report on the impacts, adaptations and vulnerabilities stemmed from climate change (IPCC 2022), heat waves will, undoubtedly, increase in frequency and intensity. Thus, save for a progressive adaptation to higher temperatures, their health impact will only worsen (Díaz et al., 2019).

In many countries, the heat-related impact on health has decreased significantly in recent decades (Schifano et al., 2012; Chung et al., 2017; Díaz et al., 2018a, Sheridan & Dixon, 2017). The reasons are multifactorial including geographic variability (high temperatures have lower health impact the warmer the location, most likely due to a "greater awareness"), air conditioning use, better health services, and improvements in insulation in housing and in infrastructures in general, among others (Martínez GS et al., 2019). However, beyond any doubt, a key factor in this observed decrease in impact is the establishment of prevention plans (WHO, 2018) in 66% of European countries.

Improvements made to these plans would undoubtedly benefit individuals´ health on particularly hot days. Some of these improvements are epidemiological in nature, i.e., they determine at which temperature prevention plans should be implemented based on epidemiological temperature-mortality studies, rather than relying solely on climatic indices (Andersen et al., 2021). Additional improvements are based on the different meteorological patterns on a synoptic scale that condition the atmosphere favoring the high temperatures characteristic of heat waves (Yoon et al., 2018; Sfîcă et al., 2017). Previous studies conclude that the severity of dangerous heat waves is directly related to the specific meteorological conditions originating them (Kalstein et al 2011; Hajat et al., 2010; Metzger et al., 2010). Clearly, this is in addition to the usual factors typifying a heat wave such as intensity and duration (Diaz et al., 2002).

Thus, data on synoptic meteorological conditions originating heat waves have been increasingly considered in research starting with Kalstein and Greene for Central and Eastern U.S. (Kalstein & Green, 1997) and later redefined by Sheridan and Kalstein for Canada and Western U.S. (Sheridan & Kalstein, 2004) as well as Bower and colleagues for Western Europe (Bower et al., 2007).

Synoptic-scale meteorological conditions present during heat waves have been analyzed for Spain (García et al., 2005) in general and for Madrid in particular (García et al., 2002). Most cases involve strong anticyclonic stagnation conditions produced by the Azores anticyclone in the absence of wind and with high insolation levels. This stagnation situation, which by itself can generate a heat wave, can be amplified by the advection of warm and dry air from North Africa and particulate matter from the Sahara. The result is a more intense and longer heat wave compared to those resulting solely from an anticyclonic blockade (García et al 2005).

The aim of this study is to analyze whether the impact of high temperatures on morbidity and mortality from all natural causes and from certain specific causes is modified by the synoptic-scale meteorological event generating those temperatures. Specifically, we differentiate between heat waves generated by an advection of dust from the Sahara and those created exclusively as the result of a situation of anticyclonic stagnation. In this study we analyze data for the province of Madrid (Spain) (2022 population: 6.7 million) with the idea of including all he 17 Spanish regions (total population: 47.5 million) in future analyses. Based on our results, we will study the inclusion of synoptic conditions in the Spanish Ministry of Health's high temperature prevention plans. Current plans are based solely on epidemiologically defined heat wave threshold temperatures (Ministry of Health 2022).

2. Materials and Methods.

2.1. Direct Variables

Independent variables include six years worth of meteorological and air pollution data recorded between January 1st, 2013 and December 31st, 2018. The meteorological data were collected in the meteorological observatory of reference located in the district of Retiro in the downtown area of the city of Madrid. It was specifically chosen because it provided the daily maximum temperature data used to determine the official threshold temperature defining a heat wave for the Community of Madrid according to the Spanish Ministry of Health (Ministerio de Sanidad, 2022). The meteorological data examined were: Daily maximum and minimum temperatures (Tmax and Tmin, respectively), average values in Celsius (˚C); daily average wind speed (km/h); daily insolation or sunlight hours (hours) and daily average relative humidity (%). These data came from the State Meteorological Agency (AEMET for its Spanish acronym).

Pollution data correspond to the average daily concentrations of the pollutants PM_{10}, $PM_{2.5}$, NO_2, and O_3 (all in $\mu g/m^3$). These represent the averages of the mean concentration values from every meteorological station located in the Community of Madrid. These data were provided by the Ministry for Ecological Transition and Demographic Challenge (MITERD for its Spanish acronym).

Based on data provided by the Spanish National Institute of Statistics (INE for its Spanish acronym) we examined six outcome variables: daily mortality (3 causes) and morbidity (3 causes). The mortality variable consisted on the average daily mortality reported in municipalities with populations over 10,000 inhabitants in the Community of Madrid between 2013 and 2018. We included mortality for all natural causes (ICD-10: A00-R99), circulatory causes (ICD-10: I00-I99), and respiratory causes (ICD-10: J00-J99). As a measure of heat wave-related morbidity, we used daily emergency hospital admissions based on the INE´s annual Hospital Morbidity Survey data. Specifically, we analyzed daily-unscheduled emergency hospital admissions during the study period for the same causes and ICD-10 codes as mentioned above.

2.2. Derived Variables.

We recoded the variables above to create additional variables reflecting different actual functional relationships among dependent and independent variables.

To account for the impact of high temperatures on morbidity and mortality, we adopted the definition of a "heat wave" used by the Spanish Ministry of Health for the Community of Madrid, i.e., a daily T_{max} of 34 ºC. We justify the use of T_{max}, rather than T_{min}, based on the results reported by different studies indicating that it is the daily T_{max}, which actually better correlates with mortality during heat waves (Guo et al., 2017; Alberdi et al., 1999; Díaz et al., 2002).

Thus, heat wave is defined by the variable T_{heat} as shown below (Díaz et al., 2015):

$T_{heat} = 0$ if $T_{max} < 34^{\circ}C$

$T_{heat} = T_{max} - 34$ if $T_{max} \geq 34^{\circ}C$

However, from the health point of view, just one day with a T_{max} exceeding 34°C, already a heat wave makes. The concept of heat wave refers to one or more consecutive hot days, with the number of such days termed the heat wave´s duration (Díaz et al., 2002). The higher the T_{heat} values, the greater the intensity of the heat wave.

For the pollutants analyzed, we assume a linear relationship with morbidity and mortality with no threshold for PM_{10}, $PM_{2.5}$ (Ortiz et al., 2017), and NO_2 (Linares et al., 2018). In the case of ozone (O_3), we assume a quadratic relationship with daily morbidity and mortality. Previous studies in Spain show that the threshold value for a negative health impact for daily average ozone concentrations for the Community of Madrid is set at 60 $\mu g/m^3$ (Díaz et al., 2018b). Thus, we created a new variable, O_{3a}, defined as follows:

$O_{3a} = 0$ if $O_3 < 60\ \mu g/m^3$

$O_{3a} = O_3 - 60$ if $O_3 \geq 60\ \mu g/m^3$

However, the effect of the independent variables on daily mortality and morbidity levels may come about on the same day or with a time lag. For heat, lags of up to 5 days have been included (Díaz et al; 2002). For PM_{10}, $PM_{2.5}$, and NO_2 concentrations we included up to a 5-day lag (Ortiz et al., 2016, Linares et al., 2018), and for ozone concentrations up to a 9-day lag (Díaz et al., 2018b) were included. For the rest of the meteorological variables, and since no previous studies have included them simultaneously, we considered time lags of up to 14 days.

As mentioned earlier in the introduction, the meteorological patterns on a synoptic-scale associated to heat waves in the Community of Madrid are connected to the position of the Azores anticyclone, by itself capable of producing heat waves. These are often intensified by the intrusion of very warm North Africa winds carrying suspended dust from the Sahara (García et al., 2005; García et al., 2002). Therefore, from a meteorological point of view and for the purpose of this paper, we classify heat waves into two categories:

1. A heat wave is classified as North African Dust (NAF)=1 when advection of Saharan dust is detected.
2. A heat wave is classified as NAF=0 when caused by an anticyclonic stagnation triggered by the Azores anticyclone, and characterized by strong insolation but hardly any wind.

During the study period, days are classified as NAF=1 when, according to information provided by MITERD by region (MITECO, 2019), Saharan dust advections are detected in the Central region of Spain. All other days during a heat wave will be classified as non-dust advection, i.e., NAF=0.

2.3. Other control variables.

In addition to the independent variables described above with their corresponding time lags, other variables influencing trend and seasonality of the series are also taken into account. For this purpose, a variable n1 is included. This variable equals 1 on the first day of the series, 2 on the second, and so on. The annual, semiannual, quarterly, and bimonthly seasonalities are controlled by including sine and cosine functions with the periods mentioned. Likewise, the days of the week, Monday through Sunday, and bank holidays within the study period will be considered. Finally, the autoregressive nature of the series will be controlled with the inclusion of an autoregressive component of order 1.

2.4. Modeling process and calculation of deaths and hospital admissions attributable to heat waves.

For each of the six dependent variables and for the two possible heat wave situations (NAF=1 vs. NAF=0), generalized linear models (GLM) with Poisson link were performed. In these models, all the independent and control variables, as well as the transformed variables, with their corresponding lags, were introduced. We used a stepwise process to eliminate variables failing to reach statistical significance. Thus, the final model includes only those variables that were statistically ssignificant at $p<0.05$.

From the estimate (β) of each significant variable and its corresponding confidence interval, the corresponding Relative Risk (RR) was calculated as RR = e^{β}. These RRs were calculated for increments of T_{heat} of 1°C and increments of 10 µg/m^3 for the pollutants.

Based on the RR values, we calculated the corresponding Attributable Risks (AR) following the Coste & Spira equation: AR = (RR-1) *100/RR (Coste & Spira 1991). Based on the AR values, and following the methodology outlined by Carmona and colleagues (Carmona et al., 2016), the number of attributable deaths and hospital admissions were calculated for each variable that was significant in the modeling process.

Data management and analyses were performed using the R software version 4.0.2 and STATA BE-Basic Edition version 17, IBM SPSS Statistics version 27, and Excel (with the Power Query editor) from the Microsoft Office Professional Plus 2019 package.

Results.

Table 1 shows the distribution of the independent variables during heat wave days with NAF values of 1 or 0 for the period of interest. Values for the primary pollutants (PM_{10} and NO_2) and for T_{max} and T_{min} are statistically significantly higher on days with NAF=1 compared to days with no Saharan dust advection (NAF=0).

There were 39 heat waves shaped by NAF=1 meteorological conditions versus 33 generated by an anticyclonic stagnation pattern (NAF=0). Heat waves based on NAF=1 conditions were longer and more intense than heat waves due to NAF=0 conditions. Differences were statistically significant.

Table 2 shows the distribution of daily mortality and daily emergency hospital admissions for natural, circulatory, and respiratory causes across heat wave days with NAF=1 and NAF=0 conditions. Both daily mortality and admissions are higher on days with heat wave and advection (NAF=1) than on days with heat wave but no Saharan dust advection. All differences detected are statistically significant except for daily morbidity and mortality due to circulatory causes.

Table 3 and 4 show the statistically significant results of the Poisson regression models for the mortality and hospital admissions outcomes, respectively, according to NAF conditions, with their corresponding ARs for each day of the heat waves. Figure 1 shows the RRs for the statistical significant variables associated with those same outcomes. Heat wave days with no Saharan dust advection (NAF=0) have a greater adverse impact on mortality due to natural causes than days with advection (NAF=1), though the difference fails to reach statistical significance. The same is true for mortality due to circulatory causes. In this case, however, there are two other results worth mentioning. First, the impact of PM_{10} concentrations on mortality due to circulatory causes though only in the presence of dust advection (NAF=1); and, second, the impact of O_{3a} concentrations on that same outcome, though only on days with no dust advection (NAF=0). Regarding mortality due to respiratory causes, T_{heat} is only a prognostic factor on days with advection of Saharan dust (NAF=1). Finally, regardless of dust advection conditions, tropospheric ozone has an impact on death due to respiratory causes.

Despite these observed differences, if we add the daily mortality caused by heat and pollutants, the values are similar on days with or without dust advection. In fact, no differences reach statistical significance.

Regarding results from the Poisson models for daily hospital admissions (Table 4 and Fig.1), we find the absence of impact of T_{heat} on morbidity on heat wave days with NAF=1 conditions, remarkable. Especially since heat wave days with NAF=0 conditions do impact hospital admissions. The increase of hospital admissions on heat wave days with advection (NAF=1) would be related to PM_{10} concentrations in all-cause admissions, and to levels of the pollutant ozone in the case of respiratory-cause admissions. Whereas increases on hospital admissions on heat wave days due to an anticyclonic stagnation pattern (NAF=0) would be associated to rises in ozone concentrations. Finally, for both mortality and morbidity, the impact of air pollution on circulatory-related causes transpires quicker, 0 to 3-day lags, than on respiratory-related causes, which register 6 to 8-day lags.

3. Discussion.

During the six-year period of interest (2013-201), Spain registered 232 heat wave days. Saharan dust advections took place in 144 (62.1%) of those days, which were distributed across 39 heat waves. The other 88 days (37.9%) were distributed across 33 heat waves with anticyclonic stagnation conditions.

Consistent with their meteorological origin, heat waves associated to dust advections reach higher extreme temperatures (T_{heat} values) and longer durations than those related to anticyclonic conditions only. Although in Madrid heat waves usually stem from an anticyclonic stagnation pattern, the advection of dust carried by Saharan air flow intensifies the heat waves effects (García et al., 2002).

We also observed that for all pollutants, except ozone, their concentrations during heat waves are statistically significantly higher in dust advection conditions than in anticyclonic stagnations patterns. This increase is especially striking for PM_{10}. These results support previous work carried out in Spain (Moreira et al., 2020), Barcelona (Spain) (Pandolfi et al 2014) and Madrid (Spain) (Salvador et al., 2019). The increase in concentration of all pollutants, especially PM_{10}, observed in heat waves with advection of particulate matter, may be related to a decrease in incident solar radiation caused by the blocking effect of the suspended particles themselves. Lower radiation, in turn, may cause convective currents to decrease, which would diminish the thickness of the mixing layer and result in higher pollutant concentrations (Li et al., 2017). This decrease in solar radiation during dust advection days was also observed in our analyses (Table 1). It is also likely that higher solar radiation on non-dust advection days translates into the ozone levels not being as low as on dust-advection days, which would render the difference in ozone levels across the two types of heat wave days not statistically significant.

Given the greater intensity and duration of heat waves with dust advection, one may expect high temperatures to have a greater impact on mortality and morbidity in the presence of suspended dust particles than in their absence; however, our results suggest the opposite. The impact of both types of heat waves on mortality is very similar. However, their impact on hospital admissions varies. No impact was observed during dust-advection days but the impact during heat waves caused by anticyclonic stagnation conditions was quite significant. Therefore, from the public health perspective, we should avoid classifying all heat waves as having similar health impacts or risk levels. In fact, heat waves vary significantly in risk level and, furthermore, shorter and milder heat waves may turn out to be more fatal than longer, more intense ones. Our findings confirm reports from previous studies (Kalstein et al. 2011; Hajat et al., 2010; Metzger et al., 2010). The conclusions of this body of work call for the inclusion of the synoptic conditions causing each heat wave as part of the data informing health-related prevention plans for high temperatures (Kalstein &Greene, 1997; Sheridan & Kalstein 2004; Bower et al., 2007; Zhang et al., 2012).

The lack of association between the presence of extreme temperatures and morbidity in heat wave days with Saharan dust advection may seem to suggest that the strong impact on health related to these very high temperatures causes immediate death and, thus, the individual is not even admitted to the hospital (Linares & Díaz, 2008; Mastrangelo et al., 2006); thus, not impacting morbidity. However, our results do not support this hypothesis since the relative risks for mortality during heat wave days with dust advection are not higher than the relative risks during heat wave days with no dust advection.

One possible explanation for this fact could be that the first heat waves of each year normally were originated in situations of anticyclonic blocking. This is the situation analyzed in this study and these first heat waves have the greatest effect on mortality due to the greater number of people susceptible to heat (Díaz et al., 2002). Furthermore, as explained in the introduction, heat waves in Spain usually start with a situation that can be amplified by the advection of warm and dry air from North Africa and particulate matter from the Sahara (García et al. 2005). These linked events entail a greater effect on mortality of the heat waves at the beginning of each wave (Díaz et al., 2002) and, therefore, a greater impact due to situations of anticyclonic blocking.

Our analyses also show that, in addition to the health impact of intense heat, the impact of pollutants on both daily hospital admissions and mortality is not only notable but greater than the impact of very high temperatures. This impact also varies by type of heat wave. On heat wave days with dust advection the impact of PM_{10} on health outcomes is predominant, whereas in the absence of dust advection the only pollutant with a significant health impact is tropospheric ozone. These observations confirm findings from similar studies conducted in Spain and elsewhere in Europe regarding suspended Saharan dust and mortality (Diaz et al., 2017; Stafoggia et al., 2016) and morbidity (Reyes et al., 2014). Therefore, the health consequences of any heat wave are not only related to the number of days with temperatures above 34 ˚C, but also to pollutants acting synergistically. In sum, high temperatures and pollution may boost the impact of both PM_{10} (Parry et al., 2019) and ozone (Yang et al., 2022).

Conventionally, heat wave prevention plans focus exclusively on temperature-related effects. Our results strongly suggest that these plans must be more comprehensive (Linares et al., 2020), i.e., they should integrate all factors with potential health impacts that may be exacerbated by a heat wave. These include the aforementioned increase in air pollution, forest fires (Linares et al., 2018b), the increase in foodborne diseases (Duchenne-Moutien & Neetoo, 2021), and the exacerbation of droughts (Salvador et al., 2020).

3.1. Limitations of the study.

We followed the methodology commonly used in this type of studies (Samet et al., 2002). We have tried to minimize any potential methodological biases by including in our models all relevant control variables available in our data such as seasonality, trend, days of the week, vacation periods, and autoregressive nature of the series.

As an ecological study, there are additional limitations such as the difficulty of extrapolating our results, applicable to the general population, to the individual level. In addition, there are limitations inherent to the representativeness of the exposure of each individual to the environmental variables considered (Barceló et al., 2016). Although the network of weather stations collecting air pollution data is very extensive, working with average concentrations could introduce a bias in the results. Further, data for all meteorological variables were collected in a single observatory, which may also bias our results, despite this being the observatory of reference of the Madrid region (Díaz et al., 2002). No specific validation was performed within the project to assess representativeness of spatial variability in air pollutants, thus, our study suffers from Berkson-type measurement error (Barceló et al., 2016). In addition, the inevitable misclassification of the causes of hospital admissions also introduces some errors.

Finally, it should be noted that the data for this study came from only one province in one of the 9 regions of interest. Whereas Spain is geographically and politically divided into 17 autonomous regions, for the study of Saharan dust advections, Spain is divided into 9 regions (MITECO, 2019), so it would be necessary to extend it to at least one province for each of these 9 regions.

4. Conclusions.

Our findings indicate that heat waves originating in anticyclonic stagnation patterns have a greater impact on morbidity (measured here as daily hospital admissions) than heat waves characterized by Saharan dust advections. This is so despite the fact that the latter tend to be more intense and last longer periods. Thus, prevention plans should take the synoptic-scale meteorological origin of the heat wave into account in order to be more effective. In addition, on heat wave days the concentration of the pollutants PM_{10} and ozone undergo important increases, which have an even greater impact on mortality and morbidity than the very high temperatures. Therefore, prevention plans should include both risk factors, type of heat wave and pollutant levels, in their estimates to improve their implementation and effectiveness.

Disclaimer

The researchers declare that they have no conflict of interest that would compromise the independence of this research work. The views expressed by the authors are not necessarily those of the institutions they are affiliated with.

Acknowledgements

The authors wish to thank the funding provided by the ENPY 304/20, and ENPY 436/21 projects of the National Health Institute Carlos III (ISCIII).

References:

Alberdi JC, Díaz J, Montero JC, Mirón IJ. *Daily mortality in Madrid Community (Spain) 1986-1991: Relationship with atmospheric variables.* European Journal of Epidemiology. 1998; 14:571-578. https://www.ncbi.nlm.nih.gov/pubmed/9794124

Andersen NB, Böckman M, Bowen K, Díaz J, Flouris A, Hajat S, Katsouyanni K, Kovats S, Linares C et al., *"Heat and health in the WHO European Region: Update evidence for effective prevention". WHO Regional Office for Europe*. Copenhagen. 2021. Licence: CC BY-NC-SA3.0 IGO.

Barceló, M.A., Varga, D., Tobias, A., Diaz, J., Linares, C., Saez, M., 2016 May. *Long term effects of traffic noise on mortality in the city of Barcelona, 2004–2007*. Environ. Res. 147, 193–206.

Bower D, McGregor GR, Hannah D, Sheridan SC. *Development of a spatial synoptic classification scheme for western Europe*. Int J Climatol 2007;27:2017–40.

Carmona R, Díaz J, Ortiz C, Luna MY, Mirón IJ, Linares C. *Mortality attributable to extreme temperatures in Spain: A comparative analysis by city.* Environment International 2016;91:22-28. https://doi: 10.1016/j.envint.2016.02.018.

Chung, Y., Noh, H., Honda, Y., Hashizume, M., Bell, M.L., Guo, Y.L., Kim, H.. *Temporal changes in mortality related to extreme temperatures for 15 cities in Northeast Asia: adaptation to heat and mal adaptation to cold.* Am. J. Epidemiol. 2017, 185 (10), 907–913 May 15.

Coste, J., Spira, A., 1991. *Le proportion de cas attributable en Santé Publique: definition(s), estimation(s) et interpretation*. Rev. Epidemiol. Sante Publique 51, 399–411.

Díaz J, López C, Jordán A, Alberdi JC, García R, Hernández E, Otero A. *Heat waves in Madrid, 1986-1997: effects on the health of the elderly.* International Archives Occupational and Environmental Health. 2002;75:163-170. https://www.ncbi.nlm.nih.gov/pubmed/11954983.

Díaz J, Carmona R, Mirón IJ, Ortiz C, León I, Linares C. *Geographical variation in relative risks associated with heat: update of Spain's Heat Wave Prevention Plan.* Environment International. 2015; 85:273-283. https://doi: 10.1016/j.envint.2015.09.022

Díaz, J., Linares, C., Carmona, R., Russo, A., Ortiz, C., Salvador, P., Trigo, R.M., 2017. Saharan dust intrusions in Spain: health impacts and associated synoptic conditions. Environ. Res. 156, 455–467.

Díaz J, Carmona R, Mirón IJ, Luna MY, Linares C. *Time trend in the impact of heat waves on daily mortality in Spain for a period of over thirty years (1983-2013).* Environment International 2018a; 116:10-17. https://doi: 10.1016/j.envint.2018.04.001.

Díaz J, Ortiz C, Falcón I, Linares C. *Short-term effect of tropospheric ozone on daily mortality in Spain.* Atmospheric Environment.2018b; 187:107-116. https://doi.org/10.1016/j.atmosenv.2018.05.059

Díaz J, Sáez M, Carmona R, Mirón IJ, Barceló MA, Luna MY, Linares C. *Mortality attributable to high temperatures over the 2021-2050 and 2051-2100 time horizons in Spain: adaptation and economic estimate*. Environmental Research. 2019; 172:475-485. https://doi.org/10.1016/j.envres.2019.02.041.

Duchenne-Moutien, R.A., Neetoo, H., 2021. *Climate Change and Emerging Food Safety Issues: A Review.* J. Food Prot. 84(11),1884-1897. https://doi.org/10.4315/JFP-21-141

García R, Prieto L, Díaz J, Hernández E, Del Teso MT. *Synoptic conditions leading to extremely high temperatures in Madrid (Spain).* Annales Geophysicae. 2002;20:237-245. https://core.ac.uk/download/pdf/25960694.pdf.

García-Herrera R, Díaz J, Trigo RM, Hernández E, Dessai S. *Extreme summer temperatures in Iberia: health impacts and associated synoptic conditions.* Annales Geophysicae. 2005;23:239-251.https://doi.org/10.5194/angeo-23-239-2005

Guo Y, Gasparrini A, Armstrong BG et al., *Heat Wave and Mortality: A Multicountry, Multicommunity Study*. Env Health Perspect 2017; 128, 8:

Hajat S, Sheridan SC, Allen MJ, Pascal M, Laaidi K, Yagouti A, et al. *Heat–health warning systems: a comparison of the predictive capacity of different approaches to identi-fying dangerously hot days.* Am J Public Health 2010;100(6):1137–44

IPCC 2022. *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press.

Kalkstein LS, Greene JS. *An evaluation of climate/mortality relationships in large U.S. cities and the possible impacts of a climate change.* Environ Health Perspect 1997;105:84–93

Kalkstein L, Greene S, David M, Samenow J. *An evaluation of the progress in reducing heat-related human mortality in major U.S. cities*. Nat Hazards 2011;56(1):113–29.

Li, Z., Guo, J., Ding, A., Liao, H., Liu, J., Sun, Y., Wang, T., Xue, H., Zhang, H., Zhu, B., 2017. *Aerosol and boundary-layer interactions and impact on air quality.* Nat. Sci. Rev. 4 (6), 810–833.

Linares, C., Díaz, J., 2008. *Impact of high temperatures on hospital admissions: comparative analysis with previous studies about mortality (Madrid*). Eur. J. Pub. Health 18, 318–322.

Linares C, Falcón I, Ortiz C, Díaz J. *An approach estimating the short-term effect of NO2 on daily mortality in Spanish cities*. Environment International, 2018a; 116:18-28. https://doi: 10.1016/j.envint.2018.04.002.

Linares, C., Carmona, R., Salvador, P., Díaz, J., 2018b. *Impact on mortality of biomass combustion from wildfires in Spain: a regional analysis.* Sci. Total Environ. 622– 623, 547–555.

Linares C, Sanchez-Martinez G, Kendrovski V, Diaz J. *A New Integrative Perspective on Early Warning Systems for Health in the Context of Climate Change.* Environmental Research 187 (2020) 109623. https://doi.org/10.1016/j.envres.2020.109623

Martinez GS, Linares C, Ayuso A, Kendrovski V, Boeckmann M, Díaz J. Heat–health action plans in Europe: challenges ahead and how to tackle them. Environ Res. 2019; 176:108548. doi:10.1016/j. envres.2019.108548.

Mastrangelo, G., Hajat, S., Fadda, E., et al., 2006. *Contrasting patterns of hospital admissions and mortality during heat waves: are deaths from circulatory disease a real excess or an artifact?* Med. Hypotheses 66, 1025–1028

Metzger KB, Ito K, Matte TD. *Summer heat and mortality in New York city, how hot is too hot?* Environ Health Perspect 2010;118(1):80–6.

Ministerio de Sanidad. *Plan Nacional de Actuaciones Preventivas por Altas Temperaturas*. 2002. https://www.sanidad.gob.es/ciudadanos/saludAmbLaboral/planAltasTemp/2021/Plan_nacional_actuaciones_preventivas.htm.

MITECO, 2019. https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/atmosfera-y-calidad-del-aire/calidad-del-aire/evaluacion-datos/fuentes-naturales/anuales.aspx

Moreira I, Linares C, Follos F, Sácnhez-Martínez G, Vellón JM, Díaz J. *Short-Term Effects of Saharan Dust Intrusions and Biomass combustion on Birth Outcomes in Spain*. Science of the Total Environment. 20 January 2020, 134755. https://doi.org/10.1016/j.scitotenv.2019.134755

Ortiz C, Linares C, Carmona R, Díaz J. *Evaluation of short-term mortality attributable to particulate matter pollution in Spain.* Environmental Pollution.2017;224:541-551. https://doi: 10.1016/j.envpol.2017.02.037.

Pandolfi, M., Tobias, A., Alastuey, A., Sunyer, J., Schwartz, J., Lorente, J., Pey, J., Querol, X., 2014. *Effect of atmospheric mixing layer depth variations on urban air quality and daily mortality during Saharan dust outbreaks*. Sci. Total Environ. 1 (494–495), 283–289.

Parry M, Green D, Zhang Y, Hayen A. *Does Particulate Matter Modify the Short-Term Association between Heat Waves and Hospital Admissions for Cardiovascular Diseases in Greater Sydney, Australia*? Int J Environ Res Public Health. 2019 Sep 5;16(18):3270.

Reyes M, Díaz J, Tobías A, Montero JC, Linares C. *Impact of Saharan dust particles on hospital admissions in Madrid*. International Journal Environmental Health Research.2014; 24:63-72. https://doi: 10.1080/09603123.2013.782604

Salvador, P., Artíñano, B., Molero, F., Viana, M., Pey, J., Alastuey, A., Querol, X., 2013. *African dust contribution to ambient aerosol levels across central Spain: characterization of long-range transport episodes of desert dust.* Atmos. Res. 127, 117–129.

Salvador C, Nieto R, Linares C, Díaz J, Gimeno L. *Effects of Droughts on Health: Diagnosis, Repercussion and Adaptation in Vulnerable regions under Climate Change. Challenges for Future research..* Science of the Total Environment. 703 (2020) 134912. https://doi.org/10.1016/j.scitotenv.2019.134912.

Samet, J., Dominici, F., Zeger, S., Schwartz, J., Dockery D., 2000. *The National Morbidity, Mortality and Air Pollution study, Part I: Methods and Methodologic Issues*, Report No.94, Part I. Boston: Health Effects Institute

Sfîcă L, Adina-Eliza C,Iordache J, Ciupertea AF. *Synoptic Conditions Generating Heat Waves and Warm Spells in Romania*. Atmosphere 2017; 8: 50. https://doi.org/10.3390/atmos8030050

Sheridan, S.C., Dixon, P.G. *Spatiotemporal trends in human vulnerability and adaptation to heat across the United States.* Anthropocene. 2017, 20, 61–73.

Sheridan SC, Kalkstein LS. *Progress in heat watch/warning system technology.* B Am Meteorol Soc 2004;85(12):1931–41

Schifano, P., Leone, M., De Sario, M., De Donato, F., Bargagli, Am, Díppoliti, D., et al. Changes in the effects of heat on mortality among the elderly from 1998–2010: results from a multicenter time series study in Italy. Environ. Health 2012, 1, 58.

Stafoggia M, Zauli-Sajani S, Pey J, Samoli E, Alessandrini E, et al. *Desert Dust Outbreaks in Southern Europe: Contribution to Daily PM10 Concentrations and Short-term Associations with Mortality and Hospital Admissions.* Environmental Health Perspectives 2016, 124:413-419. https://doi: 10.1289/ehp.1409164.

Yang X, Zeng G, Iyakaremye V, Zhu B. *Effects of different types of heat wave days on ozone pollution over Beijing-Tianjin-Hebei and its future projection*. Sci Total Environ 2022 May 6;837:155762

Yoon D, Cha DY, Lee G, Park C , Lee MY, Min KY. *Impacts of Synoptic and Local Factors on Heat Wave Events Over Southeastern Region of Korea in 2015*. JGR Atmospheres 2018; 123:12081-96

WHO Regional Office for Europe. *Public health and climate change adaptation policies in the European Union. Copenhagen: WHO Regional Office for Europe.* 2018 (https://www.euro.who.int/en/healthtopics/environment-and-health/Climate-change/ publications/2018/public-health-and-climate-changeadaptation-policies-in-the-european-union-2018).

Zhang K, Rood RB, Michailidis G, Oswald EM, Schwartz JD, Zanobetti A, Ebi KL, O'Neill MS. *Comparing exposure metrics for classifying 'dangerous heat' in heat wave and health warning systems*. Environ Int 2012 Oct 1;46:23-9

Table 1. Descriptive statistics of the independent variables on heat wave days with and without Saharan dust advection.

	Dust advection (NAF[a]=1) N=144				No dust advection (NAF=0) N=88			
	Mean	**Max**	**Min**	**SD[b]**	**Mean**	**Max**	**Min**	**SD**
PM_{10} (µg/m³)*	33.6	85.7	16.5	10.6	22.2	32.2	12.3	4.4
$PM_{2.5}$ (µg/m³)*	14.9	33.1	6.7	3.9	11.0	17.9	6.1	2.5
NO_2(µg/m³)*	28.2	51.8	12.8	8.4	24.5	47.8	11.1	6.2
O_3 (µg/m³)	83.4	112.1	47.4	13.2	80.5	113.7	47.5	12.6
T_{max}[c](˚C)*	36.2	40.0	34.1	1.6	35.6	39.2	34.1	1.2
T_{min}[d] (˚C)*	22.2	25.9	17.0	1.7	21.4	25.1	17.9	1.3
Wind speed (km/h)	6.4	10.5	2.8	1.5	6.6	10.7	3.2	1.4
Insolation (hours)	12.1	14.4	2.1	1.9	12.9	14.4	7.9	1.4
Relative humidity (%)	39.5	61.9	28.9	5.6	40.4	53.8	30.6	4.5
T_{heat}[e] (˚C)*	2.2	6.0	0.1	1.6	1.6	5.2	0.1	1.3
Heat wave duration (days)*	3.7	15	1	3.0	2.7	7	1	1.6

* Statistically significant differences at p<0.05.

[a] North African Dust; [b] Standard Deviation; [c] Daily maximum temperature; [d] Daily minimum temperature; [e] Degrees of daily temperature in excess of 34˚C.

Table 2. Descriptive statistics of cause-specific daily mortality and daily hospital admissions according to the presence of Saharan dust advection on heat wave days.

	Dust advection (NAF[a]=1) N=144				**No dust advection (NAF=0) N=88**			
	Mean	**Max**	**Min**	**SD[b]**	**Mean**	**Max**	**Min**	**SD**
Natural causes mortality*	113.7	168	78	18.3	105.8	135	72	13.7
Circulatory causes mortality	27.7	45	12	6.5	26.0	42	13	6.4
Respiratory causes mortality*	16.1	34	6	5.2	14.4	23	5	3.7
Natural causes admissions*	864.4	1131	537	136.6	824.3	1034	545	123.4
Circulatory causes Admissions	124.8	194	64	26.3	119.9	171	54	26.7
Respiratory causes Admissions *	112.1	197	52	28.3	100.8	161	50	22.7

*Statistically significant differences at p<0.05.

[a] North African Dust; [b] Standard Deviation.

Table 3. Statistically significant variables derived from Poisson models for cause-specific daily mortality. Attributable Risks (AR) in % corresponding to 10 g/m^3 increase in pollutants and 1˚C increase in T_{heat}. Deaths attributable to each variable for each day of heat wave.

	Natural-cause mortality	**Circulatory-cause mortality**	**Respiratory-cause mortality**
NAF[c]=1 (N=144) Saharan Dust advection	**T_{heat}[a] (0)[b]** AR: 1.47 (0.42 2.50) [d] Deaths/heat wave day: 3.9 (1.1 6.6)[e]	**T_{heat} (3)** AR: 2.25 (0.32 4.15) Deaths/heat wave day: 1.5 (0.2 2.7) **PM_{10} (lag 1)** AR: 3.18 (0.18 6.10) Deaths/heat wave day: 3.0 (0.2 5.7)	**T_{heat} (2)** AR: 2.52 (0.00 5.08) Deaths/heat wave day: 1.0 (0.0 1.9) **O_{3a} (lag 6)** AR: 5.23 (1.38 8.92) Deaths/heat wave day: 2.1 (0.5 3.6)
NAF=0 (N=88) No Saharan Dust advection	**T_{heat} (0)** AR: 2.86 (1.10 4.59) Deaths/heat wave day: 4.9 (1.9 7.9)	**T_{heat} (0)** AR: 5.83 (2.48 9.07) Deaths/heat wave day: 2.5 (1.1 3.9) **O_{3a} (lag 2)** AR: 4.21 (0.25 8.02) Deaths/heat wave day: 2.3 (0.1 4.4)	**O_{3a} (lag 8)** AR: 6.36 (1.80 10.71) Deaths/heat wave day: 1.9 (0.5 3.2)

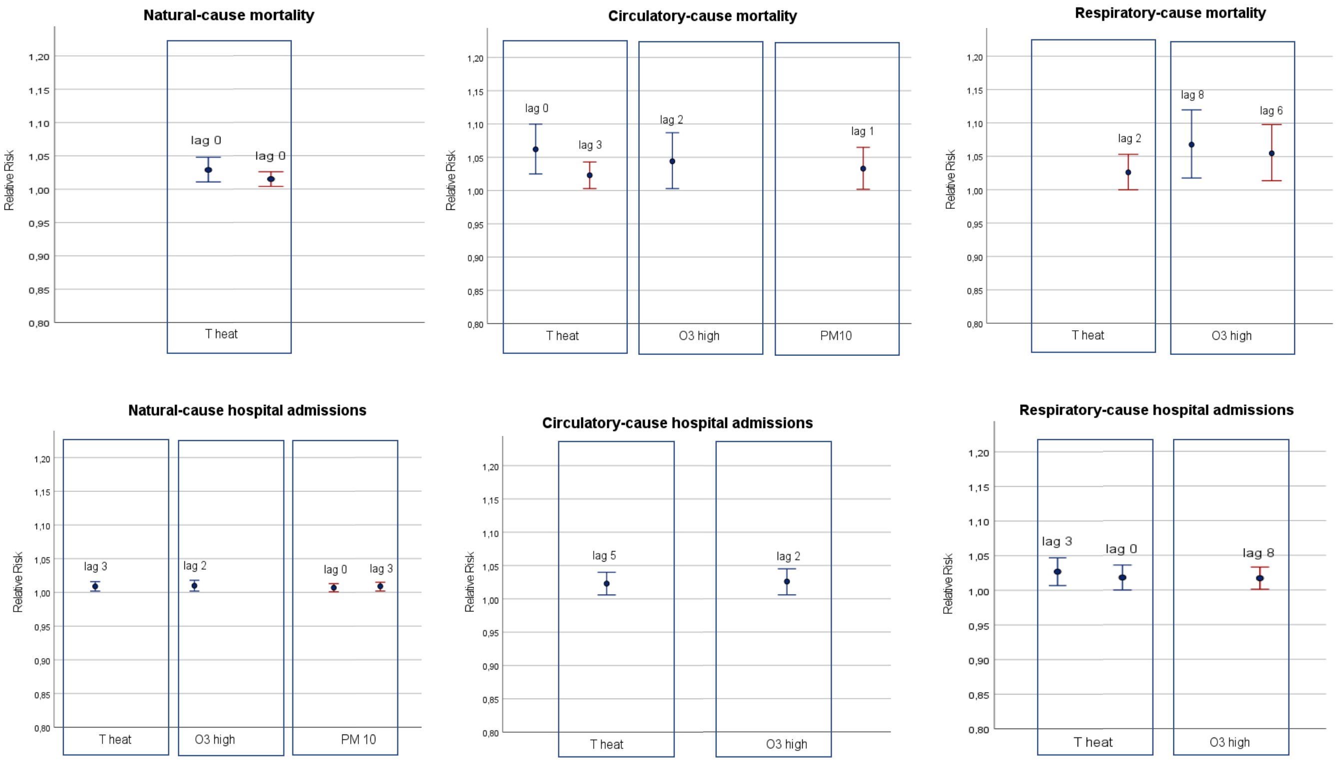
[a]Degrees of daily temperature in excess of 34˚C; [b]Time lag, in days, in which the association occurs; [c]North African Dust;; [d] Attributable Risk (95% Confidence Interval); [e]Number of deaths (95% Confidence Interval)

Table 4. Statistically significant variables derived from Poisson models for cause-specific daily hospital admissions. Attributable Risks (AR) in % corresponding to 10 g/m^3 increase in pollutants and 1˚C increase in T_{heat}. Admissions attributable to each variable for each day of heat wave.

	Natural-cause hospital admissions	Circulatory-cause hospital admissions	Respiratory-cause hospital admissions
NAF[b]=1 (N=144) Saharan Dust advection	**PM_{10} (lag 0)[a]** AR: 0.71 (0.14 1.28)[c] Admissions/heat wave day: 20.8 (4.2 37.4)[d] **PM_{10} (lag 3)** AR: 0.87 (0.22 1.51) Admissions/heat wave day: 25.3 (6.4 44.1)		**O_{3a} (lag 8)** AR: 1.69 (0.14 3.21) Admissions/heat wave day: 4.5 (0.4 8.6)
NAF=0 (N=88) No Saharan Dust advection	**T_{heat}[e] (lag 3)** AR: 0.85 (0.17 1.53) Admissions/heat wave day: 11.1 (2.2 19.9) **O_{3a} (lag 2)** AR: 1.00 (0.25 1.75) Admissions/heat wave day: 17.2 (4.3 30.1)	**T_{heat} (lag 5)** AR: 2.27 (0.63 3.88) Admissions/heat wave day: 4.2 (1.2 7.3) **O_{3a} (lag 2)** AR: 2.51 (0.63 4.35) Admissions/heat wave day: 6.2 (1.6 10.8)	**T_{heat} (lag 0)** AR: 1.77 (0.00 3.52) Admissions/heat wave day: 2.9 (0.0 5.7) **T_{heat} (lag 3)** AR: 2.62 (0.70 4.51) Admissions/heat wave day: 4.2 (1.1 7.3)

[a]Time lag, in days, in which the association occurs; [b]North African Dust; [c] Attributable Risk (95% Confidence Interval); [d]Number of hospital admissions (95% Confidence Interval); [e] [a]Degrees of daily temperature in excess of 34˚C.

Figure 1. Relative risks (RR) of the statistically significant independent variables by cause-specific mortality and hospital admissions. Values corresponding to days with no Saharan dust advection (NAF=0) appear in blue; values corresponding to days with Saharan dust advection (NAF=1) appear in red.



T_{heat}: Degrees of daily temperature in excess of 34˚C

Lag: Time lag, in days, in which the association occurs