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Greening mitigates heat-related mortality in Paris

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Cities are vulnerable to heat-related health impacts due to the compounding effects of urban heat island (UHI) and rising temperatures because of climate change. Here we characterise the contextual factors exacerbating and attenuating the risk of mortality associated with high temperature in the city of Paris. Findings suggest that reducing urban heat and mitigating UHI through urban greening should be at the forefront of adaptation strategies to prevent heat-related health impacts in cities.

Cities experience higher temperatures than the surrounding rural areas, a phenomenon commonly known as "urban heat island" (UHI), which is most pronounced at night, when the heat energy stored by urban materials throughout the day is slowly released into the atmosphere[1]. As the global temperatures rise, urban areas are becoming even hotter due to the compounding effects of UHI and climate warming, which, in conjunction with simultaneous processes of urbanisation and population ageing, represent a major challenge for public health[2]. This situation is especially noticeable in some regions such as Europe, where over four percent of deaths in cities during the summer season are attributable to UHI[3], a proportion that is expected to grow in the future in absence of mitigation actions.

Research conducted in various European countries in recent years has documented a higher heat-related mortality in urban areas compared to rural areas[4–6], with overexposure to heat (i.e., UHI) and air pollution being the potential drivers of this rural-urban gap in susceptibility to high temperatures in France[7]. However, the intra-urban variation in the mortality risk from heat and, particularly, the contextual factors accounting for it have been poorly studied thus far, presumably due to challenges in obtaining high resolution (i.e., within-city) data on health, exposure and area-level characteristics. The scarce literature available to date is conflicting on the role of socioeconomic variables in shaping the heat–mortality association within the city, while it is consistent with regard to the benefits of the natural environment (e.g., vegetation)[8–10]. Nonetheless, existing evidence can be expanded by analysing a wider range of contextual characteristics potentially linked with disparities in vulnerability to heat, such as those relating to health and socioeconomic status, natural environment, and built environment.

In this Brief Communication, we aimed to characterise the contextual factors exacerbating and attenuating the risk of mortality associated with high temperature in Paris and, in this way, inform strategies for building climate resilience in cities. The City of Light represents a unique case study because it is one of the European cities with the highest population density (around 21,000 inhabitants per km^2 between 2008 and 2018), summer UHI intensity (>2 °C [90th percentile])[11] and socioeconomic inequalities[12]. Former investigations of this kind in France were conducted at the municipal or city level and analysed a limited number of contextual factors as effect modifiers of the heat–mortality association[13,14].

During the warm season (June–September) of the study period covering 2008–2017, Paris recorded 43 141 deaths out of an average population of 2.2 million inhabitants, making a crude mortality rate of 19.5 per 10 000 people. On average, the daily number of deaths was 35.4 (inter-district range 0.2–3.9), while the daily exposure to population-weighted mean (Tmean), minimum (Tmin) and maximum (Tmax) temperature from the urban climate model UrbClim[15] was respectively 21.17 °C (range 20.78–21.39), 18.02 °C (range 17.55–18.27) and 24.23 °C (range 23.91–24.42). The difference between the highest and lowest value recorded for the contextual indicators revealed huge differences in environmental and socioeconomic conditions across the city (Table 1). For instance, the life expectancy at birth ranged from 82.8 years to 87.2 years; the median income by consumption unit from 17,307€ to 43,290€; the residential density from 155 people per hectare to 556 people per hectare; and the population-weighted percentage of vegetation surface from 1.4% to 20.4%. Moreover, many area-level variables exhibited a clear spatial pattern, with values increasing (e.g., age-standardised mortality rate, unemployment rate, proportion of people without primary education) or decreasing (e.g., life expectancy, median income, percentage of votes for the right) from West to East of the city (Supplementary Fig. 1).

The Pearson correlation coefficient (r) measuring the relationship between the 25 contextual variables included in the analysis is displayed in Supplementary Fig. 2. The Paris districts with a higher potential to develop a high intensity daytime UHI had less urban vegetation (r = −0.65) (Fig. 1), lower age-standardised mortality rate (r = −0.75), diminished percentage of people without primary education (r = −0.74), and reduced unemployment rate (r = −0.69). Moreover, those same districts had more impervious surfaces (r = +0.61), increased life expectancy (r = +0.77), more houses constructed before 1971 (r = +0.83), and higher income (r = +0.77) and

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Table 1 | Summary statistics for contextual indicators

Indicator	Min.	Q1	Median	Mean	Q3	Max.
Temperature						
Mean temperature (°C)[a]	20.78	21.04	21.19	21.17	21.29	21.39
Minimum temperature (°C)[a]	17.55	17.87	18.05	18.02	18.17	18.27
Maximum temperature (°C)[a]	23.91	24.14	24.25	24.23	24.33	24.42
Health status						
Age-standardised mortality rate (per 100,000)	485	568	611	609	662	707
Life expectancy at age 65 (years)	82.8	83.7	84.8	84.8	85.4	87.2
Population ageing						
People over 64 years (%)	9.9	13.5	16.1	15.8	17.0	21.8
Social isolation						
People over 64 years living alone (%)	38.9	43.3	46.2	45.3	47.3	52.0
Education						
People over 24 years without primary education (%)	6.1	7.8	8.9	10.0	11.0	18.0
Socioeconomic conditions						
Median income by consumption unit (€)	17,307	24,935	30,114	29,792	32,780	43,290
GINI index of income	0.40	0.43	0.46	0.48	0.51	0.59
Households with 2 or more cars (%)	2.1	2.9	3.9	4.7	5.1	12.9
Unemployment rate (%)	6.3	7.2	8.2	8.3	9.1	11.9
Housing characteristics						
Houses built before 1971 (%)	48.7	66.9	82.5	77.4	89.0	91.2
Houses with energy performance certificate E-G (%)	51.7	55.8	58.2	58.3	61.5	65.3
Energy consumption						
Electricity, gas and district heating (kWh/person)	3808	4598	5412	6405	6839	16,112
Voting behaviour						
Votes for the right (%)	31.5	37.0	45.9	49.0	59.2	77.8
Population density						
Residential density (people/hectare)	155	286	346	349	436	556
Human density (people/hectare)	376	715	828	849	922	1514
Building characteristics						
Average building height (m)[a]	16.9	18.1	18.7	18.9	19.4	22.1
Urban vegetation						
High vegetation (%)[a]	0.7	3.5	5.7	6.3	9.7	12.7
Low vegetation (%)[a]	0.6	2.3	3.8	4.0	5.3	8.4
Vegetation (%)[a]	1.4	5.6	9.3	10.3	14.7	20.4
Urban imperviousness						
Impervious surface (%)[a]	53.9	59.6	66.9	66.5	72.0	84.1
Urban heat island (UHI)						
Potential for a high daytime UHI (unitless)[a]	5.77	6.15	6.53	6.47	6.84	6.96
Potential for a high nighttime UHI (unitless)[a]	7.04	7.18	7.35	7.35	7.51	7.72

The indicators are computed for the 20 districts of Paris.
[a]Indicators weighted by the number of residents in urban islands (UI).

GINI index of income (r = +0.78). In short, high socioeconomic status was positively correlated with exposure to UHI and impervious surfaces, and negatively correlated with exposure to urban vegetation.

Supplementary Fig. 3 depicts the average daily association between Tmean and all-cause mortality (cumulated within lag 0–1) for Paris, which indicates a monotonically increasing relative risk (RR) of mortality for temperatures above the minimum mortality temperature (MMT). The percentage change in risk (%CR) of mortality at the 99th percentile of daily distribution of Tmean (30.78 °C), Tmin (26.10 °C) and Tmax (35.56 °C), was respectively 23.4% (95% CI: 14.8–32.6), 21.1% (12.6–30.3) and 22.8% (14.4–31.8).

The effect of heat on mortality was modified by several district-level characteristics as it can be seen in Fig. 2. On the one hand, it was negatively associated with the share of urban vegetation (especially high vegetation [i.e., trees]) and the average building height, which are two uncorrelated variables (Supplementary Fig. 2). For example, the %CR of mortality at the 99th Tmean percentile between the minimum and maximum observation of high vegetation was −23.5% (95% CI: −38.9 to −4.3). On the other hand, the mortality risk from heat was positively associated with daytime/nighttime UHI intensity, the share of impervious surface, GINI index of income, and the percentage of houses built before 1971 and with energy performance certificate E-G. Note that all these variables were negatively correlated with

Fig. 1 | Geographical relationship between vegetation rate and potential of developing a daytime UHI in Paris. The geographical correlation is shown at urban island level ($N = 9600$). Black outlines in the map represent the 20 districts of Paris.

urban vegetation (UHI, imperviousness, GINI index, houses built before 1971, houses in property, housing energy efficiency) and/or building height (i.e., housing energy efficiency) (Supplementary Fig. 2).

Some contextual variables, such as vegetation cover and the potential for a strong UHI effect, may influence the heat–mortality relationship through at least two distinct pathways. First, they can modify local thermal environments—for example, vegetation can lower ambient temperatures through shading and evapotranspiration, whereas areas with a strong UHI effect tend to experience higher night-time temperatures. Second, these factors may influence population vulnerability independently of temperature. Vegetation, for instance, can improve air quality[16] and promote physical and mental health[17], while UHI potential may reflect aspects of the built environment and socioeconomic conditions associated with differential adaptive capacity.

To disentangle which of these pathways our models capture, we conducted a sensitivity analysis to assess whether vegetation and UHI potential modify the heat–mortality association beyond indirect effects mediated through local temperature differences. We compared estimates derived from spatially resolved UrbClim model temperatures with those based on spatially uniform temperatures from the Paris–Montsouris meteorological station. Effect modification was only slightly stronger when using station-based temperatures (Supplementary Fig. 4), suggesting that UrbClim data capture much of the influence of vegetation and UHI potential on local thermal conditions. The consistency of results across both datasets (Supplementary Fig. 4) indicates that vegetation and UHI potential modify heat-related mortality through non-thermal pathways, independent of their effect on ambient temperature.

The results from this study contribute to identify the contextual factors modifying the effect of high-temperature exposure on mortality within Paris. We found that urban districts with higher vegetation and buildings had lower mortality risk from heat, while those with higher daytime/nighttime UHI, more impervious surfaces, older buildings, less housing energy efficiency and income inequality were at increased risk of mortality due to high temperature. Moreover, in contrast to the natural and built environment variables, demographic and socioeconomic characteristics played no significant role in vulnerability to heat-related mortality.

In line with former intra-city investigations[8–10,18], our study suggested a protective effect of urban vegetation against heat-related mortality. But, in addition to that, we identified the typology of vegetation contributing the most to mitigating heat impacts in order to maximise the health benefits and to inform cost-effective implementation. High vegetation (i.e., trees) seems to prevent more deaths from heat than low or short vegetation (e.g., lawn), although the difference is small and not statistically significant. Paris has set an ambitious and commendable plan to become one of Europe's greenest capitals by 2030. This initiative is part of the city's broader climate adaptation strategy, which includes planting 170,000 trees by 2026 and creating 300 hectares of additional green spaces[19]. Our results suggest the implementation of these actions to be beneficial for the health of the Parisians, but further action should be taken to tackle the inequalities in vegetation cover across the city, given the disparities between central districts or neighbourhoods and the others (Fig. 1). In a scenario in which all districts of Paris had had 20.4% of vegetation surface (the highest district value recorded for this variable), the number of deaths attributable to heat during the study period could have been reduced by 581 (31.6%) for Tmean above 22 °C, or by 356 (37.6%) for Tmean above 25 °C.

The UHI intensity exacerbates the susceptibility to heat-related mortality within Paris, a modifiable risk factor that is being intensified by rising temperatures associated with climate change[20]. Hence, UHI mitigation strategies such as increasing the vegetative cover (which cools down temperatures through shading and evapotranspiration)[21], incorporating solar-reflective materials (on walls, roofs and pavements)[22] and improving building energy efficiency (e.g., emitting less heat [most of which is from air conditioning use] to the environment)[23], are a pressing need to minimise the health risks posed by UHI. Furthermore, reducing car traffic in the city not only would mitigate UHI (i.e., less waste heat from cars, greater cumulative heat release from high traffic volumes)[24], but also reduce air pollution and thus save deaths due to high temperature, as prior studies found a greater impact of heat on mortality on highly polluted days[25].

This study had strengths and limitations. On the one hand, we used high quality health, temperature and contextual data, which allowed us to accurately characterise intra-urban heat-related mortality risk in Paris,

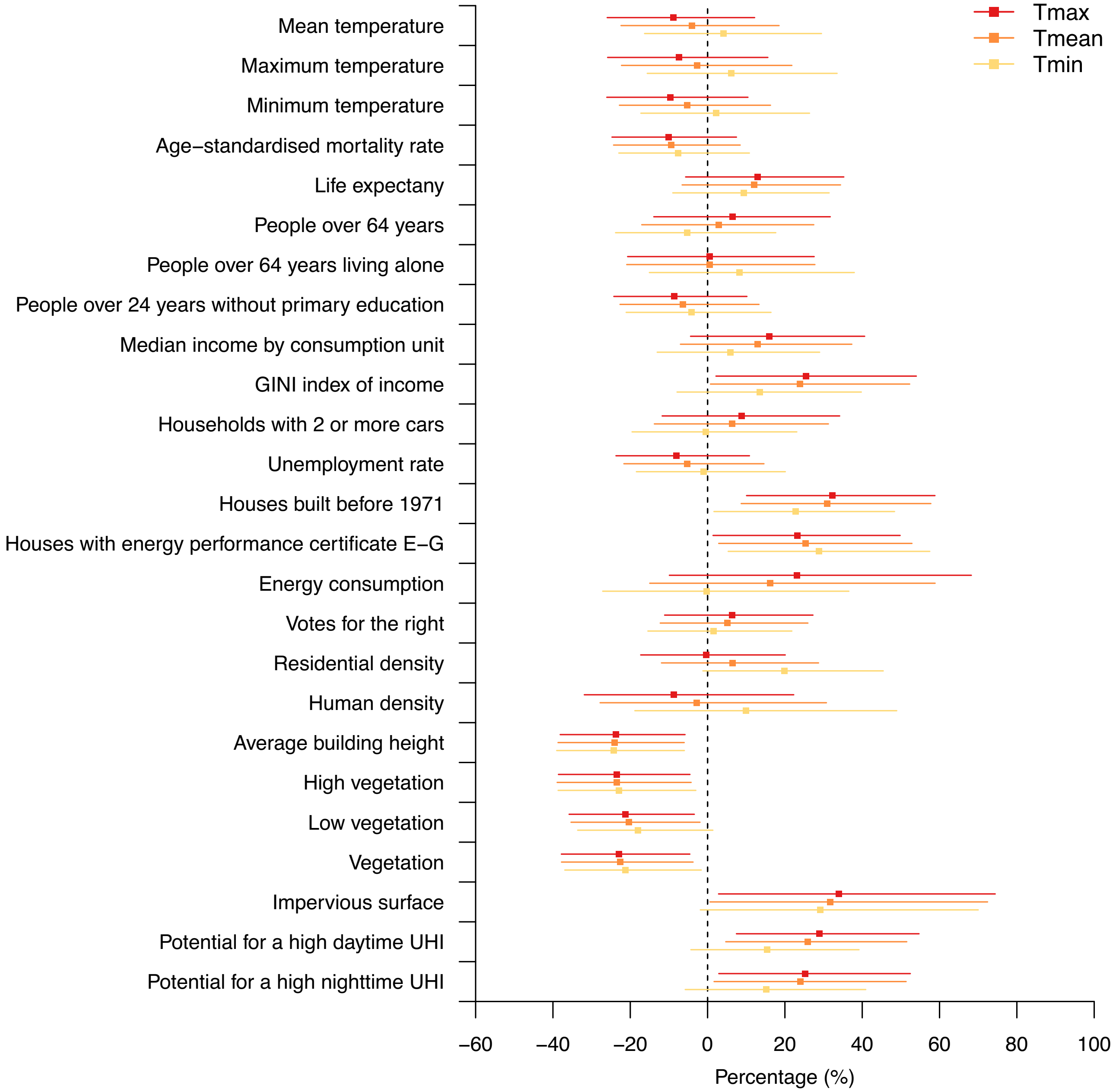

Fig. 2 | Variation in heat-related mortality risk by contextual factors. The figure represents the %CR of mortality at the 99th percentile of daily temperature (cumulated within lag 0–1) between the minimum and maximum observation for each contextual indicator. Error bars represent the 95% confidence interval. Numerical information is reported in Supplementary Table 2.

making use of the most advanced methods in environmental epidemiology. We also expanded the previous literature by assessing a wider range of contextual factors potentially explaining the spatial variation in vulnerability to high ambient temperatures within the city. On the other hand, although UrbClim model provides spatially resolved temperature data that may offer valuable insights into heterogeneous exposure-response associations[26,27], the modelled air temperatures are not exempted from biases as it has been shown in previous validation exercises[28]. Second, adjusting for confounding factors such as air pollution and humidity in the models may have provided more robust estimates of the effect of heat on mortality. Moreover, we did not examine the potential non-linear effects of community-level factors on heat-related risks, as this can be very complex and imprecise. Finally, the factors modifying the health effects of heat might not act in isolation as analysed in this study, but rather there might be complex associations and causal pathways requiring further investigation.

In conclusion, this study suggests that reducing urban heat and mitigating UHI through urban greening should be at the forefront of adaptation strategies to prevent heat-related health impacts in cities.

Methods

Data sources

We collected data on mortality, temperature and contextual factors across the 20 *arrondissements* (or districts) of the city of Paris. Individual mortality records with identifier of district of residence and date of death were provided by the Epidemiology Centre on Medical Causes of Death (CépiDc) of the National Institute of Health and Medical Research (Inserm), and then aggregated as district-specific daily series of all-cause mortality counts. Hourly air temperature values on 100 m × 100 m grid cells for a 10-year period (2008–2017) were extracted from the urban climate model UrbClim[15], and then we derived the corresponding district-specific daily (mean, minimum and maximum) temperature series as follows: we first computed the area-weighted average of the temperature values of the grid cells intersecting the 9600 urban islands of Paris (see Fig. 1), with weights proportional to the intersection areas, and then we calculated the average temperature in each district weighting by the number of residents in urban islands. Lastly, a set of 25 contextual indicators potentially linked with differential vulnerability to heat was computed for Paris districts (Table 1). Those contextual variables included measures of temperature exposure, health, population ageing, social isolation, education, socioeconomic conditions, housing characteristics, energy consumption, voting behaviour, and urban morphology. Details on data sources and a description of contextual indicators are provided in the Supplementary Table 1.

Statistical analysis

The statistical analysis was restricted to the summer season (June–September) over the period 2008–2017. Following the case time series (CTS) design for small-area analysis[29], we assessed the mortality risks associated with daily summer temperatures through a conditional quasi-Poisson regression. The CTS model included: (i) intercepts defined by district-year-month strata indicators allowing within-district variation in baseline risks, (ii) a categorical variable of day of the week to account for intra-weekly variation in mortality, (iii) a natural cubic B-spline of day of the season with 4 degrees of freedom in interaction with year indicator to control for the seasonal trend, and (iv) a cross-basis function produced by distributed lag non-linear models (DLNM)[30] to describe the non-linear and delayed effects of temperature on mortality. The exposure-response function (ERF) of the cross-basis was modelled through a natural cubic B-spline with one internal knot placed at the 90th percentile of the daily summer temperature distribution, whereas the lag-response function (LRF) was modelled with an integer function of 0-1.

To assess how vulnerability to high temperatures varies according to district-level characteristics, we extended the baseline model by introducing a linear interaction between the temperature cross-basis and each contextual variable in turn (Table 1). Because the study uses a self-matched design with district-specific intercepts, all time-invariant differences across districts are inherently controlled by design. As a result, the main effects of time-invariant contextual variables cannot be separately estimated, as they are absorbed by the fixed intercepts. However, their interactions with the time-varying exposure (daily temperature) remain identifiable and can therefore be used to assess effect modification. For the same reason, multiple time-invariant contextual variables cannot be mutually adjusted within the same interaction model. Each contextual variable was therefore analysed in a separate model to evaluate its modification of the temperature–mortality association.

Next, we used the interaction model to predict the relative risk (RR) of mortality associated with summer temperatures (i.e., temperature-mortality curves) and related 95% confidence interval (CI) for the maximum and minimum value of the contextual variables, using the minimum mortality temperature (MMT) as a reference. Lastly, we took the RR of mortality at the 99th temperature percentile from the two predicted temperature-mortality curves and calculated the ratio between both RR, which was then transformed into a percentage change in risk (%CR) of mortality. A positive value of %CR indicated increased risk of mortality from heat associated with the contextual variable, and vice versa for a negative value of %CR.

All statistical analyses were performed with R software (version 4.5.1), using the *gnm* and *dnm* packages.

Data availability

Mortality data can be obtained under request from the Epidemiology Centre on Medical Causes of Death (CépiDC) of the National Institute of Health and Medical Research (Inserm). Meteorological and contextual data are freely available through the web links that have been provided in the supplementary information.

Code availability

The replication codes for all epidemiological analyses performed in this study are available upon request from the corresponding authors.

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Author contributions
H.A. conceived and designed the study, collected the data, performed the statistical analysis and wrote the manuscript. G.R. and A.G. contributed to the study design and the interpretation of the results, and reviewed/edited the manuscript. P.M. and J.B. contributed to the interpretation of the results and reviewed/edited the manuscript. All authors reviewed and approved the final version of the manuscript.

Competing interests
The authors declare no competing interests.

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