THE LETHAL GRIP OF HEAT: MAPPING THE HEATWAVE-MORTALITY NEXUS IN SPAIN (1975-2019)

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ABSTRACT

Nowadays, the rise in the global temperatures are a source of apprehension, particularly in the Mediterranean region, where Spain is witnessing notable consequences for its population. Predictions for the end of the XXI century reveal a persistent increase in air temperatures along with an increment of extreme episodes. Abnormal heat, once considered an 'environmental accident', is now a serious public unease. The study aims to measure the impact of heat waves on mortality by age and sex over 45 years across Spanish provinces.

Here we leverage daily individual mortality data from the National Institute of Statistics and air temperature estimates from the ERA5 global reanalysis. We also use the historical settlement data as a proxy for population distribution from 1975 onward. To estimate the main and added effects of heat waves we fit a quasi-Poisson time-series regression model using a distributed lag non-linear model with 10 days of lag, controlling for trends and day of the week.

This analysis examines 15.8 million deaths in Spain from 1975 to 2019. Over this period, we anticipate a shift in the temperature-mortality relationship, indicating a gradual flattening of the response curve and overall reduction in temperature-related mortality. We expect a more pronounced decrease in cold-related risks compared to heat-related ones, with latitudinal variations. Heat wave incidence is steadily increasing, with a positive effect on mortality, albeit smaller than the primary temperature effect. This heat wave effect is expected to vary as function of the heat wave type, location and demographic strata.

Keywords Climate Change · Heat wave · Mortality · Time-series regression

1 Introduction

The health effects of exposure to non-optimal ambient temperatures have been extensively studied Guo et al. [2014], Gasparrini et al. [2015], Song et al. [2017]. This subject has garnered attention from not only the scientific community but also healthcare experts and policymakers. The concerning increase of global temperatures has raised significant apprehension regarding the potential exacerbation of adverse health effects due to heightened and progressively extreme temperature exposures.IPCC [2021]. The southern Mediterranean region is becoming a major hotspot due to the persistent warming of the air temperatures Vicedo-Cabrera et al.. In particular, Spain is now one of the countries most impacted by increasing temperatures and heat waves. The progressive increase in the average annual and seasonal values of air temperatures in Spain is presented in all the projections used for the period 2081-2100 IPCC [2021]. For maximum temperatures, the rise in the annual scale is predicted to be between 2.0°C and 3.4°C under the RCP4.5 scenario, while for the minimum temperatures the expected increment ranges from 1.7°C to 2.9°C under the same intermediate pathway Amblar Francés et al. [2017]

Abnormal heat was a well known threat for human health for many decades, though it was mostly treated as an 'environmental accident' without any implications at the governmental level and for public policies until recently. A serious public concern related to the adverse health effects of the emerging heat wave phenomena starts to gradually arise from the end of the 1980-s as more evidence comes in. The 2003 heat wave resulted in a burst of scientific literature of diverse disciplines as the detrimental outcomes represented an undeniable piece of evidence. However, long-term studies of heat waves based on the individual mortality data at the regional scale in Spain are still rare Linares et al. [2015], Miron et al. [2015], deCastro et al. [2011].

Present study endeavors to quantify the added effects of heat wave exposure on mortality by age and sex during the period of 45 years in Spain at the provincial level. Moreover, we aim to explore the temporal evolution in these effects and variations in the spatial patterns.

2 Methods

2.1 Data collection

All data collected in the present study cover the Iberian Peninsula and Balearic Islands between Jan 1, 1975 and Dec 31, 2019. The original temporal and spatial resolution of datasets used in this study differed, therefore we employed a series of procedures in order to create a unified dataset where the units of choice are **days** (time-wise) and **provinces** (space-wise).

2.1.1 Environment

- **Temperature of air at 2m above the surface of land, sea or inland waters.** Daily mean, maximum and minimum temperature from the ERA5 reanalysis [Hersbach et al., 2020] was used to estimate exposure indicators. ERA5 is the fifth generation ECMWF reanalysis for the global climate and weather from 1940 onwards and provides hourly values of a large number of atmospheric, ocean-wave and land-surface variables globally, with a $0.25° \times 0.25°$ horizontal resolution (approximately 25x25km).
- **Historical settlement data.** As a proxy for human distribution in space we leveraged the cadastral data with rich thematic property attribution, such as building usage and construction year [Uhl et al., 2023]. These data comes as gridded surfaces, describing the evolution of human settlements in Spain from 1900 to 2020, at 100 m spatial and 5-year temporal resolution. In the present study we included the surfaces representing the measures of building density from 1960 to 2020.

2.1.2 Population

- **Mortality data.** Individual anonymised mortality data were provided by the Spanish National Institute of Statistics (INE) on special request in the form of microdata files. These data were further aggregated by day, age, sex and province of registry of the individuals.
- **Population data.** The reference yearly data were retrieved from the official publicly available database on population maintained by INE (INEBase).

2.2 Indicator of exposure to heat waves

Among different heat wave definitions in the literature Barriopedro et al. [2023], we followed a modification of the one adopted by the Spanish Weather Service (AEMET), also similar to the warm spell duration index by Alexander et al. [2006], which are calculated using a percentile-based threshold. AEMET issues a heat wave special alert when there are 3 or more consecutive days with daily maximum temperature above the 95^{th} climatological percentile in July and August for the period 1971-2000 in more than 10% of the stations in the region. In this work, we included two effects which can accentuate the negative impacts of heat stress. First, the effect of night-time heat by considering daily minimum temperature together with daily maximum counterparts, since residents may not recover from the daytime heat and suffer from sleep loss because populated areas often cannot cool down at night Oke et al. [1991]. Secondly, we considered prolonged summer seasons for the percentile calculation, since summers tend to extend beyond July and August in a climate change context. Thus, we consider a heat wave a spell of 3 or more days with daily maximum and minimum temperatures above their 95th climatological percentiles calculated in June-September for the period 1981-2010. Heat waves are estimated for each ERA5 grid box independently but only grid boxes with a minimum of 10% urban land cover are considered (hereafter urban grid boxes). A heat wave occurs in a province when at least 10% of the urban grid boxes are under the effect of a heat wave.

2.3 Statistical analysis of temperature-mortality associations

We explore the association between heat waves and mortality spikes by disentangling temperature-related risk into two components: a "primary effect" stemming from the independent influence of daily mean temperatures, and an "added effect" arising from prolonged periods of elevated heat during heatwaves. The primary effect is quantified using distributed lag nonlinear functions of temperature, which consider non-linear delayed consequences and short-term harvesting Gasparrini et al. [2010], similarly to the approach suggested by Gasparrini et al. Gasparrini and Armstrong [2011]. The added effect is defined using a simple binary indicator (explained in section 2.2) and subsequently as a function of consecutive days within a heat wave and its intensity.

To evaluate changes in the mortality burden from heat waves, we split the study period into equal 10-year intervals. For each period, we fit a quasi-Poisson time-series regression model Bhaskaran et al., where we control for seasonal and long-term trends using a natural cubic spline of time with 10 degrees of freedom per year and indicator variables for the day of the week. We use a natural cubic spline with three internal knots placed at the 10^{th}, 75^{th}, and 90^{th} percentiles of the temperature distribution and the lag-response, up to 10 days, with a natural cubic spline with 3 internal knots placed at equally spaced values in the log scale. These modelling choices are based on extensive previous work using an overlapping data set and have been thoroughly tested by sensitivity analyses Tobías et al. [2021], Iñiguez et al. [2021].

The analysis is performed in R 4.2.0, and for the statistical modelling we use the dlnm-package Gasparrini et al. [2010]. Spatial operations with vector and raster data are executed in ArcGIS Pro 3.0.2.

3 Expected results

We analyse approximately 15.8 million of deaths registered in Spain between 1975 and 2019. During the selected time window we expect to see a shift in the temperature-mortality association from a V-shape in the first decades of the observation to a U-shape by the end of the period all across the provinces, thus revealing a progressive flattening of the exposure-response curve. We also expect to observe an overall reduction in the mortality burden associated with the temperatures. In particular, we anticipate more significant and rapid decline in the cold-related risks and attributable fractions in comparison with the heat-related ones, with some latitudinal variations across the country.

On the other hand we witness a steady increase in the incidence of the heat wave episodes with time (Fig. 1.) all over the country. We expect to see a positive added effect of heat wave o mortality, however this effect is suspected to be smaller than the primary effect. Also, we anticipate to see the variations in the effect depending on the heat wave order, duration, intensity, geographic location and demographic strata. The largest added effects are expected for the longest and strongest heat waves in the elderly female population in the less accustomed to extreme heat areas.

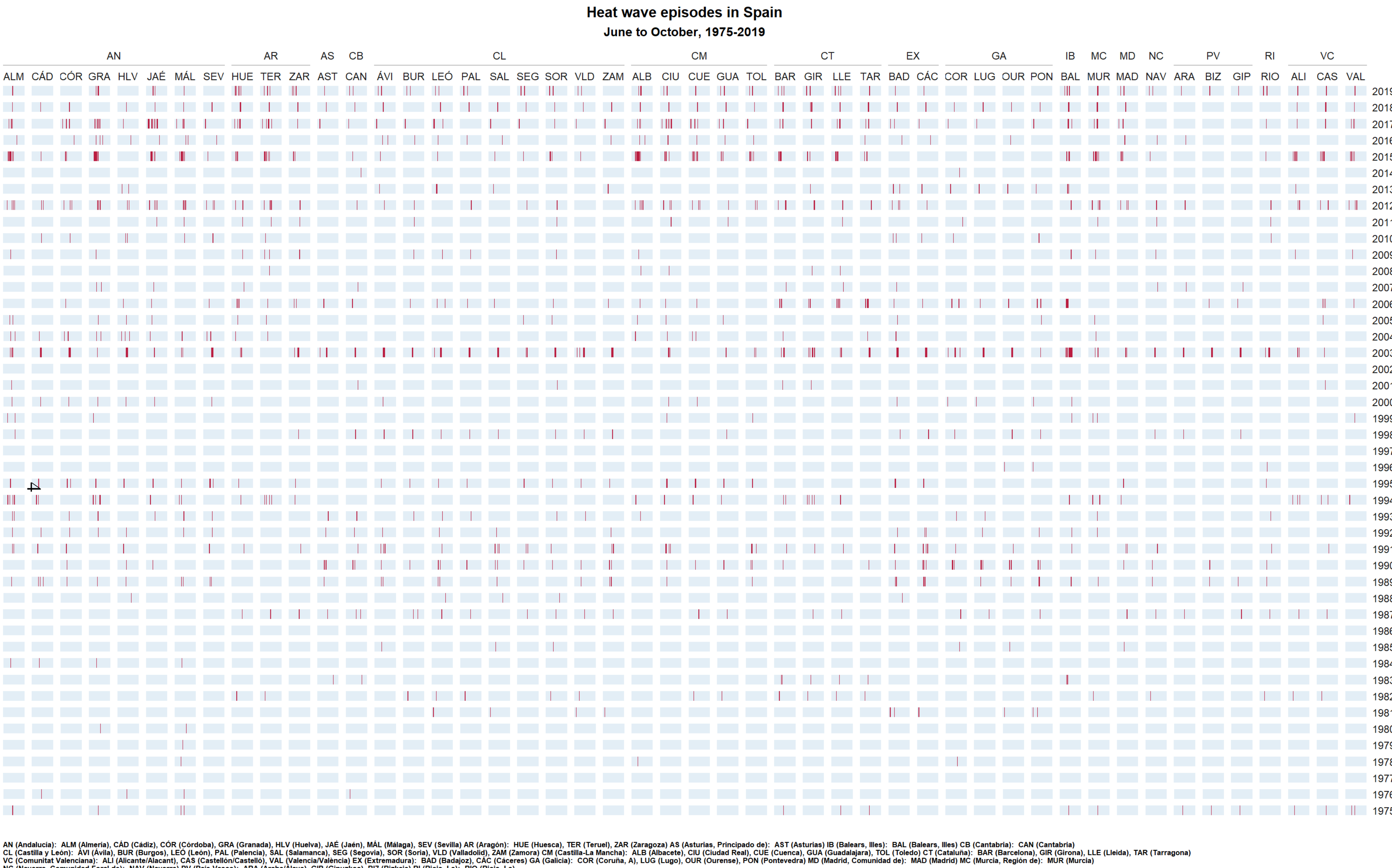

Figure 1: Heat wave episodes during extended summer periods registered in each province according to the custom criteria, by year.

References

L. V. Alexander, X. Zhang, T. C. Peterson, J. Caesar, B. Gleason, A. M. G. Klein Tank, M. Haylock, D. Collins, B. Trewin, F. Rahimzadeh, A. Tagipour, K. Rupa Kumar, J. Revadekar, G. Griffiths, L. Vincent, D. B. Stephenson, J. Burn, E. Aguilar, M. Brunet, M. Taylor, M. New, P. Zhai, M. Rusticucci, and J. L. Vazquez-Aguirre. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research: Atmospheres*, 111(D5), 2006. doi:https://doi.org/10.1029/2005JD006290. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2005JD006290.

P. Amblar Francés, M. J. Casado Calle, A. Pastor Saavedra, P. Ramos Calzado, and E. Rodríguez Camino. *Guía de escenarios regionalizados de cambio climático sobre España a partir de los resultados del IPCC-AR5*. Agencia Estatal de Meteorología, 2017. doi:10.31978/014-17-010-8. URL http://www.aemet.es/es/conocermas/recursos_en_linea/publicaciones_y_estudios/publicaciones/detalles/Guia_escenarios_AR5.

D. Barriopedro, R. García-Herrera, C. Ordóñez, D. G. Miralles, and S. Salcedo-Sanz. Heat waves: Physical understanding and scientific challenges. *Reviews of Geophysics*, 61(2):e2022RG000780, 2023. doi:https://doi.org/10.1029/2022RG000780. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2022RG000780. e2022RG000780 2022RG000780.

K. Bhaskaran, A. Gasparrini, S. Hajat, L. Smeeth, and B. Armstrong. Time series regression studies in environmental epidemiology. 42(4):1187–1195. ISSN 0300-5771. doi:10.1093/ije/dyt092. URL https://doi.org/10.1093/ije/dyt092.

M. deCastro, M. Gomez-Gesteira, A. M. Ramos, I. Álvarez, and P. deCastro. Effects of heat waves on human mortality, Galicia, Spain. *Climate Research*, 48(2-3): 333–341, Aug. 2011. ISSN 0936-577X, 1616-1572. doi:10.3354/cr00988. URL https://www.int-res.com/abstracts/cr/v48/n2-3/p333-341/.

A. Gasparrini and B. Armstrong. The Impact of Heat Waves on Mortality. *Epidemiology*, 22(1), 2011. ISSN 1044-3983. URL https://journals.lww.com/epidem/fulltext/2011/01000/the_impact_of_heat_waves_on_mortality.11.aspx.

A. Gasparrini, B. Armstrong, and M. G. Kenward. Distributed lag non-linear models. *Statistics in Medicine*, 29(21):2224–2234, 2010. ISSN 1097-0258. doi:10.1002/sim.3940. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/sim.3940. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/sim.3940.

A. Gasparrini, Y. Guo, M. Hashizume, E. Lavigne, A. Zanobetti, J. Schwartz, A. Tobias, S. Tong, J. Rocklöv, B. Forsberg, M. Leone, M. De Sario, M. L. Bell, Y.-L. L. Guo, C.-f. Wu, H. Kan, S.-M. Yi, M. de Sousa Zanotti Stagliorio Coelho, P. H. N. Saldiva, Y. Honda, H. Kim, and B. Armstrong. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet (London, England)*, 386(9991):369–375, July 2015. ISSN 1474-547X. doi:10.1016/S0140-6736(14)62114-0.

Y. Guo, A. Gasparrini, B. Armstrong, S. Li, B. Tawatsupa, A. Tobias, E. Lavigne, M. de Sousa Zanotti Stagliorio Coelho, M. Leone, X. Pan, S. Tong, L. Tian, H. Kim, M. Hashizume, Y. Honda, Y.-L. L. Guo, C.-F. Wu, K. Punnasiri, S.-M. Yi, P. Michelozzi, P. H. N. Saldiva, and G. Williams. Global variation in the effects of ambient temperature on mortality: a systematic evaluation. *Epidemiology (Cambridge, Mass.)*, 25(6):781–789, Nov. 2014. ISSN 1531-5487. doi:10.1097/EDE.0000000000000165.

H. Hersbach, B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. De Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R. J. Hogan, E. Hólm, M. Janisková, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. de Rosnay, I. Rozum, F. Vamborg, S. Villaume, and J.-N. Thépaut. The era5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730):1999–2049, 2020. doi:https://doi.org/10.1002/qj.3803. URL https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.3803.

IPCC. Sixth assessment report (ar6) of the intergovernmental panel on climate change, 2021. URL https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/.

C. Iñiguez, D. Royé, and A. Tobías. Contrasting patterns of temperature related mortality and hospitalization by cardiovascular and respiratory diseases in 52 Spanish cities. *Environmental Research*, 192:110191, Jan. 2021. ISSN 0013-9351. doi:10.1016/j.envres.2020.110191. URL https://www.sciencedirect.com/science/article/pii/S0013935120310884.

C. Linares, J. Diaz, A. Tobías, R. Carmona, and I. J. Mirón. Impact of heat and cold waves on circulatory-cause and respiratory-cause mortality in Spain: 1975–2008. *Stochastic Environmental Research and Risk Assessment*, 29(8): 2037–2046, Dec. 2015. ISSN 1436-3259. doi:10.1007/s00477-014-0976-2. URL https://doi.org/10.1007/s00477-014-0976-2.

I. J. Miron, C. Linares, J. C. Montero, J. J. Criado-Alvarez, and J. Díaz. Changes in cause-specific mortality during heat waves in central Spain, 1975–2008. *International Journal of Biometeorology*, 59(9):1213–1222, Sept. 2015. ISSN 1432-1254. doi:10.1007/s00484-014-0933-2. URL https://doi.org/10.1007/s00484-014-0933-2.

T. R. Oke, G. T. Johnson, D. G. Steyn, and I. D. Watson. Simulation of surface urban heat islands under 'ideal' conditions at night part 2: Diagnosis of causation. *Boundary-Layer Meteorology*, 56(4):339–358, Sep 1991. ISSN 1573-1472. doi:10.1007/BF00119211. URL https://doi.org/10.1007/BF00119211.

X. Song, S. Wang, Y. Hu, M. Yue, T. Zhang, Y. Liu, J. Tian, and K. Shang. Impact of ambient temperature on morbidity and mortality: An overview of reviews. *Science of The Total Environment*, 586:241–254, May 2017. ISSN 0048-9697. doi:10.1016/j.scitotenv.2017.01.212. URL https://www.sciencedirect.com/science/article/pii/S0048969717302292.

A. Tobías, M. Hashizume, Y. Honda, F. Sera, C. F. S. Ng, Y. Kim, D. Roye, Y. Chung, T. N. Dang, H. Kim, W. Lee, C. Íñiguez, A. Vicedo-Cabrera, R. Abrutzky, Y. Guo, S. Tong, M. d. S. Z. S. Coelho, P. H. N. Saldiva, E. Lavigne, P. M. Correa, N. V. Ortega, H. Kan, S. Osorio, J. Kyselý, A. Urban, H. Orru, E. Indermitte, J. J. K. Jaakkola, N. R. I. Ryti, M. Pascal, V. Huber, A. Schneider, K. Katsouyanni, A. Analitis, A. Entezari, F. Mayvaneh, P. Goodman, A. Zeka, P. Michelozzi, F. de'Donato, B. Alahmad, M. H. Diaz, C. De la Cruz Valencia, A. Overcenco, D. Houthuijs, C. Ameling, S. Rao, F. Di Ruscio, G. Carrasco, X. Seposo, B. Nunes, J. Madureira, I.-H. Holobaca, N. Scovronick, F. Acquaotta, B. Forsberg, C. Åström, M. S. Ragettli, Y.-L. L. Guo, B.-Y. Chen, S. Li, V. Colistro, A. Zanobetti, J. Schwartz, D. V. Dung, B. Armstrong, and A. Gasparrini. Geographical Variations of the Minimum Mortality Temperature at a Global Scale: A Multicountry Study. *Environmental Epidemiology (Philadelphia, Pa.)*, 5(5):e169, Oct. 2021. ISSN 2474-7882. doi:10.1097/EE9.0000000000000169.

J. H. Uhl, D. Royé, K. Burghardt, J. A. Aldrey Vázquez, M. Borobio Sanchiz, and S. Leyk. HISDAC-ES: historical settlement data compilation for Spain (1900–2020). *Earth System Science Data*, 15(10):4713–4747, Oct. 2023. ISSN 1866-3508. doi:10.5194/essd-15-4713-2023. URL https://essd.copernicus.org/articles/15/4713/2023/. Publisher: Copernicus GmbH.

A. M. Vicedo-Cabrera, Y. Guo, F. Sera, V. Huber, C.-F. Schleussner, D. Mitchell, S. Tong, M. d. S. Z. S. Coelho, P. H. N. Saldiva, E. Lavigne, P. M. Correa, N. V. Ortega, H. Kan, S. Osorio, J. Kyselý, A. Urban, J. J. K. Jaakkola, N. R. I. Ryti, M. Pascal, P. G. Goodman, A. Zeka, P. Michelozzi, M. Scortichini, M. Hashizume, Y. Honda, M. Hurtado-Diaz, J. Cruz, X. Seposo, H. Kim, A. Tobias, C. Íñiguez, B. Forsberg, D. O. Åström, M. S. Ragettli, M. Röösli, Y. L. Guo, C.-f. Wu, A. Zanobetti, J. Schwartz, M. L. Bell, T. N. Dang, D. Do Van, C. Heaviside, S. Vardoulakis, S. Hajat, A. Haines, B. Armstrong, K. L. Ebi, and A. Gasparrini. Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios. 150(3):391–402. ISSN 1573-1480. doi:10.1007/s10584-018-2274-3. URL https://doi.org/10.1007/s10584-018-2274-3.