This manuscript has not been yet peer-reviewed
This version is posted in Zenodo (a translation into Spanish language is available): doi:10.5281/zenodo.12754647

From heat wave Zoe to heat wave Vera: a two-year ex post evaluation of the categorization and naming heat wave system ProMeteo in Seville, Spain

José-María Martín-Olalla

*Departamento de Física de la Materia Condensada de la Universidad de Sevilla, ES41012 Sevilla, Spain**

Yuval Baharav

Adrienne Arsht-Rockefeller Foundation Resilience Center at the Atlantic Council, Washington, DC, USA

Laurence Kalkstein

Applied Climatologists, Inc. Marco Island, FL, USA

Scott Sheridan

Department of Geography, Kent State University, Kent, OH, USA

Kurt Shickman and Kathy Baughman McLeod

Adrienne Arsht-Rockefeller Foundation Resilience Center at the Atlantic Council, Washington, DC, USA

Gregory A Wellenius

Center for Climate and Health, Boston University School of Public Health, Boston, MA, USA

(Dated: July 25, 2024)

The heat wave *Zoe* in Seville (Spain) (July 24th, 2022) was the first heat wave event named after a health-based categorization system. It was followed in 2023 by their siblings *Yago*, *Xenia*, *Wenceslao*, and *Vera*.
We report here how the pilot project ProMeteo addressed the forecast, and the main climatic characteristics of the heat waves identified during those years. We also provied a comparison between model expectations and observed daily mortality.

```
Total
Words in text: 4493
Words in headers: 39
Words outside text (captions, etc.): 792
Number of headers: 12
Number of floats/tables/figures: 13
Number of math inlines: 87
Number of math displayed: 3
Files: 3
```

Heat waves have been identified since the late 20th century and early 21st century as hazardous events with strong negative impact on health, including premature mortality(Becker *et al.*, 2022; Campbell *et al.*, 2018; Sheridan and Allen, 2018; Sheridan *et al.*, 2021). Among other heat waves, the European heat wave of 2003, in which it's estimated that over 70 000 people died, was pivotal in motivating efforts to mitigate the societal impact of heat waves(Robine

* olalla@us.es; https://orcid.org/0000-0002-3750-9113; https://ror.org/03yxnpp24

et al., 2008), especially as the frequency and intensity of heat waves are projected to increase during the coming years(IPCC, 2021; King and Karoly, 2017; Masson-Delmotte *et al.*, 2021; Perkins, 2015).

In this line, the Adrienne Arsht-Rockefeller Foundation Resilience Center at the Atlantic Council, in collaboration with international climate and health experts in the United States and in Seville, Spain, embarked on an effort to develop and pilot the use of a synoptic heat wave categorization system based on forecast local excess mortality, rather than meteorological variables alone. The categorization system was initially implemented in summer 2022 as a pilot evaluation in six cities, including four system demonstrations in the U.S. (Kansas City, Los Angeles, Miami, Milwaukee) and two publicly communicated pilots in Europe (Seville, Spain and Athens, Greece). In Seville, the pilot was given a public facing name – ProMeteo. In partnership with Seville City Council, ProMeteo tested a naming protocol for heat waves to increase awareness and facilitate communication among citizens and public officials, making Zoe the first ever named heat wave in July 2022. Seville was the only city to implement naming of high category heat waves as part of an awareness and communications strategy that mimics the standard protocol for storms and other hazardous tropospheric phenomena. If a heat wave reached a predefined category based on excess mortality projection, the Seville pilot system issued a name for the heat wave. Incidentally, the start of this pilot system coincided with the notable heat wave that swept Western Europe during the summer of 2022(Copernicus, 2022a,b) which has been associated which excess mortality(Ballester *et al.*, 2023). The hot 2022 was followed by an even hotter summer in 2023.(Copernicus, 2023, 2024) The Spanish National Meteorological Office (AEMET) reports for the province of Seville two heat waves in 2022 and three heat waves in 2023.(AEMET, 2023)

Previously, we reported the impact of the naming system in beliefs and behaviours of residents(Metzger *et al.*, 2024) and a retrospective analysis of the correlation between excess heat and excess mortality in the city of Seville(Kalkstein *et al.*, 2024)

The goal of this paper is to present an evaluation of how well this novel system performed in 2022 and in 2023 in order to provide insights and suggestions for continued improvement of the system.

The municipality of Seville (37.24° North, 5.99° West, population 681 998 as of January 1 2022 (Royal Decree 1037/2022), area 140 km^2, elevation 7 m) and the surrounding Seville province (NUTS code ES618, population 1 948 393, area 14 000 km^2) are located along the lower basin of the Guadalquivir river in Southwestern Spain (see Figure S1 in Supplementary Material). The city has a Mediterranean, temperate climate (Köppen classification Csa) characterized by a dry, hot summer(Kottek *et al.*, 2006; Tullot, 2000). For the purpose of testing a pilot system that characterizes the impact of heat waves on mortality, Seville has unique characteristics that include high summer temperatures and a large population–the latter being necessary for a proper statistical characterization of excess mortality associated with heat(Royé *et al.*, 2020). Additionally, Seville is the hottest major metropolitan area in Europe with frequent daily maximum temperatures above 40 °C in the summer and a record hottest temperature of 46.6 °C in 1995. The city of Seville also experiences high summer heat variability associated with the prevailing winds; westerlies bring warm air masses while easterlies usually bring dry, hot air masses.

1. METHODS

The novel heat warning, categorization and naming system has been thoroughly described elsewhere(Kalkstein *et al.*, 2024). It is based on the retrospective analysis of the synoptic air masses affecting Seville since 1995 and on the impact that those air masses produced on mortality.

To evaluate of the performance of the system in summer 2022 we made use of the following data sets, all publicly available:

1. The daily meteorological observations at Seville Airport (LEZL) weather station (WMO 08391), operated by AEMET (Agencia Estatal de Meteorología). The series starts in 1951.

2. The 3-hour/5-day forecast available at OpenWeather for the city of Seville (city 6361046)

3. The Spanish Mortality Monitor (by Instituto de Salud Carlos III, ISC3) which produces daily estimates of the crude, all-cause deaths in Spain disaggregated by province, sex and wide age group. The series starts on January 1, 2015. Hereafter the mortality monitor will be quoted as MoMo.

   This data-set broadcasts daily an estimate of the death counts in the preceding days M, an estimate of the expected deaths E based on population, seasonality and previous death records, and a model estimate of deaths attributed to excess temperature A should daily maximum temperature overshoot a local threshold placed at 40 °C(Jiménez *et al.*, 2015). Their model weights the impact of excess temperature seven days back(Nogueira and Paixão, 2008).

Category	Expected Excess Mortality	Percentile	EHF/K^2	$\sqrt{\text{EHF}}$/°C
0	$<10\,\%$	32	<1.7	<1.3
1	$<20\,\%$	74	<7.8	<2.8
2	$<30\,\%$	93	<15.5	<3.9
3	$>30\,\%$	>93	>15.5	>3.9

TABLE 1 ProMeteo Sevilla category system based on our retrospective analysis(Kalkstein *et al.*, 2024). This table lists expected excess mortality, quantile distribution of the category, excess heat factor EHF and its square root.

The data-set was retrieved in 2024, therefore under-reporting does not have an impact this study.

The severity of a heat wave in this study is defined by the Nairn-Fawcett Excess Heat Factor (EHF)(Nairn *et al.*, 2014). The factor combines two components of a daily characteristic temperature T:

1. The excess heat or significance index EH, which is the difference between the three-day sample moving average of T and its climatological 95th percentile T_{95}:

$$\text{EH} = \text{SMA}_3 - T_{95}. \tag{1}$$

It measures how hot one day is in relation to the historical records of the location. For this purpose, the 95th percentile of the series 1981 to 2010 was determined.

2. The acclimatization factor or index A, which is the difference between the same three-day sample moving average and the 30-day sample moving average:

$$A = \text{SMA}_3 - \text{SMA}_{30}. \tag{2}$$

The acclimatization index measures how hot one day is in relation to the recent past.

The Nairn-Fawcett EHF is defined as the product of the two preceding indexes provided that EH are positive (excesses):

$$\text{EHF} = \begin{cases} \text{EH} \times \max([1\,^\circ\text{C}, A]), & \text{if EH positive,} \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

By construction the square root of the Nairn-Fawcett EHF is always real. It also has a simple arithmetic interpretation: when $A \geq 1\,^\circ\text{C}$, the $\sqrt{\text{EHF}}$ is the geometric mean of the two indexes (EH and A). In other words $\sqrt{\text{EHF}}$ is smaller than one of two indexes, and greater than the remaining index.

In our analysis the input of the EHF will be the daily mean apparent temperature (hereafter DMAT) which combines day and night temperatures and the impact of humidity and wind(Staiger *et al.*, 2012; Steadman, 1984). The climatic 95th percentile of this metric in Seville was 30.8 °C.

From 1973 to 2023 we found 527 non-zero EHF days, 11 % of the 4692 days in June, July and August. Accumulated values of EHF display largest values in late July and early August (epidemiological weeks 29 to 33) when DMAT also attains the highest average values, see Figure S2 in Supplementary Material. To understand the increase of average temperature in the city we note that until 1982 the non-zero EHF days grew at a rate of 5.8 days per year; since 1990 they have grown at a rate of 13 days per year.

In our retrospective analysis we divided heat waves in Seville into four categories based solely on the level of increased mean mortality during the event(Kalkstein *et al.*, 2024). Table 1 lists the main characteristics of each category level.

Finally, we set a protocol to name the heat wave based on the forecast. We require a 3-day non-zero EHF series with at least one Category 3 day or a 3-day accumulated EHF above $34\,\text{K}^2$, meaning on average a 3-day series in the upper tier of Category 2. That is Category 2^+ in Figure 1; see also Section 3.

Start date	Duration d	max($T_{\max}$) °C	max($T_{\min}$) °C	$\mathrm{EHF}_{\mathrm{ac}}$ K^2	$\mathrm{EHF}_{\max}$ K^2	Category	Name (label)	Announced
2022-Jun-11	5	42.6	23.3	13.6	4.8	1	(a)	
2022-Jul-09	3	42.5	23.0	6.9	3.7	1	(b)	
2022-Jul-13	6	44.8	26.0	45.8	13.6	2^+	(c)	
2022-Jul-22	5	44.5	28.1	57.7	17.0	3	Zoe	2022-Jul-24
2022-Jul-31	4	41.0	23.9	7.5	3.0	1	(d)	
2023-Jun-24	6	42.0	23.0	77.2	23.0	3	Yago	2023-Jun-23
2023-Jul-03	2	38.2	24.3	5.4	3.2	1	(e)	
2023-Jul-10	5	41.7	25.3	27.4	8.8	2	Xenia	2023-Jul-09
2023-Jul-18	3	41.7	25.2	11.6	6.8	1	(f)	
2023-Jul-31	1	39.9	23.7	0.1	0.1	0	(g)	
2023-Aug-07	7	43.7	24.5	51.7	12.2	2^+	Wenceslao	2023-Aug-07
2023-Aug-20	7	42.6	24.2	76.5	15.0	2^+	Vera	2023-Aug-24

TABLE 2 Catalogue of the heat waves identified during 2022 and 2023 in Seville, Spain, with characteristics based on final observed values at the AEMET weather station. First column shows the onset date, then the duration (number of continued days), the maximum day temperature and the maximum night temperature, the accumulated EHF, the peak $\mathrm{EHF}_{\max}$, the category assessment, the heat wave name or label, and heat wave name announcement date. See figure 1 (top panels) for a visualization of the heat waves. Notice that the name and announcement were not based on observations, but on forecasts, see Figures S4 to S8 in Supplementary Material.

2. RESULTS

Figure 1 shows the basic observations associated with temperature (top panels) and mortality (bottom panels) during the summer of 2022 (left panels) and 2023 (right panels) in Seville. The horizontal axis expands 105 days (15 weeks) corresponding to epidemiological week 22 to week 36.

Top panels in either figure shows in thin step lines SMA3 and SMA30 for the daily mean apparent temperature (DMAT). The historical 95th percentile $T_{95} = 30.8\,°\mathrm{C}$ is noted. They also show EH (excess heat, see Eq. 1) and the A (acclimatization excess, see Eq. 2) by thick step lines when they are positive. Finally the square root of the Nairn-Fawcett EHF (see Eq. 3) is shown by filled steps. Excess values can be read at the right-most axis. Category levels are annotated following Table 1.

The top panels in figure 1 show several excursions of the EHF during the summer. Each excursion makes a heat wave. Unnamed events are labeled by Latin letters; else the name associated with the event is annotated. Table 2 lists the primordial meteorological characteristics of the heat waves identified during 2022 and 2023: onset date, duration, maximum daily temperature, the largest of the daily night temperature, the accumulated EHF, and the highest EHF in the heat wave, which served to identify the category according to table 1.

The first heat wave in June 2022 —label (a)— came shortly before the pilot project was launched, and reached category 1 (C1) in our categorization system. Thereafter, several excursions occurred along July and early August 2022, coincident with the heat wave that swept Western Europe(Copernicus, 2022a,b). The first excursion brought a 10-day series with EHF at category 1 —label (b)— and category 2 —label (c)—. After a brief, 3-day break a new heat wave was onset on July 21st. The daily forecast on July 24th reached a condition to name the event (see Figure S4 in Supplementary Material) and heat wave Zoe was released. It was the first named heat wave following a categorization system based on the health risks.

Heat wave Zoe was characterized by daily maximum temperatures ranging from 44.5 °C (July 25th, 11th highest in records) to 40.3 °C; daily minimum temperatures from 28.1 °C (July 25th, 3th highest in records) to 22.3 °C; and daily mean apparent temperature ranged 34.9 °C (July 25th, 22th highest in record) to 30.6 °C. See table 2. Following heat wave Zoe, a category 1 heat wave was observed in early August —label (d)—. In 2022 there were 23 dates with non-zero EHF that accumulated $131.5\,\mathrm{K}^2$.

In 2023, we identified seven heat waves four of which were given a name: Yago, Xenia, Wenceslao and Xenia, see Table 2. Figure S5 in Supplementary Material shows the conditions when heat wave Yago was called in late June. Yago was fueled by the acclimatization excess A which is usually larger during the first third of the summer, see Figure 1. Heat wave Xenia and heat waves (e) and (f) occurred in early July. In retrospect, none of these heat waves reached the preset condition to give a name. Those conditions existed in our forecasts, see Figure S6 in Supplementary Material. The last two heat waves, Wenceslao and Vera, accumulated 14 days with excess heat were formed in early August reached category 2^+ and either of two sustained for one week, see Figures S7 and S8 in Supplementary

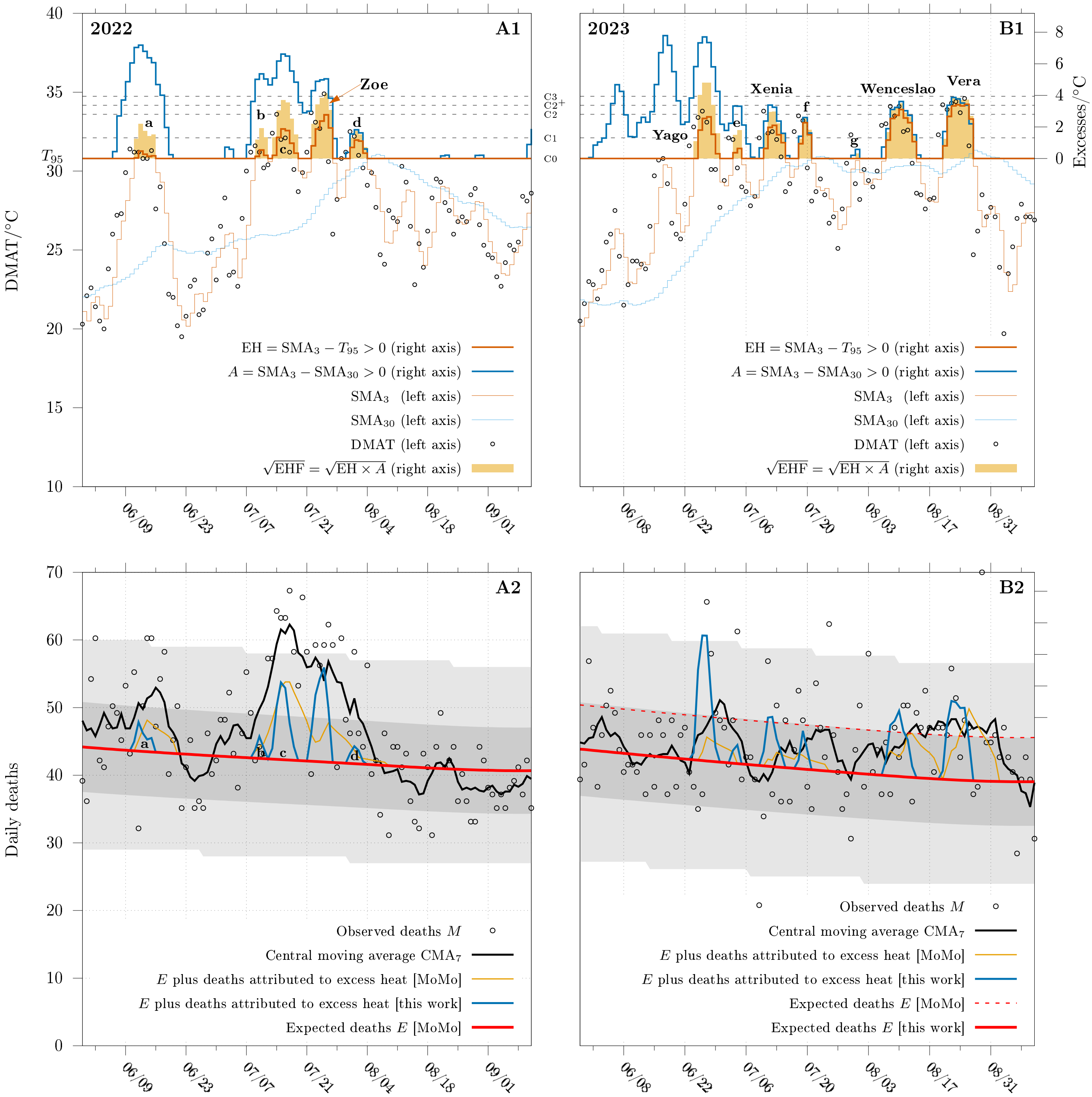

FIG. 1 The meteorological observations in Seville (top panels) and the observed all-cause mortality in the province of Seville (bottom panels) during the summer of 2022 (left panels) and 2023 (right panels. Dates are printed in big-endian format month/day. The top panels show the daily mean apparent temperature (DMAT, circles) its 3-day sample moving average (SMA_3) and its 30-day sample moving average (SMA_{30}) along with the climatic 95th percentile $T_{95} = 30.8\,^\circ\mathrm{C}$ (left axis); the climatic excess EH (orange), the acclimatization excess A (blue), and the square root of the excess heat factor in shaded area (all excess values are read at the right axis). The dashed lines display the levels at which Category 1, 2, 3 and 4 are reached. Latin letters label unnamed heat waves. The bottom panels show the all-cause daily mortality reported by MoMo (circles M) and its 7-day central moving average (black line); the expected deaths (red line E); the expected deaths plus the deaths attributed to heat by MoMo (orange line $E + A$); and the expected deaths plus deaths attributed to EHF by our retrospective analysis (blue line, $E + C$). The darker shade shows $E \pm \sqrt{E}$ and the lighter shade shows the $1\,\%$–$99\,\%$ confidence interval of E as reported by MoMo. In panel A2, expected deaths are attributed by MoMo. In panel B2, MoMo expected deaths are shown by a dashed red line.

Metric	2022	2023
Observed deaths (MoMo)	4813	4271
Expected deaths (MoMo)	4426	4587
Excess deaths (MoMo)	387	−316
P−score (MoMo)	9 %	−7 %
Expected deaths (this work)	4426	3957
Excess deaths (this work)	387	314
P−score	9 %	8 %
Attributed to excess temperature (MoMo)	163	155
Attributed to EHF (this work)	111	186

TABLE 3 Mortality counts associated with epidemiological weeks 22 to 36 in Seville, Spain. See Figure 1 (bottom panels) for a visualization of the metrics.

Material. We report 31 dates in 2023 with non-zero EHF that accumulated 250 K^2. Compared with the previous observed accumulated EHF in the series 1995 to 2023, the year 2023 is ranked the fourth hottest after 1995, 2003 and 2004; whereas 2022 is ranked 6th, with 1998 taking 5th place, see Figure S3 in Supplementary Material.

Bottom panels in Figure 1 show mortality data extracted from MoMo in the province of Seville. Data points show the observed mortality with the thick black line displaying the central one-week moving average. The thick red line shows the expected mortality. The darker shaded area shows the strip band $E \pm \sqrt{E}$, the expected daily deaths plus/minus the square root of their expected variance. The lighter shaded area highlights the $1\,\% - 99\,\%$ confidence interval of the E as reported by MoMo. The impact of meteorological variables is shown by two models. The orange line shows E plus the expected deaths attributed to excess temperature as reported by MoMo. The blue lines shows the excess deaths attributed to EHF by our model.(Kalkstein *et al.*, 2024)

Table 3 lists the basic mortality numbers associated with the 15 weeks in our analysis. In 2022 there were 4426 expected deaths (death rate of 23.6 deaths per day and per one million population) of which 2101 would be female deaths (rate 20.2) and 2325 would be male deaths (rate 21.7). There were 4813 observed deaths (rate 23.6), 9 % up relative to the expected deaths, 2391 female deaths (rate 23.0, 14 % up) and 2421 male deaths (rate 24.3, 4 % up).

The observed mortality shows two excursions in 2022, see Figure 1 panel A2. The first excursion was coincidental with heat wave (a) and occurred before the pilot project started. The second excursion was coincident with heat wave (b), Zoe, and heat wave (c), and prolonged during July and early August.

Relative to the expected deaths, MoMo attributes 163 deaths (3.7 %) to excess temperature, of which 124 would be females and 40 would be males. Our model model adds 111 (2.5 %) to MoMo expected deaths.

In 2023 (panel B2 in Figure 1) the dashed red line shows the base expected deaths (E) reported by MoMo. The full range of dates adds up 4587 expected deaths (death rate of 22.5 deaths per day per one million population) of which 2231 would be female deaths (rate 21.5) and 2356 would be male deaths (rate 23.6). The observed death count adds up 4271 (rate 21.0), 7 % lower relative to the expected deaths, 2063 female deaths (rate 19.9, 8 % lower) and 2209 male deaths (rate 22.1, 6 % lower).

In view of these numbers and from a visual inspection of the dashed red line in panel B2 we removed six deaths per day to the expected deaths reported by the Spanish MoMo to obtain our estimate given by the red thick line (3957 deaths, 19.4 per one million population). Relative to this expectations there were 314 excess deaths (8 % higher). MoMo excess deaths attributed to excess temperature add up 155 (4 % higher than the expected mortality). Our model adds 186 deaths (4.5 %) to the expected deaths.

Figure 2 attempts to visualize the relationship between observed excess deaths and predictions by our model in 2022 (top) and 2023 (bottom) on a daily basis. The horizontal axis displays the EHF and the vertical axis display the daily excess mortality percentage relative to the expected deaths (red line in Figure 1 bottom). The high dispersion at EHF = 0 is attributed to the size of the model that usually lists some 45 deaths per day. Also we must take into account that when a heat wave ends, deaths may accumulate in the following days, even though these days may not exhibit excess heat. In 2022, daily excess deaths were consistently greater than predictions associated with heat excess. Whereas in 2023 daily excess death were mostly in line with our expectations.

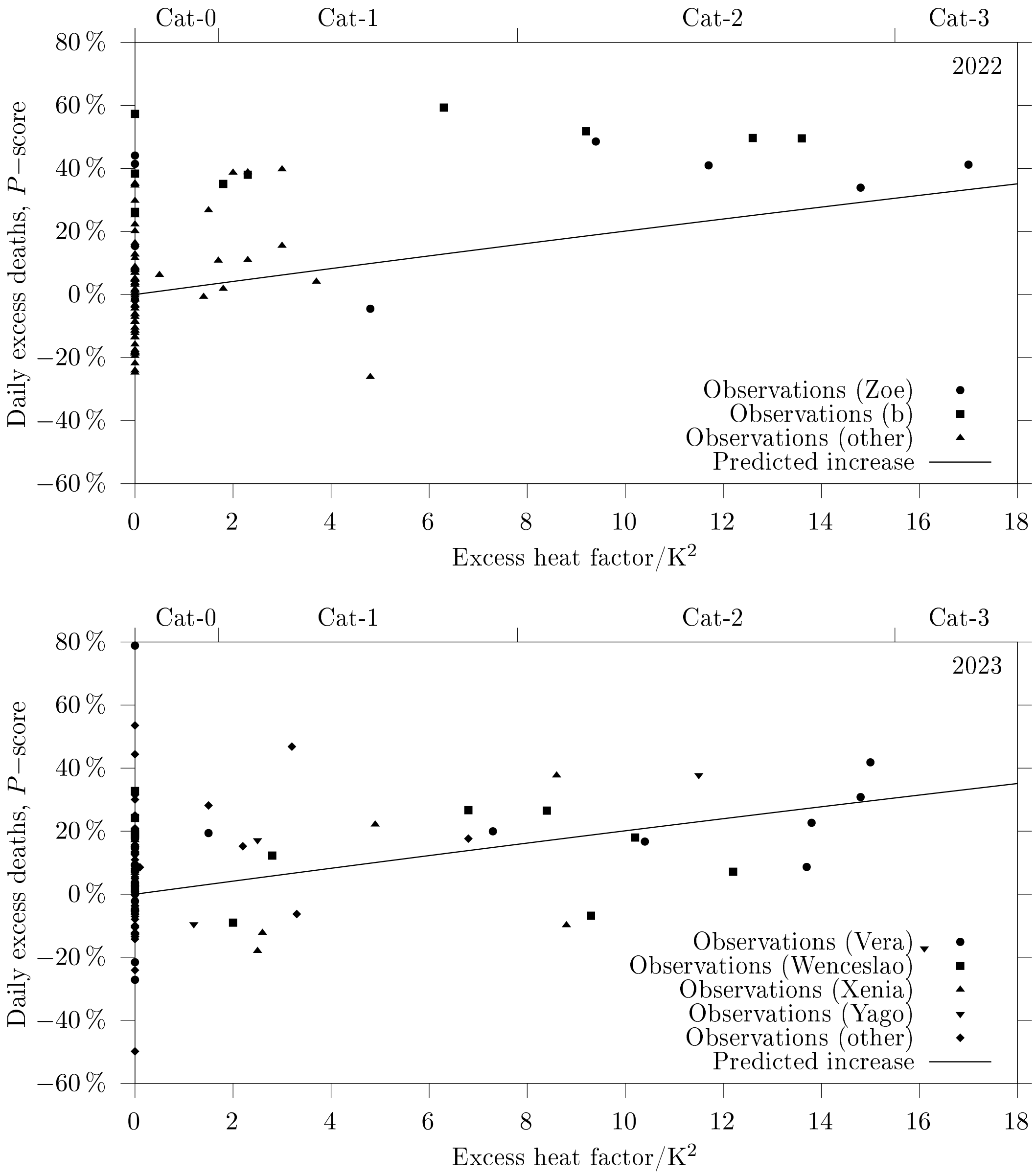

FIG. 2 The relationship between the daily excess heat factor (horizontal axis) and the P−score daily excess mortality (vertical axis) along with the predictions based in our model (thin line). See Table 2 for heat wave labels. Top: the year 2022. Bottom: the year 2023.

3. DISCUSSION

On 2022-Jun-21, the pilot project ProMeteo started monitoring the 5-day/3-hour forecast by OpenWeather for the city of Seville, ES and producing a systematic 5-day forecast based on the daily mean apparent temperature and the Nairn-Fawcett excess heat factor (EHF) associated with the OpenWeather data. The forecast was broadcast as a web-page that was forwarded to the partners of the project, including the City Hall. The web-page was not publicly available.

In Supplementary Material Figures S4 to S8 show a snapshot of the web-page with forecast close to the call of a named event. In figures S4 to S8 the top left frame lists the five categories and their associated colors: green, light orange, orange, light red, red. The right frame lists the output of the 5-day forecast, including the category level and the category color. While the forecast shows 5-day ahead, ProMeteo focused on the first three days only (D, D+1 and D+2), as the meteorological predictions tend to be more accurate in shorter terms. It must be noted that during 2022 the EHF was mistaken due to a miscalculation: the 30-day sample moving average was being inadvertently computed as a 50-day sample moving average. Since the categorization was based on the quantile distribution of EHF and since the miscalculation amplified the EHF systematically, the categorization system was unaffected by this mistaken.

ProMeteo identified two major heat waves during 2022. The first one —labeled (b) on Figure 1— started on July 10th, and ended on July 21st, peaking on July 16th. It was soon followed by a second heat wave starting on July 22nd, ending in July 29 and peaking in July 26th. These heat waves are concurrent with the massive heat wave that swept Europe in July 2022(Copernicus, 2022a).

ProMeteo warned the local authorities of the municipality of Seville of these two major heat waves and agreed with the City Council to publish a press release and other social media warnings. On July 12 ProMeteo alerted to an incoming heat wave categorized as high risk for the vulnerable population based on our retrospective analysis. Warning messages remained on social media until July 20. On July 22 a second press release warned of a new moderate heat wave for the following days. It was updated on July 23 when the risk increased to high. On July 24, the forecast predicted for the following two days DMAT 6 °C above the climatic 95th percentile (located at 30.8 °C), daily maximum temperatures seven degrees above the 95th percentile (38.2 °C) and daily minimum temperatures seven degrees above the 95th percentile (22 °C).

During this series of days the category 3 condition, which would have resulted in naming the event, was only attained in some forecasts during heat wave (b). At that time the partners of the project hesitated on launching a name due to, among other reasons, the novelty of the naming system, which prompted the pilot project to be cautious. Also the time difference between local partners and US partners played a role since the first forecast of the day arrived at 07:00UTC (09:00 local time), midnight on the other side of the Atlantic.

Eventually, the conditions that had sustained since July 10 prompted the project to re-evaluate the naming criterion and the decision making process. As a result of this, it was determined on July 19 that the local partners should make the call based on the morning update. It was also agreed that a series of three days with average accumulated EHF per day in the upper tier of Category 2 should also merit a name. This level is shown by $C2^+$ (category 2^+) in Figure 1.

With the arrival of the early morning forecast on 2022-Jul-24 (shown in Figure S4) the new condition was satisfied, the local scientific advisor (JMM-O) made the call and the City Hall agreed to name the incoming heat wave as Zoe, following a preset alternating list of female and male proper names in reverse alphabetic order.

In 2023 ProMeteo identified four named events and three unnamed events. Six warning messages were broadcasts as a press release and in social media.

An interest point to discuss is how well the forecast performed. Figure 1 show the final observations taken at the AEMET weather station located at Seville's Airport, 7.5 km ENE from downtown, whereas Figures S4 to S8 display the forecast condition when a named event was called. In retrospect, category 3 was effectively achieved during heat wave Zoe. Likewise, during heat wave (b) category 2^+ condition was achieved and the heat wave (b) would have merit a name, had the protocol considered such category at that time. In 2023 heat wave Xenia was given a name based on the available forecasts (see Figure S6 in Supplementary Material) but final observations ranked the event in the lower tier of Category 2, which do not qualify for a name. The retrospective analysis of each of the remaining six events in 2023 agrees with the initial call by ProMeteo including three named events —Yago, Wenceslao and Vera— and three unnamed events —labels (e), (f) and (g)—.

Another point of interest is readiness of our warnings. The model is based in a three-day average, which need three days to climb up. Understandably heat waves also have an uprising onset, followed by a downfall. Heat wave Zoe was announced after it had started, once the naming criterion was met. The warning was effective for the target day (2022-Jul-24), which eventually was the most dangerous of the heat wave. Heat waves Yago, Xenia and Wenceslao were identified and announced before or at their onsets. Finally, heat wave Vera was only alerted on 2023-Aug-24, four days after its onset. On Aug-21 ProMeteo launched a heat wave warning but no named event was presented, based on the available forecast which showed the accumulated EHF in the following three days in 33 K^2, just shy of category 2^+. It was not until Aug-24 that the alert was upgraded and the name Vera was launched (see Figure S8). In retrospect, and based on actual observations, Aug-22 and Aug-23 attained worse conditions than those observed on Aug-24.

AEMET report of heat waves in the province of Seville(AEMET, 2023) differs from our story line in several ways. The heat wave (a) in June 2022 and Yago in June 2023 were not called by AEMET. Both heat waves were impacted by the acclimatization, a contribution that is missed in AEMET analysis. Second, in 2022 AEMET merged heat waves (b), (c) and Zoe in one event that started on July 9th and ended on July 26th. Also AEMET reports a heat wave from July 30 to August 14, longer than the heat wave (d) in Table 2. Finally, AEMET did not call heat waves (e), (f) and (g) in 2023, the weakest events in our catalogue.

Figure 1 (bottom panels) show an excursion in daily mortality synchronous with the predictions by MoMo (based on daily maximum temperature excess) and ProMeteo's retrospective analysis (based on the Nairn-Fawcett excess heat factor deduced from daily mean average temperature). In contrast, either model failed to estimate accurately the excess deaths in 2022. The 163 (MoMo) and 111 (ProMeteo) excess deaths are largely shy from the 387 observed excess deaths. This may be an evidence of the existence of further causes of deaths other than heat excess but, also, it is an evidence of the limitations of current models, specifically when excess heat condition prevailed during a long series of days like in July 2022 and in the context of the aftermath of the COVID-19 disease.

In 2023 the scenario was reversed and the observed death count in summer fell 7 % below the expected deaths predicted by MoMo (see Figure 1 panel B2). As a plausible explanation we understand that the large excess deaths in 2022 has had an impact in the observed deaths in 2023, relative to standard models. Our educated guess of the expected deaths brings 8 % excess deaths in 2023, half of which is explained by MoMo excess deaths attributed to excess temperature, and by our model.

We must emphasize that ProMeteo does not aim to accurately assess excess mortality but to early identify and categorize potential hazards so that individual and decision makers can take preemptive actions. This aim was accomplished during 2022 and 2023 since every call associated with EHF was sadly followed by a perceptible increase in mortality in line with our expectations.

The task of accurately predicting excess mortality from raw meteorological data faces the usual problem of descriptive statistics: sample size and its associated variability. Here the variability of death counts, roughly estimated as $1/\sqrt{E}$ or 20 % in the province of Seville, is sizeable with the impact observed in Category 3 events. Therefore when building the relationship between EHF and excess mortality small EHF events are poorly determined because of signal noise and high EHF events due to scarcity. This scarcity suggests that the knowledge of this association is currently limited and that mismatches can happen. The analysis could be improved by considering more populated conurbations, and having a larger series of years. Alternatively, aggregated values where the total excess mortality in a summer is associated with the accumulated EHF in that season could provide further insight.

4. KNOWN LIMITATIONS

Due to the closeness between AEMET weather station and the city of Seville we assume a high correlation between temperatures at either locations. Eventually, and because the EHF is built from temperature differences (see Eq. 1 and Eq. 2), we find no reason to believe that the mismatch between the weather station and downtown has a relevant impact in our results. It must only bear in mind that our predictor is always the temperature recorded at the weather station, which plays the role of a proxy for the urban temperature.

For the lack of the daily mortality in the municipality of Seville (population 681 998 in 2022) that were used in ProMeteo's retrospective analysis(Kalkstein *et al.*, 2024), we made use here of the daily mortality in the province of Seville (population 1 948 393 in 2022). The null hypothesis is that the ratio of the two daily death counts are roughly independent of date, and is explained by the variations in the population size. Indeed the association of the ratio versus index for the 552 dates in June, July and August from 2015 to 2020 gives Pearson's $R^2 = 0.004$ ($p = 0.13$): the null hypothesis sustains at the standard level of significance ($\alpha = 0.05$). Furthermore log-log regressions of the two death counts give slope $m = 0.96[0.86, 1.06]$ with Pearson's $R = 0.63$, and Spearman's $R = 0.62$. The bottom line is that our predicted excess mortality $P-$score associated with EHF roughly applies for the mortality in the province of Seville.

5. CONCLUSIONS

We have presented an ex post evaluation of a health-based heat wave categorization and naming system during two continued years. The monitoring system was able to forecast the major, hazardous events that hit the city of Seville during the summer of 2022 and 2023 in a timely manner.

The hazardous events were contemporaneous with spikes in daily mortality. Our predicted excess mortality based on excess heat factor(Kalkstein *et al.*, 2024) was able to explain the excess mortality observed in 2023. However, excess mortality in 2022 was worse than expectations from heat excess models.

DATA AVAILABILITY

AEMET data can be accessed by API-key from AEMET Open Data `https://opendata.aemet.es/centrodedescargas/inicio`.

Openweather forecast can be downloaded by API-key, see `https://openweathermap.org/api`.
The Spanish daily Mortality Monitor can be downloaded at `https://momo.isciii.es/panel_momo/`

DISCLOSURES

Dr. Wellenius serves as a consultant to Google, LLC (Mountain View, CA) and the Health Effects Institute (Boston, MA).

FUNDING

This research was funded under Atlantic Council/Arsht Rockefeller Foundation Contract #AARFRC-008-FY22-HEAT.

ACKNOWLEDGMENTS

We thank Esperanza Caro (Ayuntamiento de Sevilla) for her valuable help, Concha Ortiz (`https://conchaortiz.es`) for her translation and interpretation services to this work, Geraldine Henrich-Koenis (Addrienne Arsht-Rockefeller Foundation Resilience Center), Rosa Llacer (Descubre Comunicación) and Descubre Comunicación (`https://descubrecomunicacion.com`) for their outstanding effort in bringing this project to the public.

CREDIT

Conceptualization: Laurence Kalkstein, Yuval Baharav, Kurt Shickman, Kathy Baughman-McLeod, José-María Martín-Olalla; Methodology: Scott Sheridan, José-María Martín-Olalla, Yuval Baharav, Gregory A Wellenius; Formal analysis and investigation: José-María Martín-Olalla, Scott Sheridan, Laurence Kalkstein, Gregory A Wellenius; Writing original draft preparation: José-María Martín-Olalla, Gregory A Wellenius; Writing review and editing: José-María Martín-Olalla, Gregory A Wellenius, Yuval Baharav; Funding acquisition: Kathy Baughman-McLeod, Kurt Shickman ; Supervision: Kurt Shickman, Gregory A Wellenius.

REFERENCES

AEMET, (2023), "Olas de calor en españa desde 1975," .
Ballester, Joan, Marcos Quijal-Zamorano, Raúl Fernando, Méndez Turrubiates, Ferran Pegenaute, François R Herrmann, Jean Marie Robine, Xavier Basagaña, Cathryn Tonne, Josep M Antó, and Hicham Achebak (2023), "Heat-related mortality in Europe during the summer of 2022," Nature Medicine 2023 29:7 **29**, 1857–1866.
Becker, Florian N, Andreas H. Fink, Peter Bissolli, and Joaquim G. Pinto (2022), "Towards a more comprehensive assessment of the intensity of historical European heat waves (1979–2019)," Atmospheric Science Letters **23**, e1120.
Campbell, Sharon, Tomas A. Remenyi, Christopher J. White, and Fay H. Johnston (2018), "Heatwave and health impact research: A global review," Health and Place **53**, 210–218.
Copernicus, (2022a), "Prolonged and intense heatwave affecting parts of Western and Northern Europe breaks temperature records; globally, july 2022 was one of three warmest julys on record," .
Copernicus, (2022b), "Summer 2022 Europe's hottest on record," .
Copernicus, (2023), "Summer 2023: the hottest on record," .
Copernicus, (2024), "Europe experiences widespread flooding and severe heatwaves in 2023," .
IPCC, (2021), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Vol. In Press (Cambridge University Press) type: Book.
Jiménez, Julio Díaz, Rocío Carmona Alférez, and Cristina Linares Gil (2015), *Temperaturas umbrales de disparo de la mortalidad atribuible al calor en España en el periodo 2000-2009*, Vol. 725-15-015-7 (Instituto de Salud Carlos III, Escuela Nacional de Sanidad).
Kalkstein, Laurence, Scott Sheridan, José-María Martín-Olalla, Elizabeth Berg, Nicholas Maillaux, Sara Pabich, Rebecca Rose, Gregory Wellenius, Kathy Baughman McLeod, Kurt Shickman, and Yuval Baharav (2024), "Development and evaluation of a health-based heat wave categorization system: A case study of Seville, Spain," submitted to International Journal of Biometeorology 10.5281/zenodo.11407481.
King, Andrew D, and David J Karoly (2017), "Climate extremes in Europe at 1.5 and 2 degrees of global warming," Environmental Research Letters **12**, 114031.

Kottek, Markus, Jürgen Grieser, Christoph Beck, Bruno Rudolf, and Franz Rubel (2006), "World map of the Köppen-Geiger climate classification updated," Meteorologische Zeitschrift **15**, 259–263.

Masson-Delmotte, VP, P Zhai, SL Pirani, C Connors, S Péan, N Berger, Y Caud, L Chen, MI Goldfarb, and Pedro M Scheel Monteiro (2021), "Ipcc, 2021: Summary for policymakers. in: Climate change 2021: The physical science basis. contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change," (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA).

Metzger, Aaron, Yuval Baharav, Lilly Nichols, Megan Finke, Breahnna Saunders, Peter Mitchell, Gregory A. Wellenius, Kathy Baughman McLeod, and Kurt Shickman (2024), "Beliefs and behaviors associated with the first named heat wave in Seville Spain 2022," Scientific Reports 2024 14:1 **14**, 1–10.

Nairn, John R, Robert J B Fawcett, Kristie L Ebi, and Jeremy Hess (2014), "The excess heat factor: A metric for heatwave intensity and its use in classifying heatwave severity," International Journal of Environmental Research and Public Health 2015, Vol. 12, Pages 227-253 **12**, 227–253.

Nogueira, Paulo, and Eleonora Paixão (2008), "Models for mortality associated with heatwaves: update of the portuguese heat health warning system," International Journal of Climatology **28**, 545–562.

Perkins, Sarah E (2015), "A review on the scientific understanding of heatwaves—their measurement, driving mechanisms, and changes at the global scale," Atmospheric Research **164-165**, 242–267.

Robine, Jean Marie, Siu Lan K. Cheung, Sophie Le Roy, Herman Van Oyen, Clare Griffiths, Jean Pierre Michel, and François Richard Herrmann (2008), "Death toll exceeded 70,000 in Europe during the summer of 2003," Comptes Rendus - Biologies **331**, 171–178.

Royé, Dominic, Raquel Codesido, Aurelio Tobías, and Margarita Taracido (2020), "Heat wave intensity and daily mortality in four of the largest cities of Spain," Environmental Research **182**, 109027.

Sheridan, Scott C, and Michael J. Allen (2018), "Temporal trends in human vulnerability to excessive heat," Environmental Research Letters **13**, 043001.

Sheridan, Scott C, P. Grady Dixon, Adam J. Kalkstein, and Michael J. Allen (2021), "Recent trends in heat-related mortality in the united states: An update through 2018," Weather, Climate, and Society **13**, 95–106.

Staiger, Henning, Gudrun Laschewski, and Angelika Grätz (2012), "The perceived temperature - a versatile index for the assessment of the human thermal environment. part a: Scientific basics," International Journal of Biometeorology **56**, 165–176.

Steadman, Robert G (1984), "A universal scale of apparent temperature," Journal of Climate and Applied Meteorology **23**, 1674–1687.

Tullot, Inocencio Font (2000), *Climatología de España y Portugal* (Ediciones Universidad de Salamanca).

FIG. S1 A simple map of Spain (main) with the province of Seville (ES618) in shade and the city of Seville (black circle). The bottom-right inset locates Spain in Europe. The province of Seville is 14 000 km^2 in surface. The city is located at coordinates 5.99° West and 37.24° North.

Supplementary Material A: Supplementary material

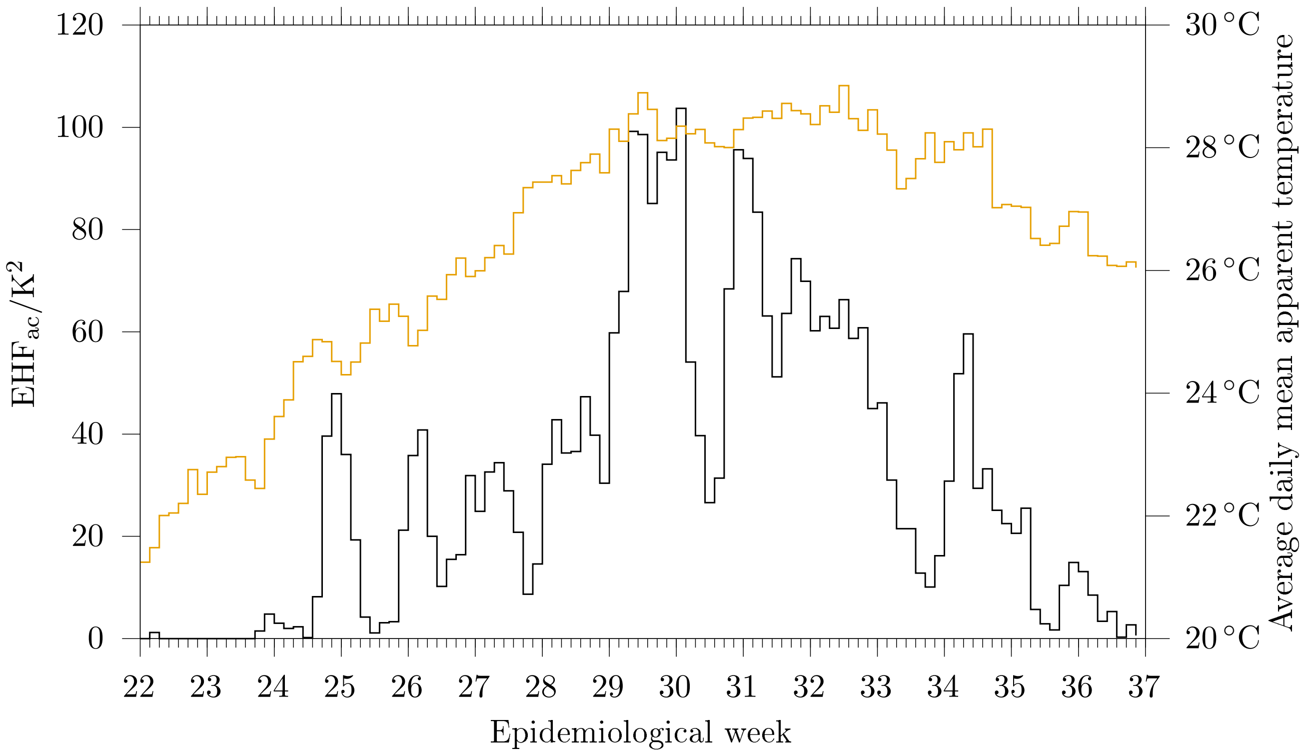

FIG. S2 Accumulated values of EHF per day (black, left axis) and average daily mean apparent temperature (orange, right axis) in Seville from 1973 to 2023. Date are given in epidemiological week format, from the start of week 22 to the end of week 36. The highest accumulated values and the highest average DMAT are observed from week 29 to week 33: late July to early August. Heat excess accumulated in weeks 25 and 26 are associated with larger values of the acclimatization excess, which are seldom observed elsewhere.

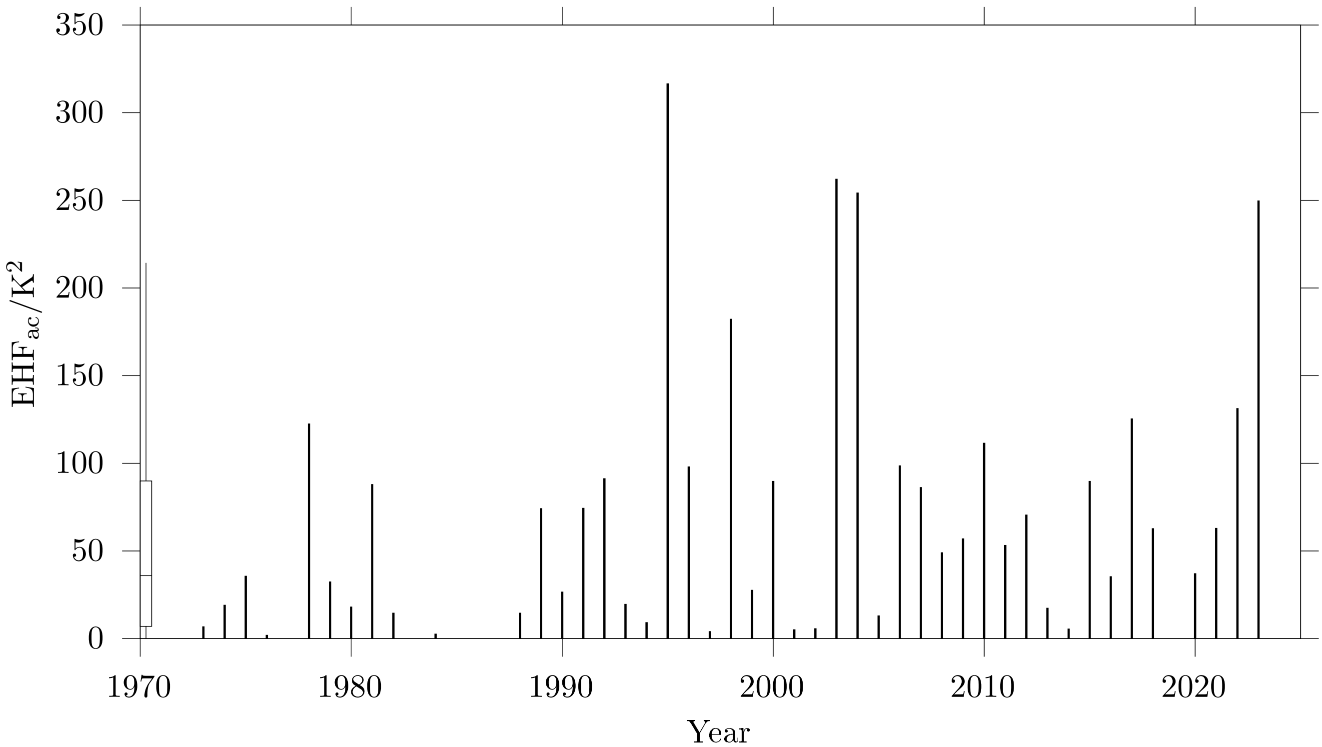

FIG. S3 Accumulated values of EHF per year with a whisker box on the left showing $Q_1 = 7\,\mathrm{K}^2$ (first quartile), $Q_2 = 35.8\,\mathrm{K}^2$ (second) and $Q_3 = 89.9\,\mathrm{K}^2$ (third). The whisker extends up to $Q_3 + 1.5 \times (Q_3 - Q_1) = 214.3\,\mathrm{K}^2$ to identify outliers in the distribution: the years 1995, 2003, 2004 and 2023.

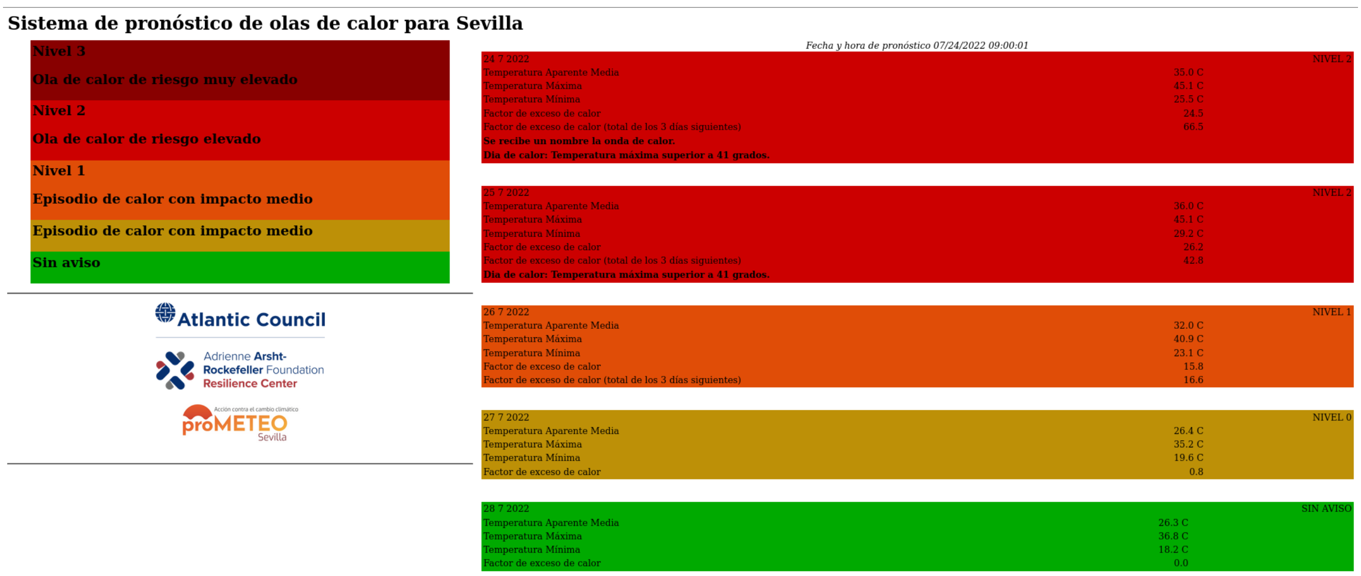

FIG. S4 A snapshot of ProMeteo webpage when Zoe heat wave was called. on 2022-Jul-24 07:00UTC. The top left frame shows the color codes associated with every of the five categories. The right frame shows the 5-day forecast with category and color code. It must be noted that the EHF was incorrectly computed at that time. The bug did not impact the categorization system.

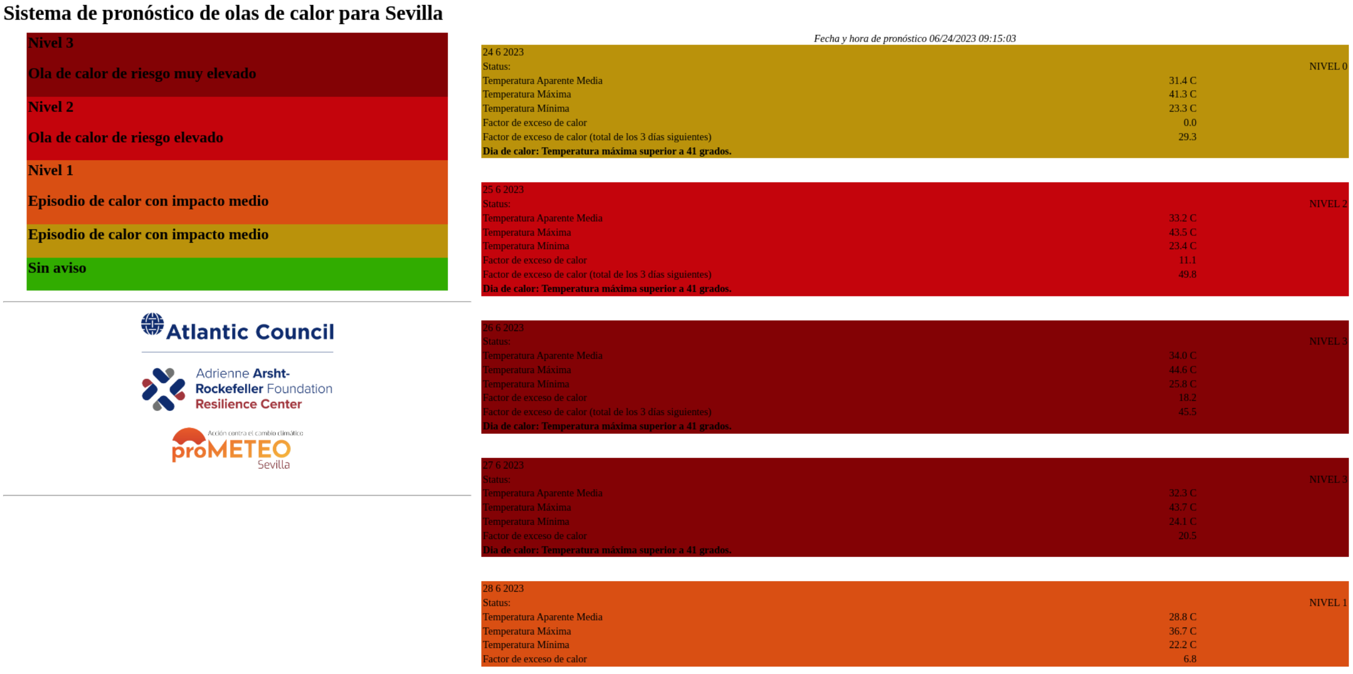

FIG. S5 A snapshot of ProMeteo webpage when Yago heat wave was called on 2023-Jun-24 07:15UTC. The top left frame shows the color codes associated with every of the five categories. The right frame shows the 5-day forecast with category and color code.

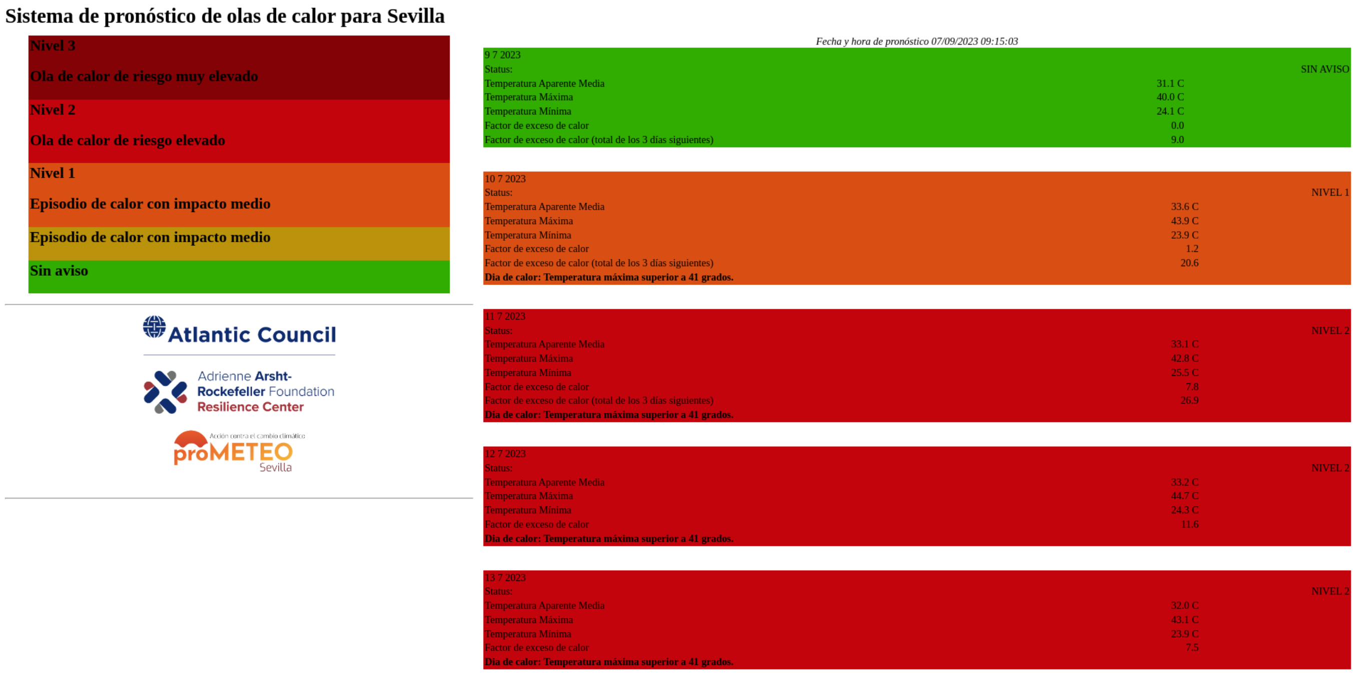

FIG. S6 A snapshot of ProMeteo webpage when Xenia heat wave was called on 2023-Jul-29 07:15UTC. The top left frame shows the color codes associated with every of the five categories. The right frame shows the 5-day forecast with category and color code.

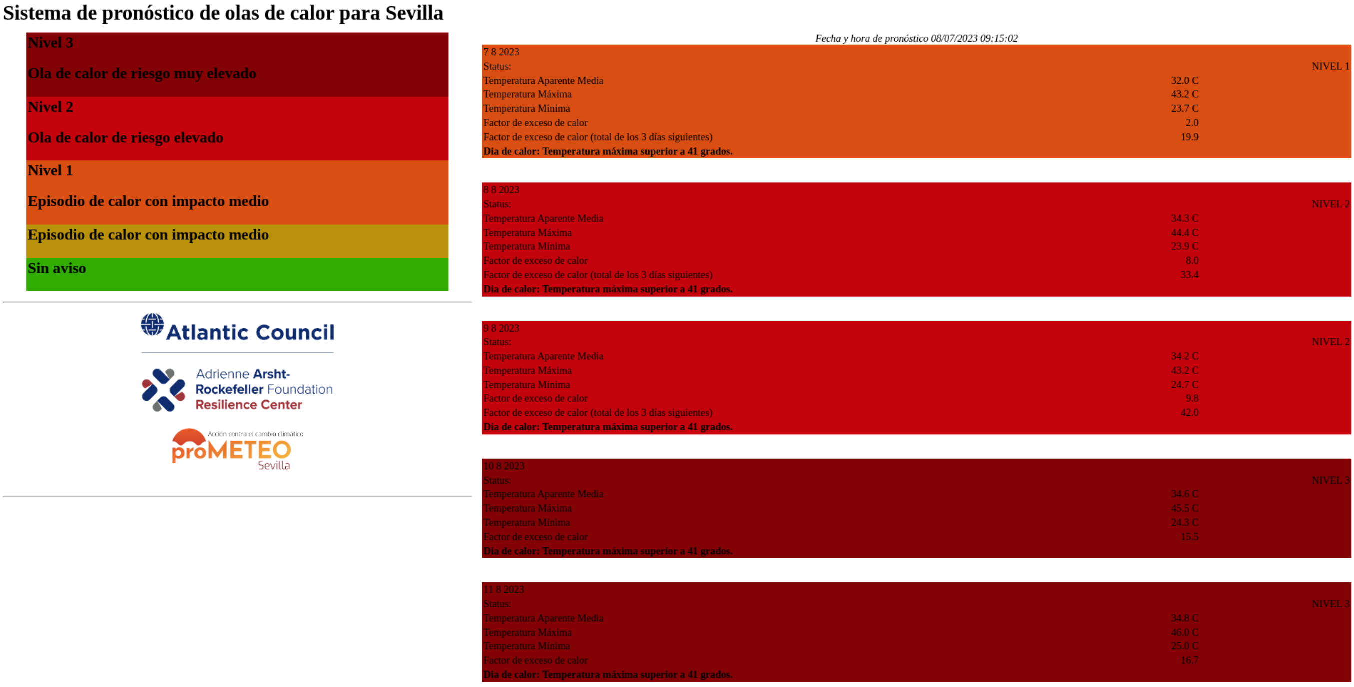

FIG. S7 A snapshot of ProMeteo webpage when Wenceslao heat wave was called on 2023-Aug-07 07:15UTC. The top left frame shows the color codes associated with every of the five categories. The right frame shows the 5-day forecast with category and color code.

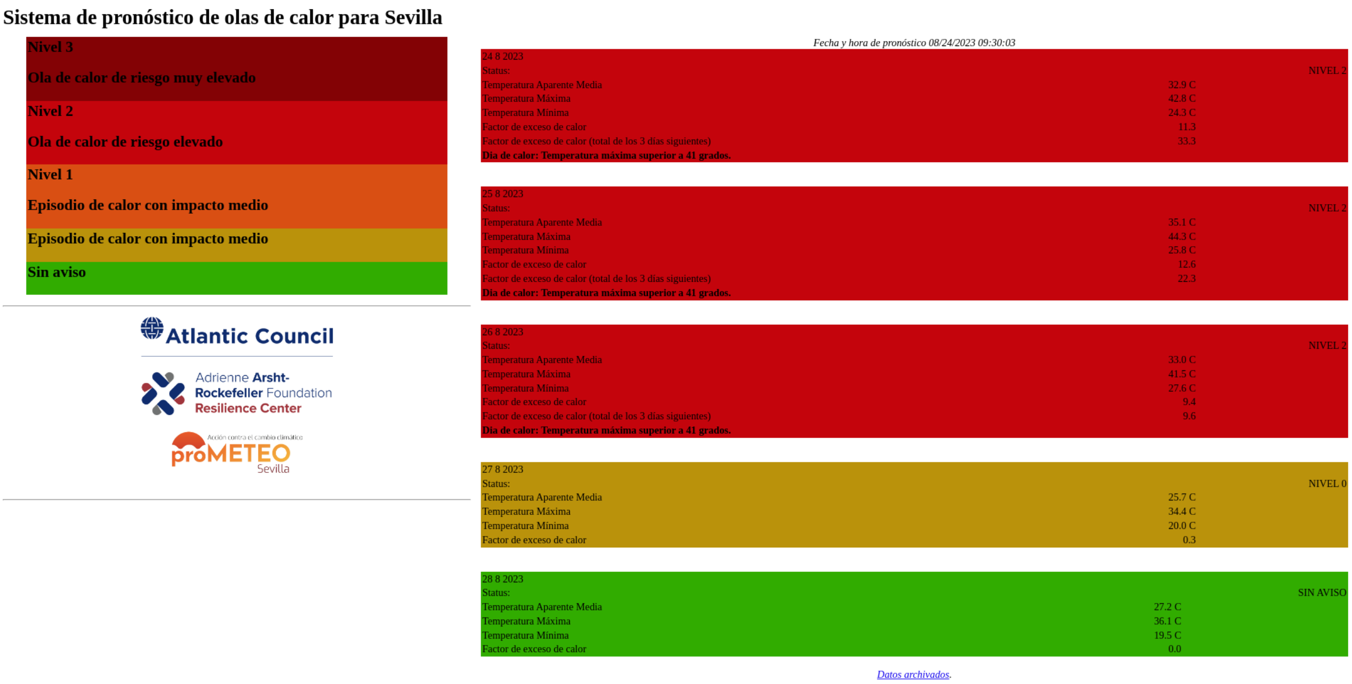

FIG. S8 A snapshot of ProMeteo webpage when Vera heat wave was called on 2023-Aug-24 07:30UTC. The top left frame shows the color codes associated with every of the five categories. The right frame shows the 5-day forecast with category and color code.