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

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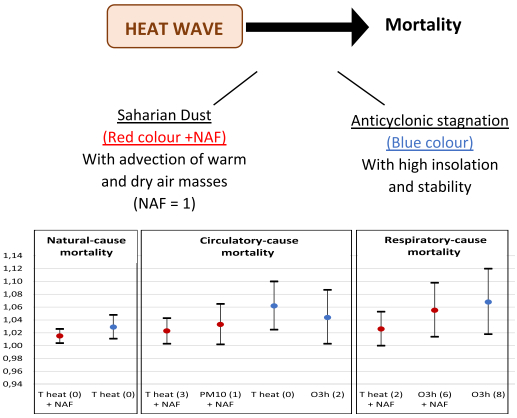
HIGHLIGHTS

- The effect of heat waves on morbid mortality depends on the synoptic situation.
- Temperature has a greater effect in heat waves due to stable atmospheric conditions.
- The health impact of PM_{10} and O_3 varies according to the synoptic situation.

GRAPHICAL ABSTRACT

Relative risks (RR) with their respective 95 % CIs of the significant independent variables for mortality due to the different causes. In brackets, the lag at which the statistical significant association occurs. Red colour when Saharan advection occurs, blue colour when there is an anticyclonic stagnation at the origin of the heat wave.



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ABSTRACT

Background: 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). Some studies show that the meteorological origin of these heat waves may affect their impact on morbidity and mortality.
Objective: To determine whether the impact of heat waves on health outcomes in Madrid (Spain) during 2013–2018 varied by synoptic-scale condition.
Methodology: 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,

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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.

Results: 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.

Conclusions: 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 and Dixon, 2017). The reasons are multifactorial, including geographical variability (high temperatures have less impact on health the warmer the location, probably due to higher heat habituation). This leads to greater use of air conditioning, better health services, and improvements in insulation in housing and in infrastructures in general, among others (Martinez 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 (Kalkstein 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 (Díaz et al., 2002).

Thus, data on synoptic meteorological conditions originating heat waves have been increasingly considered in research starting with Kalkstein and Greene for Central and Eastern U.S. (Kalkstein and Greene, 1997) and later redefined by Sheridan and Kalkstein for Canada and Western U.S. (Sheridan and Kalkstein, 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 (Serrano-Notivoli et al., 2022). 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 (Serrano-Notivoli et al., 2022).

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 the 17 Spanish regions (total population: 47.5 million) in future analyses. The current High Temperature Prevention Plan of the Spanish Ministry of Health (Ministerio de Sanidad, 2002) does not take into account the meteorological origin of heat waves to calculate the impact of temperatures on mortality. The results of this study aim to propose to the health authorities that subsequent updates of the Plan take into account the different origin of heat waves to calculate the impact of temperature and air pollution on daily mortality.

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, 2002). 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 (h) 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 °C. 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., 1998; Díaz et al., 2002).

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

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

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

From a health point of view, if in a single day Tmax surpass 34 °C, already has an impact on health; it will be considered as heat wave. 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; Montero et al., 2010; Kent et al., 2014; Guo et al., 2017; Kang et al., 2020). 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; Arroyo et al., 2019a; Reyes et al., 2014; Samoli et al., 2014; Sera et al., 2019), and NO_2 (Linares et al., 2018a, b; Meng et al., 2021; He et al., 2020; Arroyo et al., 2019b). In the case of ozone (O_3), we assume a quadratic relationship with daily morbidity and mortality (Zhang et al., 2021; Bell et al., 2006; Malley et al., 2017; Maté et al., 2010). 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 μg/m^3 (Díaz et al., 2018b). Thus, we created a new variable, O_{3h}, defined as follows:

$$O_{3\,h} = 0 \text{ if } \quad O_3 < 60\ \mu g/m^3$$

$$O_{3\,h} = O_3 - 60 \quad \text{if } O_3 \geq 60\ \mu g/m^3$$

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., 2017; Linares et al., 2018a, b), 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 (Serrano-Notivoli et al., 2022). 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

The dependent and independent variables may have the same seasonal components, the same trend or the same autoregressive character (history of the series at short term) which may mean that the significant associations between them are due to these similar components, it is necessary to include them in the models as control variables.

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

In the model described below, it can be seen how these variables form part of the models relating the dependent variables to the independent variables.

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.

This type of model has been used very frequently when relating morbidity and mortality to extreme temperatures in time series analysis (Díaz et al., 2015; Carmona et al., 2016a; López-Bueno et al., 2021; Culqui et al., 2022).

These models followed the general formula:

$$\begin{aligned} log(TM) = a + \beta 1\ lag(TM, 1)\ \mathrm{i} + \beta 2\ n1 + \beta 3j\ Seasij + \beta 4g\ lag(Theat, g) \\ + \beta 5\mathrm{h}\ lag(\mathrm{PM10, h}) + \beta 6\mathrm{l}\ lag(\mathrm{O3h, l}) + \beta \mathrm{km}\ lag(\mathrm{Other\ k, m}) \end{aligned}$$

where TM represents the mortality rate, a is the intercept, βk represents the coefficient of each of the k variables, lag(TM,1) is the autoregressive component of the first order of mortality in observation i; n1 is the value of the trend in observation i; Seas represents seasonality j observation i; (Theat, g) represents Theat lagged from 0 to 5; *lag*(PM10, h) represents PM10 lagged from 0 to 5; *lag*(O3h, l) represents O3h lagged from 0 to 8; *lag*(Other k, m) represents the meteorological and pollution variable k lagged from o to m.

We used a stepwise process to eliminate variables failing to reach statistical significance. Thus, the final model includes only those variables that were statistically significant 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 $RR = e^{\beta}$. 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 and Spira, 1991). Based on the AR values, and following the methodology outlined by Carmona and colleagues (Carmona et al., 2016b), 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.

3. 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 1
Descriptive statistics of the independent variables on heat wave days with and without Saharan dust advection.

	Dust advection (NAF[a] = 1)					No dust advection (NAF = 0)				
	N = 144					N = 88				
	Mean	Max	Min	SD[b]	CV[c]	Mean	Max	Min	SD[b]	CV[c]
PM_{10} (μg/m^3)*	33.6	85.7	16.5	10.6	32	22.2	32.2	12.3	4.4	20
$PM_{2.5}$ (μg/m^3)*	14.9	33.1	6.7	3.9	26	11	17.9	6.1	2.5	23
NO_2 (μg/m^3)*	28.2	51.8	12.8	8.4	30	24.5	47.8	11.1	6.2	25
O_3 (μg/m^3)	83.4	112.1	47.4	13.2	16	80.5	113.7	47.5	12.6	16
T_{max}[d] (°C)*	36.2	40	34.1	1.6	4	35.6	39.2	34.1	1.2	3
T_{min}[e] (°C)*	22.2	25.9	17	1.7	8	21.4	25.1	17.9	1.3	6
Wind speed (km/h)	6.4	10.5	2.8	1.5	23	6.6	10.7	3.2	1.4	21
Insolation (h)	12.1	14.4	2.1	1.9	16	12.9	14.4	7.9	1.4	11
Relative humidity (%)	39.5	61.9	28.9	5.6	14	40.4	53.8	30.6	4.5	11
T_{heat}[f] (°C)*	2.2	6	0.1	1.6	73	1.6	5.2	0.1	1.3	81
Heat wave duration (days)*	3.7	15	1	3	81	2.7	7	1	1.6	59

* Statistically significant differences at $p < 0.05$.
[a] North African Dust.
[b] Standard deviation.
[c] Coefficient of variation %.
[d] Daily maximum temperature.
[e] Daily minimum temperature.
[f] Degrees of daily temperature in excess above 34 °C.

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.

Figs. 1 and 2 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.

As an example, the final model for circulatory mortality on days with NAF = 0 is shown:

$$\log(\text{circ}) = 3.60 - 0.0037 \ \log(\text{circ},1) - 0.1753 \ \sin180 + 0.0601 \ \log(\text{Theat},0) + 0.0043 \ \log(\text{O3h},2) - 0.00467 \ \log(\text{wind},4).$$

Figs. 3 and 4 show the RRs for the statistically 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 (Figs. 2 and 3), we find the absence of impact of Theat 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.

4. Discussion

During the six-year period of interest (2013–2018), 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 (Serrano-Notivoli et al., 2022).

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., 2013). 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

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)					No dust advection (NAF[a] = 0)				
	N = 144					N = 88				
	Mean	Max	Min	SD[b]	CV[c]	Mean	Max	Min	SD[b]	CV[c]
Natural causes mortality*	113.7	168	78	18.3	16	105.8	135	72	13.7	13
Circulatory causes mortality	27.7	45	12	6.5	23	26	42	13	6.4	25
Respiratory causes mortality*	16.1	34	6	5.2	32	14.4	23	5	3.7	27
Natural causes admissions*	864.4	1131	537	136.6	16	824.3	1034	545	123.4	15
Circulatory causes admissions	124.8	194	64	26.3	21	119.9	171	54	26.7	22
Respiratory causes admissions*	112.1	197	52	28.3	25	100.8	161	50	22.7	23

* Statistically significant differences at $p < 0.05$.
[a] North African Dust.
[b] Standard deviation.
[c] Coefficient of variation %.

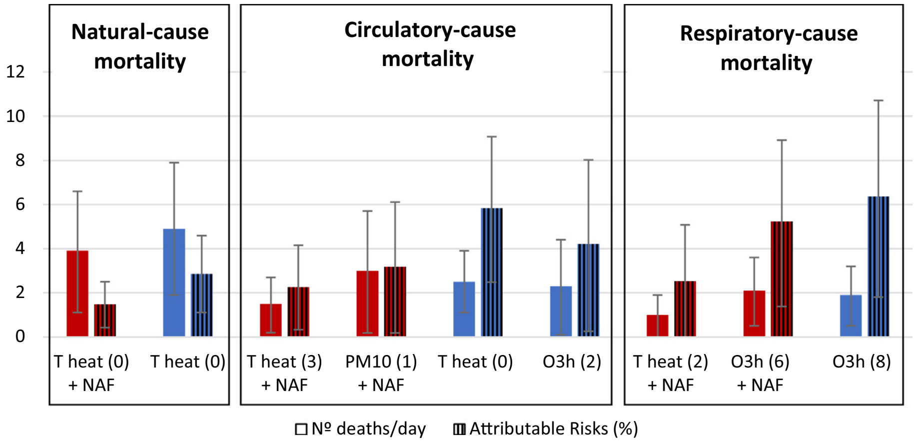

Fig. 1. Statistically significant variables derived from Poisson models for cause-specific daily mortality. In red: values corresponding to days with Saharan dust advection (NAF: North African Dust). In blue: values corresponding to days with no Saharan dust advection (NAF = 0). Without stripes: numbers of deaths attributable to each variable for each day of heat wave. With stripes: Attributable Risks (AR) in % corresponding to 10 g/m^3 increase in pollutants and 1 °C increase in T_{heat}. AR and numbers of deaths attributable to each variable for each day of heat wave with 95 % Confidence Interval. T heat: degrees of daily temperature in excess of 34 °C. O3h: ozone high. In parentheses: time lag, in days, in which the association occurs.

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 associated 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 (Kalkstein 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 (Kalkstein and Greene, 1997; Sheridan and Kalkstein, 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 and 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

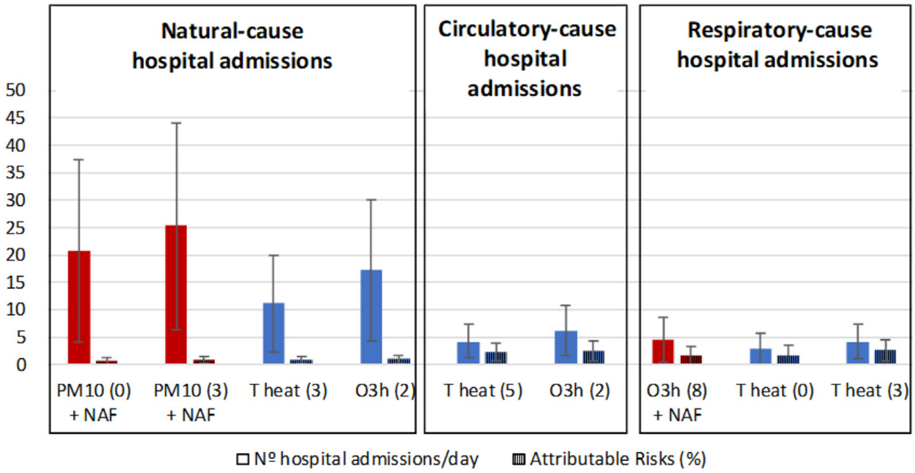

Fig. 2. Statistically significant variables derived from Poisson models for cause-specific daily hospital admissions. In red: values corresponding to days with Saharan dust advection (NAF: North African Dust). In blue: values corresponding to days with no Saharan dust advection (NAF = 0). Without stripes: numbers of hospital admissions attributable to each variable for each day of heat wave. With stripes: Attributable Risks (AR) in % corresponding to 10 g/m^3 increase in pollutants and 1 °C increase in T_{heat}. AR and numbers of hospital admissions to each variable for each day of heat wave with 95 % Confidence Interval. T heat: degrees of daily temperature in excess of 34 °C. O3h: ozone high. In parentheses: time lag, in days, in which the association occurs.

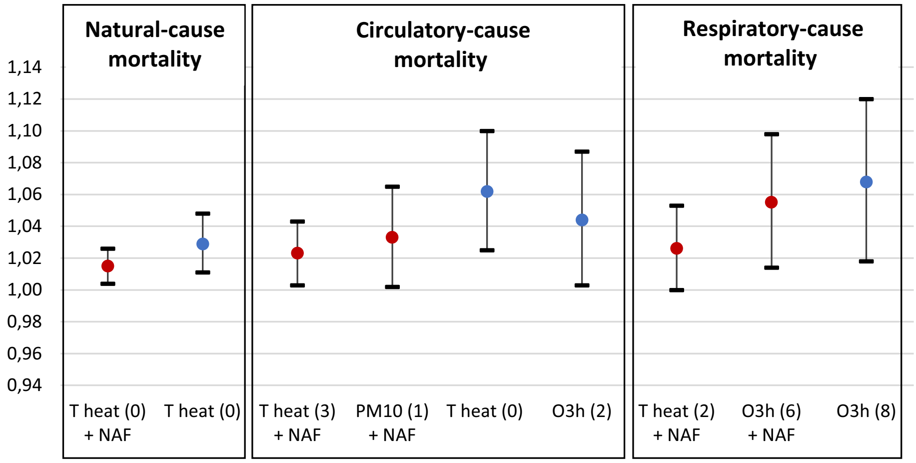

Fig. 3. The Y-axis represents the values of the RRs. The X-axis represents the variables where the statistically significant association is established with the lag in parentheses. Relative risks (RR) with 95 % Confidence Interval, corresponding to 10 g/m^3 increase in pollutants and 1 °C increase in T_{heat}, of the statistically significant independent variables by cause-specific mortality. In red: values corresponding to days with Saharan dust advection (NAF: North African Dust). In blue: values corresponding to days with no Saharan dust advection (NAF = 0). T heat: degrees of daily temperature in excess of 34 °C. O3h: ozone high.

can be amplified by the advection of warm and dry air from North Africa and particulate matter from the Sahara (Serrano-Notivoli et al., 2022). 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 (Díaz 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 and Neetoo, 2021), and the exacerbation of droughts (Salvador et al., 2020).

4.1. Limitations of the study

We followed the methodology commonly used in this type of studies (Samet et al., 2000; Díaz et al., 2015; Linares et al., 2018a, 2018b; López-Bueno et al., 2021). 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, applicability 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

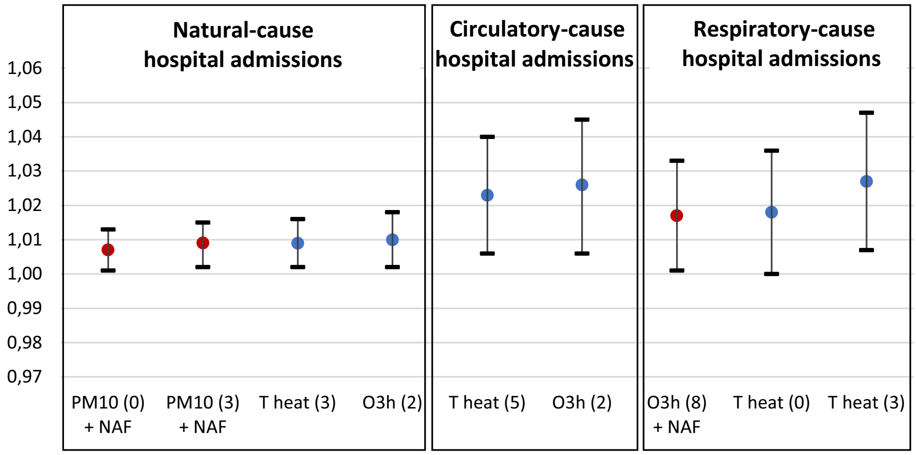

Fig. 4. The Y-axis represents the values of the RRs. The X-axis represents the variables where the statistically significant association is established with the lag in parentheses. Relative risks (RR) with 95 % Confidence Interval, corresponding to 10 g/m^3 increase in pollutants and 1 °C increase in $T_{heat,}$ of the statistically significant independent variables by cause-specific hospital admissions. In red: values corresponding to days with Saharan dust advection (NAF: North African Dust). In blue: values corresponding to days with no Saharan dust advection (NAF = 0). T_{heat}: degrees of daily temperature in excess of 34 °C. O_{3h}: ozone high.

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.

5. 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.

CRediT authorship contribution statement

Raquel Ruiz-Páez. Providing and Analysis of data; Elaboration and revision of the manuscript.

Julio Díaz. Original idea of the study. Study design; Elaboration and revision of the manuscript.

José A López-Bueno. Providing and Analysis of data; Elaboration and revision of the manuscript.

Miguel Ángel Navas. Providing and Analysis of data; Elaboration and revision of the manuscript.

Isidro J Mirón. Providing and Analysis of data; Elaboration and revision of the manuscript.

Gerardo Sánchez-Martínez. Epidemiological study design. Elaboration and revision of the manuscript.

M Yolanda Luna. Providing and Analysis of data; Elaboration and revision of the manuscript.

Cristina Linares. Original idea of the study. Study design; Elaboration and revision of the manuscript.

Data availability

The authors do not have permission to share data.

Declaration of competing interest

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.

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