Spatiotemporal assessment of heat-related infant mortality in Catalonia, Spain (2012-2022)

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Davis Solano [1], Marta Solans [1], Xavier Perafita [1,3], Manuel A. Moreno [1,2,4], Pablo Juan [5,1], Marc Saez [1,2], Maria A. Barceló [1,2]

[1] Research Group on Statistics, Econometrics and Health (GRECS), University of Girona, Girona, Spain david.solano@udg.edu
[2] CIBER of Epidemiology and Public Health (CIBERESP), Madrid, Spain
[3] Observatori-Organisme Autònom de Salut Pública de la Diputació de Girona (Dipsalut), Girona, Spain
[4] Institut Català de la Salut. Gerència d'Atenció Primària i a la Comunitat de la Catalunya Central, Unitat de Recerca i Innovació, Manresa, Spain
[5] Instituto Universitario de Investigación en Matemáticas (IMAC), University Jaume I, Castelló, Spain

Background

- **Infant** (aged <1 year) vulnerability to extreme heat remains understudied, particularly in **fine-scale geographic** analyses.
- This study aims to evaluate the association between heat exposure and infant mortality by **basic health area (ABS) in Catalonia**, Spain, from **2012 to 2022** using a novel **spatio-temporal Bayesian** approach.

Methods

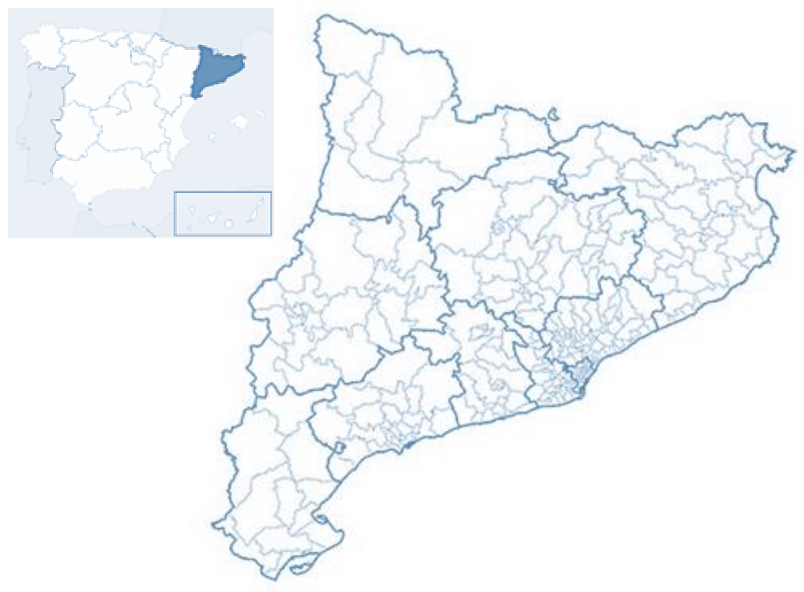

Figure 1. Catalan basic health areas (ABS).

- We conducted a **time-series ecological study** using data on daily infant deaths from June to September, aggregated by 379 Catalan ABS (**Figure 1**) over the period 2012-2022.
- A Bayesian spatiotemporal model was used to **predict daily meteorological and pollution exposures** at the ABS level [1].
- An **extreme heat** indicator was coded as 1 when the maximum temperature exceeded the trigger temperature (95th percentile of daily maximum temperature distribution for 2012-2021), and 0 otherwise. A **heatwave indicator** was defined as 1 when there were three or more consecutive days with extreme maximum temperatures recorded in at least 10% of the meteorological stations, and 0 otherwise.

- We estimated two binomial generalised linear mixed models (GLMMs), one for extreme temperature and the other for heat waves, both stratified for total infant mortality, neonatal mortality, and postnatal mortality:

$$\log(\theta'_{it}) = \gamma_0 + \gamma_1 Extreme\ heat_{i,t-l} + \gamma_2 Q4relative\_humidity_{i,t-1} + \sum_{k=2}^{3}\gamma_{3k}PM_{10,t-1} + \sum_{k=2}^{3}\gamma_{4k}NO_{2,t-1} + \sum_{k=2}^{4}\gamma_{5k}O_{3,t-1} + \sum_{k=2}^{4}\gamma_{6k}\,QIncome_{k,it} + \eta_i + S(ABS_i) + \tau_{it} + \tau_{its} + offset(\log(Population_i))$$

Where:

- θ'_{it} was the conditional risk of a death in the ABS i on day t, during the months June to September;
- extreme heat or heat wave were included with lag t (t-1), based on model fit criteria and previous literature;
- PM_{10}, NO_2 and O_3 indicated the level of concentration of air pollutants (in categories) in ABS i on day t;
- *Q4relative_humidity* was an indicator which took the value 1 if the relative humidity on day t in ABS i exceeded the fourth quartile of the relative humidity distribution in the period 2012-2022 (specific for each ABS);
- *QIncome* was an indicator of the quartile of average net income per person in which the ABS i was located;
- η_i was an unstructured random effect; τ_t and τ_{ts} structured random effects capturing trend and annual seasonality; S() structured random effects controlling spatial dependence;
- and Population denoted the population of the ABS i.

- We allowed interactions between extreme heat/heat wave and high relative humidity or air pollutants.
- Inferences were made following a Bayesian perspective, using the INLA approach[2,3] with PC priors [4]. Given the low number of daily deaths by ABS, we considered as statistically significant those relative ratios (RR) in which the 90% credible interval (CI) did not include de unit.

Results

- 1,830 infant deaths (**592 in the warm season**) were recorded in the period study, 68% of them occurring during the first month of life (i.e. neonatal mortality). Leading causes included congenital malformations (n=394), perinatal cardiorespiratory conditions (n=357), and sudden infant death syndrome (n=123). This distribution was similar among those deaths that occurred from June to September.
- Extreme heat on the previous day (lag 1) was associated with a decreased risk of overall infant mortality (**Table 1A**). However, we evidenced an **interaction with moderate O_3 levels (60–99.9 µg/m^3), which increased the risk of neonatal mortality** (RR: 3.13; 95% CI: 0.76; 28.86). This pattern was observed for prenatal mortality, while no clear associations were found for postnatal mortality. By contrast, there was no evidence of an increased risk of death after heatwaves (lag 1) (**Table 1B**).

Conclusions

- Our analytical framework advances current methodologies by generating **high-resolution temperature predictions** at the ABS level while accounting for humidity, air pollution, and area-level deprivation.
- The results demonstrate **spatial variability** in heat-related infant mortality risk and relevant **interactions with O_3** that should be accounted for in further infant mortality studies.

References

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Table 1. Relative risk of total infant mortality, prenatal mortality, and postnatal mortality one day after (lag 1) A) extreme heat and B) heatwave.

	A. Total infant mortality (n=592) RR (95% CI)	Probs	A. Neonatal mortality (n=416) RR (95% CI)	Probs	A. Postneonatal mortality (n=176) RR (95% CI)	Probs	B. Total infant mortality (n=592) RR (95% CI)	Probs	B. Neonatal mortality (n=416) RR (95% CI)	Probs	B. Postneonatal mortality (n=176) RR (95% CI)	Probs
Extreme heat $_{(t-1)}$ or Heat wave $_{(t-1)}$	0.19 (0.01; 0.95)	0.98	0.05 (0.00; 0.70)	0.99	0.29 (0.03; 3.22)	0.84	0.02 (0.00; 1.46)	0.96	0.05 (0.00; 2.37)	0.92	0.00 (0.00; 1.9E+09)	0.69
$O_{3\ (t-1)}$												
<60.0 µg/m^3	Ref	-	Ref	-			Ref	-	Ref	-	Ref	-
60.0 µg/m^3 – 99.9 µg/m^3	1.07 (0.73; 1.37)	0.76	1.01 (0.52; 1.38)	0.67	0.47 (0.06; 1.55)	0.69	1.09 (0.73; 1.37)	0.81	1.07 (0.56; 1.41)	0.77	0.99 (0.26; 1.48)	0.44
100.0 µg/m^3 – 119.9 µg/m^3	1.08 (0.50; 2.35)	0.58	1.04 (0.41; 2.65)	0.53	0.77 (0.16; 4.46)	0.65	1.12 (0.51; 2.45)	0.61	1.03 (0.41; 2.63)	0.53	1.11 (0.30; 3.86)	0.57
≥ 120.0 µg/m^3	1.15 (0.23; 5.60)	0.57	2.27 (0.40; 17.26)	0.81	0 (0.00; 4.4E+04)	0.93	1.25 (0.25; 6.16)	0.61	2.02 (0.40; 10.60)	0.80	0.00 (0.00; 7.6E+08)	0.68
$NO_{2\ (t-1)}$												
<10.0 µg/m^3	Ref	-	Ref	-			Ref	-	Ref	-	Ref	-
10.0 µg/m^3 – 24.9 µg/m^3	1.03 (0.75; 1.32)	0.62	1.01 (0.28; 1.53)	0.76	0.61 (0.17; 1.46)	0.84	0.96 (0.39; 1.29)	0.40	1.12 (0.49; 1.56)	0.87	0.77 (0.36; 1.14)	0.89
≥ 25.0 µg/m^3	1.32 (0.95; 1.82)	0.95	1.73 (1.18; 2.74)	1.00	0.84 (0.22; 2.32)	0.63	1.32 (0:97; 1.81)	0.96	1.65 (0.95; 2.38)	0.97	0.79(0.45; 1.60)	0.81
$PM_{10\ (t-1)}$												
<15.0 µg/m^3	Ref	-	Ref	-			Ref	-	Ref	-	Ref	-
15.0 µg/m^3 – 53.9 µg/m^3	0.89 (0.65; 1.11)	0.83	0.73 (0.17; 1.11)	0.86	0.60 (0.16; 1.29)	0.77	0.85 (0.40; 1.10)	0.86	0.82 (0.34; 1.11)	0.85	0.94 (0.65; 1.38)	0.63
≥ 54 µg/m^3	0.53 (0.11; 2.43)	0.79	0.31 (0.04; 2.57)	0.86	0.99 (0.09; 11.68)	0.50	0.55 (0.12; 2.51)	0.78	0.32 (0.04; 2.66)	0.85	1.40 (0.18; 11.28)	0.62
Q4 relative humidity $_{(t-1)}$												
No	Ref	-	Ref	-			Ref	-	Ref	-	Ref	-
Yes	0.91 (0.50; 1.24)	0.69	0.72 (0.13; 1.23)	0.78	0.50 (0.06; 1.76)	0.70	0.93 (0.55; 1.26)	0.63	0.88 (0.50; 1.25)	0.73	1.00 (0.52; 1.58)	0.47
Average net income per person												
<11.490.7€	Ref	-	Ref	-			Ref	-	Ref	-	Ref	-
11.490.7 € - 12.893.5 €	0.54 (0.29; 0.84)	1.00	0.88 (0.28; 13.58)	0.83	0.57 (0.00; 2.08)	0.73	0.60 (0.38; 1.27)	0.95	0.77 (0.39; 10.73)	0.90	0.68 (0.42; 1.11)	0.81
12.893.6 € - 14.650.2 €	0.54 (0.15; 0.86)	1.00	0.38 (0.02; 0.96)	0.99	0.96 (0.07; 156.44)	0.65	0.51 (0.07; 0.84)	1.00	0.70 (0.42; 1.95)	0.89	0.75 (0.33; 42.49)	0.87
>14.650.2 €	0.42 (0.21; 0.65)	1.00	0.43 (0.07; 0.77)	1.00	0.27 (0.03; 2.07)	0.94	0.37 (0.07; 0.62)	1.00	0.56 (0.33; 3.50)	0.90	0.55 (0.25; 33.55)	0.86
Extreme heat: $O_{3\ (t-1)}$												
<60.0 µg/m^3	Ref	-	Ref	-			Ref	-	Ref	-	Ref	-
60.0 µg/m^3 – 99.9 µg/m^3	3.13 (0.76; 28.86)	0.93	6.04 (0.76; 526.69)	0.94	0.59 (0.01; 47.40)	0.53	7.28 (0.15; 8.7E+04)	0.78	1.07 (0.56; 1.41)	0.77	0.06 (0.00; 1.6E+18)	0.55
100.0 µg/m^3 – 119.9 µg/m^3	0.00 (0.00; 5.4E+08)	0.73	0.00 (0.00; 7.8E+09)	0.69	0.00 (0.00; 3.4E+05)	0.91	0.00 (0.00; 1.1E+11)	0.63	1.03 (0.41; 2.63)	0.53	0.06 (0.00; 1.2E+22)	0.54
≥ 120.0 µg/m^3	0.00 (0.00; 9.3E+10)	0.69	0.00 (0.00; 6.6E+11)	0.65	0.00 (0.00; 2.2E+19)	0.68	0.01 (0.00; 5.6E+11)	0.61	2.02 (0.40; 10.60)	0.80	0.65 (0.00; 5.7E+26)	0.51
Extreme heat: $NO_{2\ (t-1)}$												
<10.0 µg/m^3	Ref	-	Ref	-			Ref	-	Ref	-	Ref	-
10.0 µg/m^3 – 24.9 µg/m^3	0.44 (0.06; 1.65)	0.88	1.10 (0.26; 4.84)	0.55	0.00 (0.00; 1.0E+03)	0.94	0.04 (0.00; 2.35)	0.93	1.12 (0.49; 1.56)	0.87	0.05 (0.00; 1.7E+18)	0.55
≥ 25.0 µg/m^3	0.33 (0.05; 1.95)	0.89	0.80 (0.11; 6.31)	0.59	0.00 (0.00; 1.2E+04)	0.93	0.00 (0.00; 7.9E+06)	0.74	1.65 (0.95; 2.38)	0.97	0.05 (0.00; 2.4E+20)	0.54
Extreme heat: $PM_{10\ (t-1)}$												
<15.0 µg/m^3	Ref	-	Ref	-			Ref	-	Ref	-	Ref	-
15.0 µg/m^3 – 53.9 µg/m^3	1.62 (0.47; 8.36)	0.76	2.74 (0.54; 38.09)	0.86	0.79 (0.04; 19.60)	0.57	9.22 (0.29; 2846.86)	0.88	8.85 (0.30; 5232.77)	0.88	0.05 (0.00; 3.7E+18)	0.55
≥ 54 µg/m^3	0.00 (0.00; 1.1E+10)	0.70	0.00 (0.00; 2.3+E11)	0.66	0.00 (0.00; 2.4E+14)	0.82	0.02 (0.00; 7.4E+17)	0.56	0.02 (0.00; 5.8E+18)	0.55	0.02 (0.00; 1.3E+25)	0.54
Extreme heat:Q4 relative humidity $_{(t-1)}$												
No	Ref	-	Ref	-			Ref	-	Ref	-	Ref	-
Yes	0.00 (0.00; 1.7E+24)	0.64	0.00 (0.00; 5.4E+24)	0.60	0.00 (0.00; 5.2E+14)	0.90	0 (0.00; 1.8E+26)	0.55	0.00 (0.00; 1.2E+26)	0.54	0.00 (0.00; 2.5E+26)	0.54

CI, credible interval; ref, reference category; RR, relative risk; Probs = Prob(|log(RR)|)>0 // Also adjusted for individual heterogeneity (ABS); seasonality (month); trend (year); and spatial dependence, with ABS population as an offset. Shaded in yellow, the 90% credible interval does not contain the unit.; Shaded in grey, the 95% credible interval does not contain the unit

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