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Urban heat island effect-related mortality under extreme heat and non-extreme heat scenarios: A 2010–2019 case study in Hong Kong

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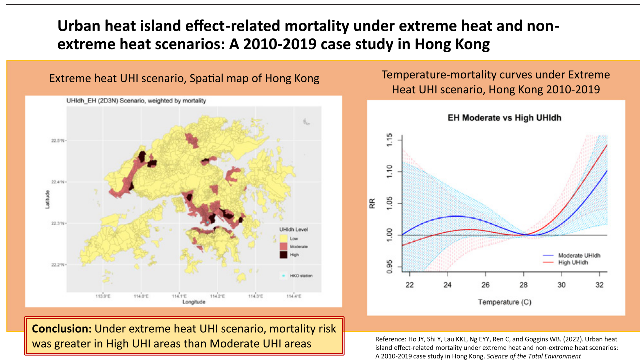
HIGHLIGHTS

- We examined temperature-mortality associations under different UHI scenarios.
- Under extreme heat (EH) scenario, high UHI areas were in more suburban "new towns".
- Mortality risk was doubled in high UHI areas (vs. moderate) under the EH scenario.
- Other scenarios found no contrast in mortality between high vs. moderate UHI areas.
- When stratified by age, temperature-mortality risk was mainly found in elderly 75+.

GRAPHICAL ABSTRACT



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ABSTRACT

The urban heat island (UHI) effect exacerbates the adverse impact of heat on human health. However, while the UHI effect is further intensified during extreme heat events, prior studies have rarely mapped the UHI effect during extreme heat events to assess its direct temperature impact on mortality. This study examined the UHI effect during extreme heat and non-extreme heat scenarios and compared their temperature-mortality associations in Hong Kong from 2010 to 2019. Four urban heat island degree hour (UHIdh) scenarios were mapped onto Hong Kong's tertiary planning units and classified into three levels (Low, Moderate, and High). We assessed the association between temperature and non-external mortality of populations living in each UHIdh level for the extreme heat/non-extreme heat scenarios during the 2010–2019 hot seasons. Our results showed substantial differences between the temperature-mortality associations in the three levels under the UHIdh extreme heat scenario (UHIdh_EH). While there was no evidence of increased mortality in Low UHIdh_EH areas, the mortality risk in Moderate and High UHIdh_EH areas were significantly increased during periods of hot temperature, with the High UHIdh_EH areas displaying almost double the risk (RR: 1.08, 95%CI: 1.03, 1.14 vs. RR: 1.05, 95 % CI: 1.01, 1.09). However, other non-extreme heat UHI scenarios did not demonstrate as prominent of a difference. When stratified by age, the heat effects were found in Moderate and High UHIdh_EH among the elderly aged 75 and above. Our study found a difference in the temperature-mortality

Abbreviations: UHIdh, urban heat island degree hours; UHIdh_EH, UHIdh under the extreme heat (2D3N) scenario; 2D3N, three consecutive hot nights with two hot days in between; HDHN, consecutive one hot day and one hot night; TPU, tertiary planning unit; DLNM, distributed lag non-linear models; GAM, generalized additive model; MMT, minimum mortality temperature.

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associations based on UHI intensity and potential heat vulnerability of populations during extreme heat events. Preventive measures should be taken to mitigate heat especially in urban areas with high UHI intensity during extreme heat events, with particular attention and support for those prone to heat vulnerability, such as the elderly and poorer populations.

1. Introduction

The climate change phenomenon has intensified in the recent years, leading to more hot extremes and heatwaves among other climate impacts (Intergovernmental Panel on Climate Change (IPCC), 2021). While the last decade contained the hottest years on record (United Nations Office of Disaster Risk Reduction (UNDRR), 2022), increasing frequency and duration of heatwaves will continue in the coming decades (Intergovernmental Panel on Climate Change (IPCC), 2021). High ambient temperatures have been associated with adverse health outcomes of mortality and morbidity globally (Astrom et al., 2011; Basu, 2009; Gasparrini et al., 2015; Gosling et al., 2009). In the subtropical city of Hong Kong, mortality was found to increase in temperatures above 28.2 °C, by 1.8 % for every 1 °C increase (Chan et al., 2012). While most studies in literature have assessed the overall relationship between temperature and mortality in different cities, studies have also begun addressing the intra-city (within-city) variations of the temperature-mortality association throughout the city.

The urban heat island (UHI) effect is a crucial aspect where cities experience heterogeneity in their temperature-mortality effect and a "threatening phenomenon" of less well-planned urbanization (United Nations Office of Disaster Risk Reduction (UNDRR), 2022). Defined as where urban areas experience warmer temperatures than the surrounding rural areas (Oke, 1982), the UHI effect develops when built-up urban environments absorb and retain more heat than natural environments, and are slower to cool down at night. The UHI effect is further intensified during heatwave events, particularly in urban areas of high-density cities. The favourable conditions for heatwaves correspond to the ideal conditions for high UHI (Heaviside et al., 2017).

However, despite the UHI phenomenon being well-documented, mortality studies on the UHI effect are typically segregated into two approaches. One approach estimates the intra-city excess mortality that occurs during heatwave events (Gabriel and Endlicher, 2011; Hondula et al., 2012; Tan et al., 2010; Taylor et al., 2015), particularly of historically significant heat events such as the 2003 European heatwave (Heaviside et al., 2016; Laaidi et al., 2012; Vandentorren et al., 2006). These studies report increased mortality risk during the heatwave in areas with higher UHI, with up to 50 % of heat mortality attributable to the UHI effect (Heaviside et al., 2016), although this may be related to the coinciding spatial distribution of building types, deprivation, and vulnerable populations (Hondula et al., 2012; Macintyre et al., 2018). However, these one-off extreme events are unable to support the continuous monitoring of the UHI effect or trace the mortality effect at different temperatures.

The other approach assesses the overall temperature-mortality relationship but use the overall summer season as reference for their UHI intra-city variability (Goggins et al., 2012; Milojevic et al., 2016; Smargiassi et al., 2009). Although heat-mortality risk was sometimes found greater in areas with high UHI (Goggins et al., 2012; Smargiassi et al., 2009), these studies using overall summer UHI models do not account for intensification of the UHI effect during heatwaves (Li and Bou-Zeid, 2013) which occur particularly in high-density cities and coastal cities (Founda and Santamouris, 2017; Jiang et al., 2019; Shreevastava et al., 2021). Furthermore, the overall summer UHI model does not account for the fact that the UHI amplification during heatwaves may not be homogenous across the city (Taylor et al., 2015; Zhou and Shepherd, 2009). A previous London UHI study found different temperature patterns between heatwave days and overall summer season (Taylor et al., 2015). However, these findings were not translated into further health-related analysis as only the spatial distribution of the overall summer UHI was used in subsequent excess mortality analysis (Taylor et al., 2015). Not accounting for the UHI intensification under heatwaves may have minimized and underestimated the mortality effect under the UHI effect and any associated heterogeneity.

A UHI model considering both the UHI effects of prolonged heatwave and spatial variation of heatwaves is needed in heat-risk assessment, especially temperature-mortality studies. Heatwaves may affect both the spatial variation of the UHI effect, and also produce compounded effects of mortality depending on the heatwave duration (Anderson and Bell, 2011; Sheridan and Lin, 2014; Son et al., 2012; Wang et al., 2019). This study examined and compared the effect modification of extreme heat and non-extreme heat UHI scenarios on the association between temperature and non-external mortality in Hong Kong from 2010 to 2019. This study builds on the previous research in Hong Kong that assessed the UHI effect during the overall summer season (Goggins et al., 2012). As the last decade is the hottest years on record (United Nations Office of Disaster Risk Reduction (UNDRR), 2022), the developed knowledge from this study would increase our understanding about the intra-urban variation of heat-related mortality risk and support the development of city-level heat action plans. The findings could be referred by other high-density cities in subtropical climate regions.

2. Material and methods

2.1. Study area and data sources

Hong Kong is a coastal sub-tropical high-density city with hot and humid summers. Its population density in 2016 had on average 6777 persons/km^2, and up to 57,530 persons/km^2 in Kwun Tong area (HKSAR Census and Statistics Department, 2017).

Daily mean temperature and other meteorological variables were obtained for the 2010–2019 period from the Hong Kong Observatory. A singular weather station from the city centre was used to be representative of the temperature exposures of the city. Air pollutant data was collected from the Hong Kong Environmental Protection Department for the same period from 12 general monitoring stations across the city, which were averaged across the stations for each day. The pollutants of fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and ozone (O_3) were adjusted for in the sensitivity analyses.

Mortality data in Hong Kong were obtained from the Hong Kong Census and Statistics Department for the 2010–2019 period. The dataset included variables of date of death, cause of death (ICD-9 to 10 updated), age, sex, occupation, marital status, and Tertiary Planning Unit (TPU) of residence for each decedent. TPUs are small geographical units set by the Planning Department of the Hong Kong Special Administrative Region government. Each TPU was later used to assign the UHIdh level (Low, Moderate, High) under different extreme heat/non-extreme heat scenarios. Non-external mortality (death by natural causes) and non-cancer non-external mortality (subsequently referred to as non-cancer mortality) were both examined in this analysis, since a previous study found non-cancer mortality to be more sensitive to heat effects (Chan et al., 2012).

2.2. Calculations for urban heat island under extreme heat and non-extreme heat scenarios

Due to the urban heat island (UHI) effect, the effects of heat may be exacerbated and unevenly distributed in cities, especially during the night-time (WMO-WHO, 2015). A multi-step process comprising of several published studies was utilized to identify extreme heat/non-extreme heat scenarios and calculate the associated Urban Heat Island effect in order to stratify the mortality data. As there is no universal definition of heatwaves or locally derived definition that accounted for heat-health outcomes, a prior local study assessed multiple combinations of 'very hot days' and 'hot nights' for the strongest association between mortality risk and extreme heat (Wang et al., 2019). These two metrics are used locally by the Hong Kong Observatory, with 'very hot day' defined as daily maximum temperature ≥ 33 °C, and 'hot night' as daily minimum temperature ≥ 28 °C (Lee et al., 2011). The study found that a combination of three consecutive hot nights with two hot days in between (2D3N) was a strong indicator of excess mortality risk (Wang et al., 2019). This 2D3N scenario was used as the representative scenario for extreme heat events (EH) in this study. Apart from this 2D3N scenario, and for better understanding of the heat-health impact during the summer period, three other extreme heat/non-extreme heat scenarios were defined based on a prior local study and used for comparison, including: No2D3N (absence of consecutive 2D3N), a milder extreme heat scenario of HDHN (consecutive one hot day and one hot night), and noHDHN (absence of all consecutive hot days and hot nights) (Ren et al., 2021).

In this study, we adopted the new concept of urban heat island degree hours (UHIdh) to evaluate the heat-health impact, as it comprehensively measures both the duration and difference in temperature of a selected meteorological station with reference to a representative rural station (Yang et al., 2017). UHIdh was calculated for 22 meteorological observation stations managed by the Hong Kong Observatory across the city for the summer seasons May–Sept of 2000–2018 (Ren et al., 2021). The spatial variation of UHIdh was then generated across Hong Kong using land use regression, a buffering analysis and regression-based spatial mapping methodology (Shi et al., 2019). Urban morphological parameters and landscape metrics were generated and analyzed as predictor variables in a multiple linear regression for each extreme heat and non-extreme heat scenario. Influential predictor variables of the regression modelling were then mapped and overlayed to generate a composite spatial data layer, which was then aggregated to the TPU level (Shi et al., 2019). This resulted in a TPU-level UHIdh value for each extreme heat and non-extreme heat scenario defined in the previous paragraph. The detailed methodology of mapping UHIdh can be further found in Ren et al. (2021) and Shi et al. (2019). The analysis found that "compact building clusters of urban areas contribute to the increased UHIdh, especially at night during extreme heat events" (Ren et al., 2021).

To stratify the mortality data, each TPU was initially weighted by the cumulative mortality count of the study period. This weighting was used to classify the TPU-level UHIdh calculations into three levels: Low (lowest 25 %), Moderate (50 %), and High (upper 25 %). The mortality data was then stratified accordingly into the three UHIdh levels and further aggregated by mortality type: non-external, non-cancer; and age group: 74 and less, 75 and above (Cheng et al., 2018; Ma et al., 2015; Ouchi et al., 2017). This was done separately for each of the four extreme heat/non-extreme heat scenarios: EH (consecutive 2D3N), no2D3N, HDHN, and noHDHN.

2.3. Analytical methods

We conducted a retrospective timeseries analysis to estimate the associations between temperature and non-external mortality of populations living in areas under four different Urban Heat Island degree hour (UHIdh) scenarios during the hot seasons from 2010 to 2019. A combination of distributed lag non-linear models (DLNM) with penalized splines and generalized additive models (GAMs) with quasi-Possion distribution was used to analyze the association between temperature and non-external mortality for each UHIdh level under the four extreme heat/non-extreme heat scenarios. Separate models were created for each outcome, classified by the UHIdh levels, age group (74 and less, 75 and above) and mortality type (non-external, non-cancer). The analysis was conducted for the hot summer season between May 15 and Oct 15. Temperature was set to have a 4-day lag (degrees of freedom (df) = 5), with doubly varying penalties (Gasparrini et al., 2017). The analysis was controlled for long-term trend (day of study, df = 5), seasonality (day of year, df = 5), day of week, and public holiday. Wind was initially added in the analysis as a confounder but was found non-significant in all the models. Since its removal did not affect the model outcomes, it was subsequently removed from the final models.

$$
\begin{aligned}
&\mathrm{E(Daily\ non-external\ mortality)} \\
&\quad = \mathrm{cb(mean\ temperature,\ df = 6; lag = 4, dflag = 5)} \\
&\qquad + \mathrm{s(day\ of\ study,\ k = 5) + s(day\ of\ year,\ k = 5)} \\
&\qquad + \mathrm{factor(day\ of\ week) + factor(holiday)}
\end{aligned}
$$

cb indicates the crossbasis of independent variables created using R package "dlnm" (Gasparrini, 2011)df indicates the maximum degrees of freedom used in the crossbasiss() indicates the smoothing function of continuous independent variables in R package "mgcv" (Wood, 2017)k indicates the basis dimension for the smooth, such that k-1 is the maximum degrees of freedomfactor() indicates the categorical independent variables.

The minimum mortality temperature (MMT) was identified for each model and used to center the final outcome. Cumulative relative risk (RR) of the entire lag period was calculated in comparison to the MMT, according to percentiles of the summer season analysis period (Table 1). Sensitivity analyses assessed the effect of individual pollutants on the models: $PM_{2.5}$, NO_2, and ozone; and the effect of different age groupings (64 and younger, 65 to 74, 75 and above). Statistical significance level was set at $p \leq 0.05$. All analyses were conducted with the statistical software R (version 3.5.2) (R Core Team, 2018), using the dlnm() (Gasparrini, 2011) and mgcv() (Wood, 2017) packages.

3. Results

3.1. Spatial patterns of extreme heat/non-extreme heat scenarios & other descriptive statistics

The four extreme heat/non-extreme heat scenarios demonstrated different spatial patterns of UHIdh heating (Ren et al., 2021), with different "hot spot" areas throughout the city [Fig. 1a–d]. For the extreme heat scenario UHIdh_EH (consecutive 2D3N), high UHIdh was found located in several "new towns" of suburban New Territories. These included areas of Tin Shui Wai, Yuen Long, Tuen Mun Town Centre, Tai Po, Kwai Chung, and Tseung Kwan O, in addition to the urban areas of To Kwa Wan-Whampoa-Homantin, Tin Hau-Fortress Hill, and Choi Hung-Ngau Tau Kok. In contrast, the other maps (no2D3N, HDHN, or noHDHN), high UHIdh comprised of more urban areas of Kowloon and Hong Kong Island.

In terms of descriptive statistics, during the summer seasons (May 15–Oct 15) of 2010–2019, there was a total of 162,262 non-external mortality counts and 104,073 non-cancer mortality counts. Mean temperature ranged from 20.5 to 32.4 °C, with an average of 28.4 °C (standard deviation = 1.64). Table 2 shows the average daily mortality counts for each outcome according to the UHIdh level (Low, Moderate, High) of the extreme heat scenario (UHIdh_EH). The mortality counts for the other scenarios can be found in Appendix A, Table A.1, with the cut-offs for each scenario shown in Fig. A.1.

3.2. Mortality associations under extreme heat scenario UHIdh_EH (2D3N) scenario

There was a substantial difference between the temperature-mortality associations in the three levels of UHIdh_EH (2D3N) scenario. While

Table 1
Percentile temperature during summer seasons of 2010–2019.

Percentile	90th	95th	98th	99th
Temperature (°C)	30.2	30.5	30.8	31.1

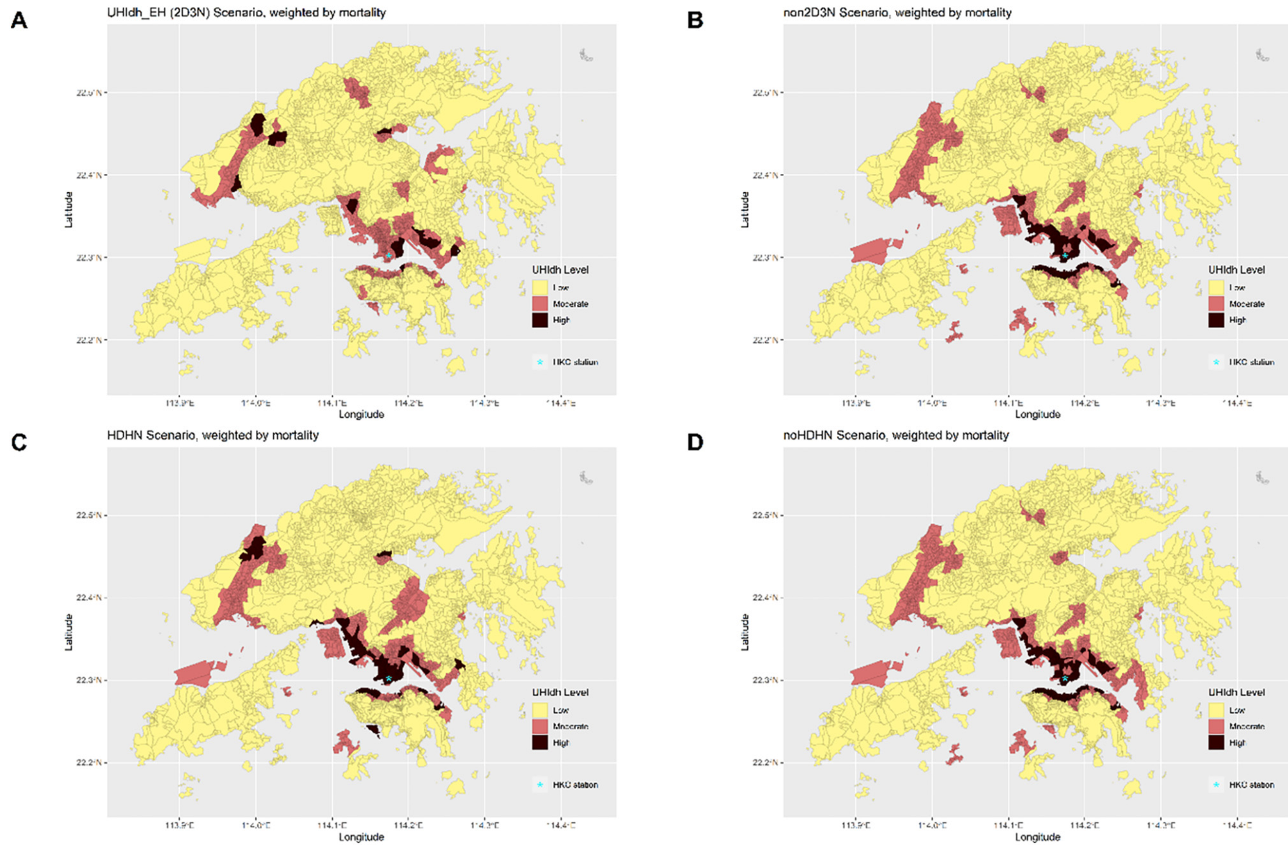

Fig. 1. Spatial map of UHIdh levels for extreme heat and non-extreme heat scenarios: A) Extreme heat 2D3N, B) non2D3N, C) HDHN, and D) noHDHN. The UHIdh levels were classified by weighting each TPU with the cumulative mortality count of the study period and grouping based on: Low (lowest 25 %), Moderate (50 %), and High (upper 25 %). Thin grey lines indicate the Tertiary Planning Unit (TPU) boundaries set by the Planning Department of Hong Kong SAR Government.

those living in Low UHIdh_EH showed no increase in mortality during hot temperatures, mortality in Moderate and High UHIdh_EH areas were significantly higher during periods of hot temperature (Fig. 2). Fig. 3a demonstrates the contrast in mortality risk between Moderate and High UHIdh_EH areas. Table 3 shows the overall RR at each percentile temperature for the extreme heat (2D3N) scenario. For those living in High UHIdh_EH areas, the 99th percentile relative risk (RR) (vs. MMT 27.7 °C) was 1.08 (95%CI: 1.03, 1.14) for non-external mortality. This was almost double the 99th percentile RR in Moderate UHIdh_EH (vs. MMT 28.4 °C) which was found at 1.05 (95 % CI: 1.01, 1.09)). A consistent doubling of RR at all percentiles can be seen between Moderate and High UHIdh_EH.

Stronger heat effects were found for non-cancer mortality outcomes. For those living in Moderate UHIdh_EH areas, the 99th percentile RR (vs. MMT 28.3 °C) was 1.06 (95 % CI: 1.01, 1.11), while the 99th percentile RR (vs. MMT 28.1 °C) reached 1.11 (95 % CI: 1.04, 1.19) for those living in High UHIdh_EH areas. A steeper rate of increase was identified for non-cancer mortality in High UHIdh_EH despite a higher MMT than that for non-external mortality.

When stratified by age, those aged 74 and younger showed no increase in mortality during hot temperatures, whether for non-external or non-cancer mortality. Among those aged 75 and older, the 99th percentile RR was 1.07 (95 % CI: 1.02, 1.12), and 1.12 (95 % CI: 1.05, 1.20), for those living in Moderate and High UHIdh_EH areas, respectively (Fig. 4a). The findings among elderly were similar for non-cancer mortality.

3.3. Comparisons with mortality associations under other extreme heat/non-extreme heat scenarios

While the outcomes in the extreme heat (2D3N) scenario consistently demonstrated a near doubling of relative risk between those living in Moderate and High UHIdh areas, the other three scenarios did not find the same contrast. Table 4 shows the findings of 90th and 99th percentile for each scenario. Fig. 3 graphically demonstrate the difference between Moderate and High UHIdh areas for each scenario for non-external mortality. Fig. 4 illustrates the same for elderly mortality, while Figs. A.2 and A.3 in Appendix A show the scenarios for overall and elderly non-cancer mortality,

Table 2
Average daily mortality counts according to UHIdh extreme heat (2D3N) scenario.

Outcomes	Mean daily mortality counts (sd)		
	Low (UHIdh < 39.8)	Moderate (39.8 < UHIdh < 52)	High (UHIdh > 52)
Overall mortality (non-external)	26.4 (5.2)	53.5 (7.9)	26.8 (6.2)
Noncancer mortality	16.8 (4.2)	34.3 (6.4)	17.4 (4.8)
Overall mortality, 74 and younger	9.0 (3.0)	18.0 (4.3)	9.8 (3.3)
Overall mortality, 75 and above	17.4 (4.2)	35.6 (6.5)	17.1 (4.8)
Noncancer mortality, 74 and younger	3.8 (2.0)	7.8 (2.8)	4.4 (2.1)
Noncancer mortality, 75 and above	13.0 (3.7)	26.5 (5.6)	12.9 (4.1)

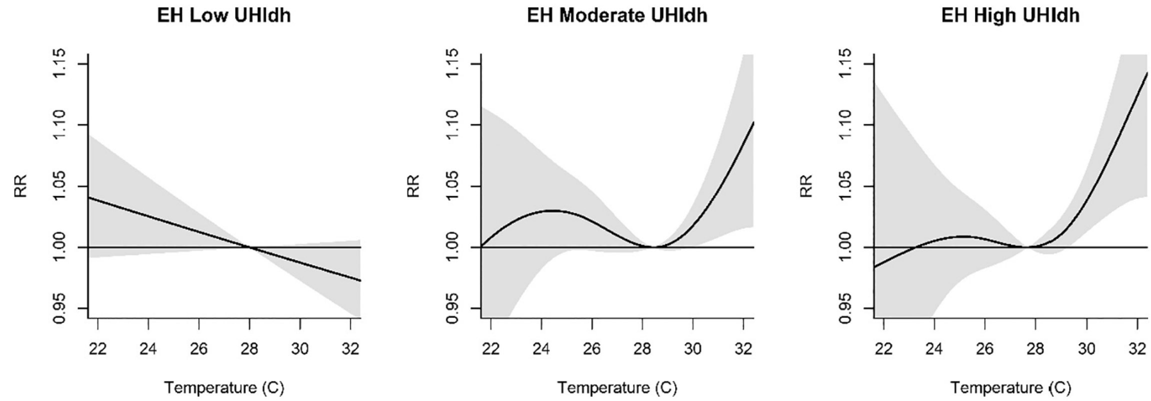

Fig. 2. Temperature-mortality associations for Low, Moderate, and High UHIdh levels under the extreme heat scenario (EH).

respectively. When comparing the outcomes of Moderate and High UHIdh areas, the scenarios of No2D3N, HDHN, and noHDHN mostly found a difference of 0–2 % relative risk. For example, the 99th percentile RR of non-external mortality was 1.05 (95 % CI: 1.01, ~1.09) for Moderate but only 1.06 (95 % CI: 1.01, ~1.11) for High areas. This was similar for other outcomes in the three scenarios. The outcomes of the HDHN scenario more closely resembled our original 2D3N scenario, especially for non-external mortality of 75 and above, with a 4 % difference in RR between Moderate and High UHIdh areas. However, this was not consistent across other outcomes. Meanwhile, the no2D3N and noHDHN scenarios found a non-significant association in High UHIdh areas for the more moderate 90th percentile RR.

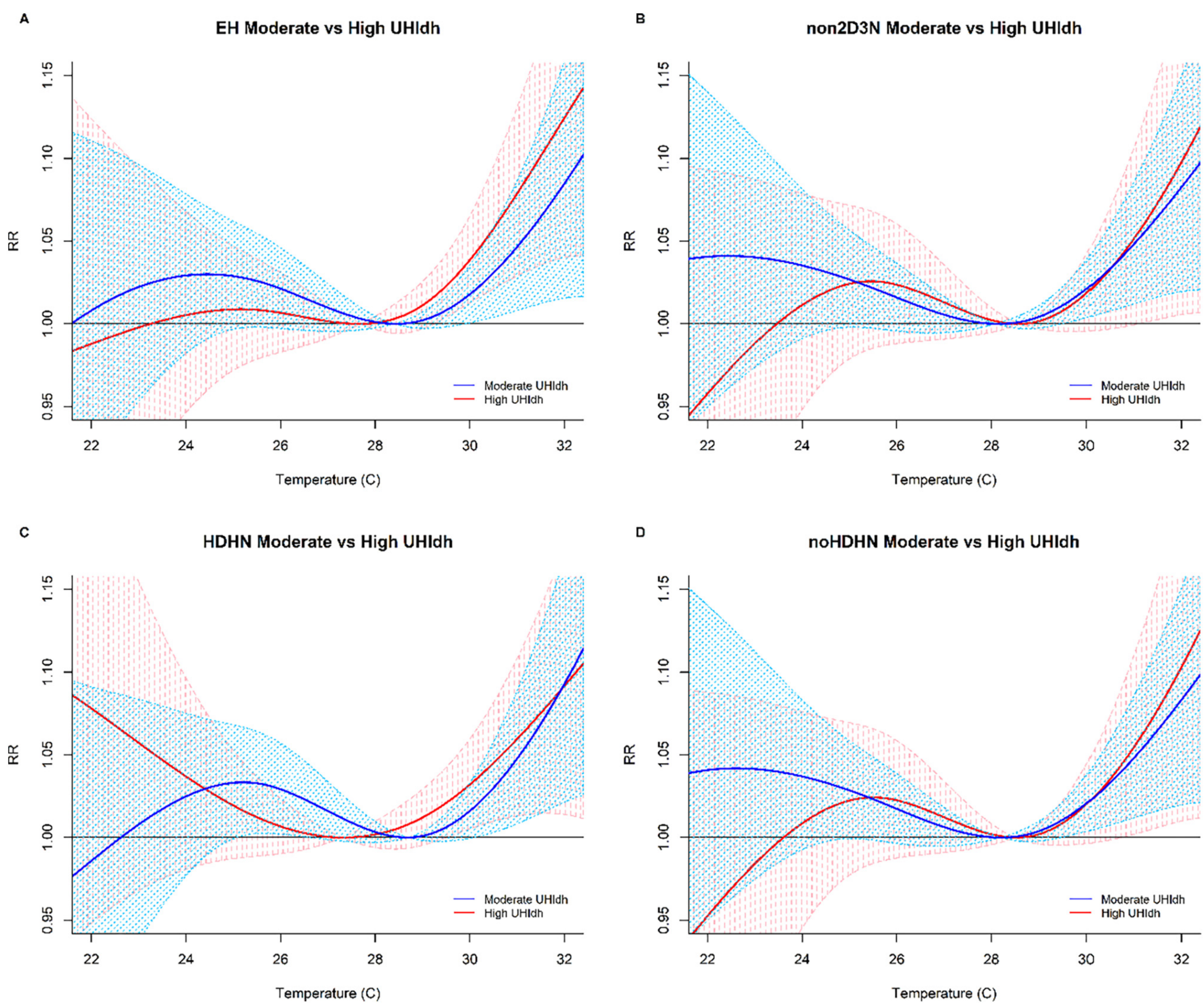

Fig. 3. Temperature-mortality associations for Moderate and High UHIdh under different extreme heat/non-extreme heat scenarios: A) Extreme heat 2D3N, B) non2D3N, C) HDHN, and D) noHDHN.

Table 3
Relative risk of mortality for the extreme heat (2D3N) scenario.

Outcomes	UHIdh_EH level	MMT	90th	95th	98th	99th
Overall mortality (non-external)	Low	28	0.99 (0.97, 1.00)	0.98 (0.97, 1.00)	0.98 (0.96, 1.00)	0.98 (0.96, 1.00)
Overall mortality (non-external)	Moderate	28.4	1.02 (1.00, 1.04)*	1.03 (1.00, 1.06)*	1.04 (1.01, 1.07)*	1.05 (1.01, 1.09)*
Overall mortality (non-external)	High	27.7	1.05 (1.02, 1.08)*	1.06 (1.02, 1.10)*	1.07 (1.03, 1.12)*	1.08 (1.03, 1.14)*
Noncancer mortality	Low	28	0.98 (0.95, 1.00)	0.97 (0.95, 1.00)	0.97 (0.94, 1.00)	0.97 (0.93, 1.00)
Noncancer mortality	Moderate	28.3	1.03 (1.00, 1.05)*	1.04 (1.00, 1.07)*	1.05 (1.00, 1.09)*	1.06 (1.01, 1.11)*
Noncancer mortality	High	28.1	1.06 (1.02, 1.10)*	1.08 (1.03, 1.13)*	1.09 (1.03, 1.16)*	1.11 (1.04, 1.19)*
Overall mortality, 74 and younger	Low	28	0.99 (0.97, 1.02)	0.99 (0.96, 1.02)	0.99 (0.96, 1.02)	0.99 (0.95, 1.03)
Overall mortality, 74 and younger	Moderate	28	1.00 (0.98, 1.02)	1.00 (0.97, 1.02)	1.00 (0.97, 1.03)	1.00 (0.97, 1.03)
Overall mortality, 74 and younger	High	28	1.00 (0.97, 1.03)	1.00 (0.97, 1.03)	1.00 (0.97, 1.03)	1.00 (0.96, 1.04)
Overall mortality, 75 and above	Low	28	0.98 (0.96, 1.00)	0.98 (0.95, 1.00)	0.97 (0.95, 1.00)	0.97 (0.94, 1.00)
Overall mortality, 75 and above	Moderate	28.2	1.03 (1.01, 1.06)*	1.04 (1.01, 1.08)*	1.05 (1.01, 1.10)*	1.07 (1.02, 1.12)*
Overall mortality, 75 and above	High	27.3	1.07 (1.03, 1.11)*	1.09 (1.04, 1.14)*	1.10 (1.05, 1.16)*	1.12 (1.05, 1.20)*
Noncancer mortality, 74 and younger	Low	28	1.00 (0.96, 1.05)	1.00 (0.96, 1.05)	1.00 (0.95, 1.06)	1.00 (0.95, 1.07)
Noncancer mortality, 74 and younger	Moderate	28	0.99 (0.96, 1.02)	0.99 (0.96, 1.02)	0.99 (0.95, 1.02)	0.98 (0.95, 1.02)
Noncancer mortality, 74 and younger	High	28	1.01 (0.97, 1.05)	1.01 (0.97, 1.05)	1.01 (0.96, 1.06)	1.01 (0.96, 1.07)
Noncancer mortality, 75 and above	Low	28	0.97 (0.94, 0.99)	0.96 (0.94, 0.99)	0.96 (0.93, 0.99)	0.95 (0.92, 0.99)
Noncancer mortality, 75 and above	Moderate	28.1	1.03 (1.00, 1.06)	1.04 (1.00, 1.07)	1.04 (1.00, 1.09)	1.06 (1.00, 1.11)*
Noncancer mortality, 75 and above	High	27.4	1.06 (1.02, 1.11)*	1.08 (1.03, 1.14)*	1.10 (1.03, 1.17)*	1.12 (1.04, 1.20)*

* Indicates statistical significance of $p \leq 0.05$. Each model was adjusted for day of study, day of year, day of week and public holidays.

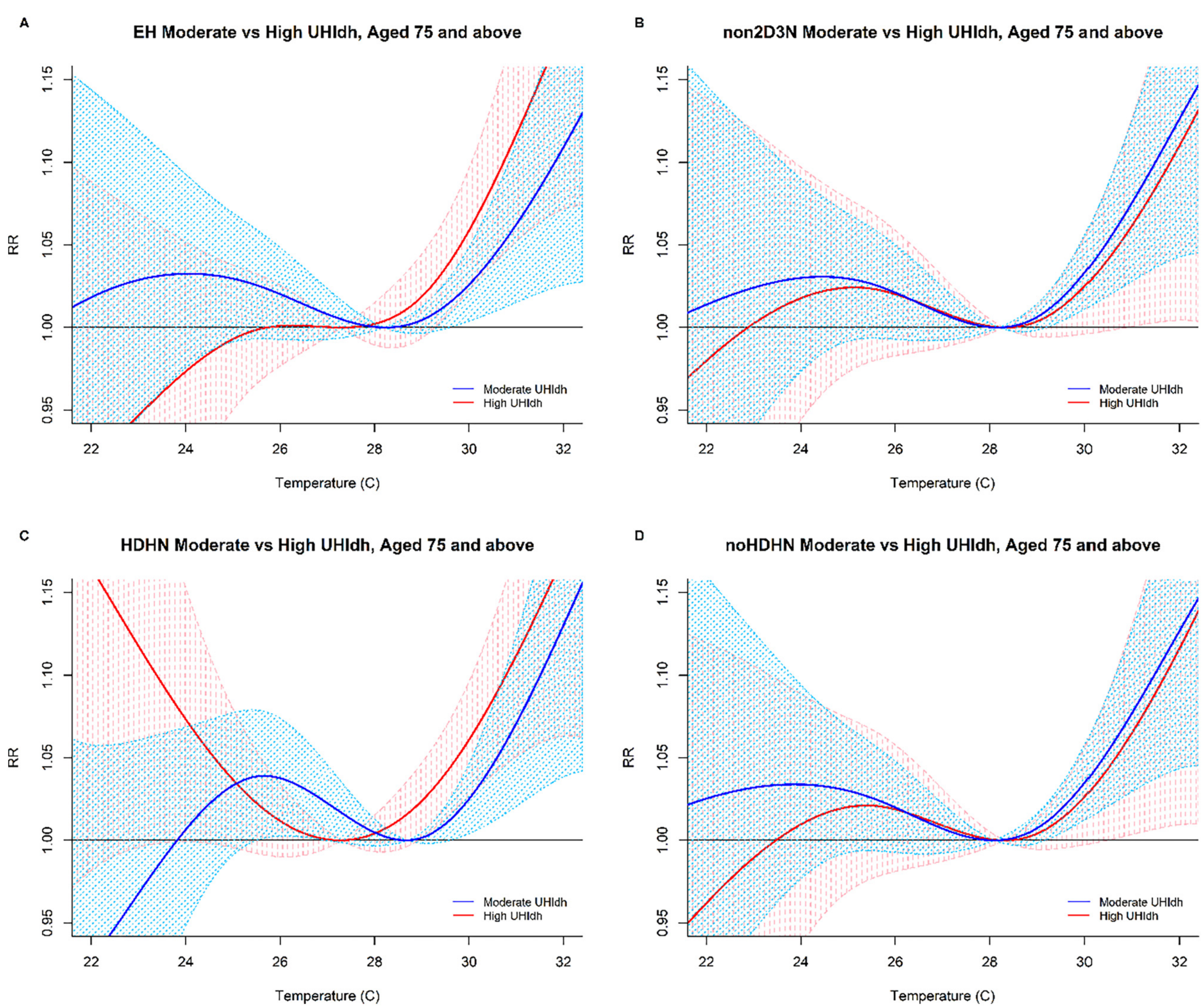

Fig. 4. Temperature-mortality associations among elderly aged 75 and above for Moderate and High UHIdh under different extreme heat/non-extreme heat scenarios: A) Extreme heat 2D3N, B) non2D3N, C) HDHN, and D) noHDHN.

Table 4
Relative risk of mortality: comparison between the four UHIdh scenarios.

Outcomes	UHIdh level	Extreme Heat (2D3N)			No2D3N			HDHN			noHDHN		
		MMT	90th	99th	MMT	90th	99th	MMT	90th	99th	MMT	90th	99th
Overall mortality (non-external)	Low	28	0.99 (0.97, 1.00)	0.98 (0.96, 1.00)	28	1.00 (0.98, 1.01)	0.99 (0.97, 1.02)	28	1.00 (0.98, 1.01)	1.00 (0.98, 1.02)	28	0.99 (0.98, 1.01)	0.99 (0.97, 1.01)
Overall mortality (non-external)	Moderate	28.4	1.02 (1.00, 1.04)*	1.05 (1.01, 1.09)*	28.1	1.03 (1.01, 1.05)*	1.05 (1.01, 1.09)*	28.7	1.02 (1.00, 1.04)*	1.05 (1.01, 1.10)*	28.2	1.03 (1.01, 1.05)*	1.05 (1.01, 1.09)*
Overall mortality (non-external)	High	27.7	1.05 (1.02, 1.08)*	1.08 (1.03, 1.14)*	28.6	1.02 (1.00, 1.05)	1.06 (1.00, 1.11)	27.3	1.04 (1.01, 1.07)*	1.06 (1.01, 1.11)*	28.5	1.03 (1.00, 1.06)	1.06 (1.00, 1.12)*
Noncancer mortality	Low	28	0.98 (0.95, 1.00)	0.97 (0.93, 1.00)	28	1.00 (0.98, 1.02)	0.99 (0.97, 1.02)	28.7	1.01 (0.98, 1.03)	1.02 (0.97, 1.07)	29.3	1.00 (0.99, 1.01)	1.00 (0.97, 1.04)
Noncancer mortality	Moderate	28.3	1.03 (1.00, 1.05)*	1.06 (1.01, 1.11)*	28.2	1.03 (1.00, 1.06)*	1.06 (1.01, 1.11)*	28.8	1.03 (1.00, 1.06)*	1.08 (1.02, 1.14)*	28.2	1.03 (1.00, 1.06)*	1.06 (1.01, 1.11)*
Noncancer mortality	High	28.1	1.06 (1.02, 1.10)*	1.11 (1.04, 1.19)*	28.5	1.04 (1.00, 1.07)*	1.08 (1.01, 1.16)*	27.2	1.05 (1.01, 1.08)*	1.08 (1.02, 1.14)*	28.5	1.04 (1.00, 1.07)	1.08 (1.01, 1.15)*
Overall mortality, 74 and younger	Low	28	0.99 (0.97, 1.02)	0.99 (0.95, 1.03)	28	0.99 (0.97, 1.02)	0.99 (0.95, 1.03)	28.2	1.00 (0.98, 1.03)	1.01 (0.96, 1.06)	28	1.00 (0.97, 1.02)	1.00 (0.96, 1.03)
Overall mortality, 74 and younger	Moderate	28	1.00 (0.98, 1.02)	1.00 (0.97, 1.03)	28	1.00 (0.98, 1.02)	1.00 (0.98, 1.03)	28	1.00 (0.98, 1.02)	1.00 (0.97, 1.02)	28	1.00 (0.98, 1.02)	1.00 (0.97, 1.02)
Overall mortality, 74 and younger	High	28	1.00 (0.97, 1.03)	1.00 (0.96, 1.04)	28	0.99 (0.96, 1.03)	0.99 (0.95, 1.04)	28	0.99 (0.96, 1.01)	0.98 (0.95, 1.02)	28	0.99 (0.96, 1.02)	0.99 (0.95, 1.03)
Overall mortality, 75 and above	Low	28	0.98 (0.96, 1.00)	0.97 (0.94, 1.00)	28	1.00 (0.98, 1.02)	1.00 (0.97, 1.02)	28	1.00 (0.98, 1.02)	1.00 (0.97, 1.02)	28	0.99 (0.97, 1.01)	0.99 (0.96, 1.02)
Overall mortality, 75 and above	Moderate	28.2	1.03 (1.01, 1.06)*	1.07 (1.02, 1.12)*	28.2	1.04 (1.01, 1.07)*	1.08 (1.03, 1.13)*	28.7	1.03 (1.01, 1.06)*	1.08 (1.02, 1.13)*	28.1	1.04 (1.02, 1.07)*	1.08 (1.03, 1.14)*
Overall mortality, 75 and above	High	27.3	1.07 (1.03, 1.11)*	1.12 (1.05, 1.20)*	28.3	1.03 (1.00, 1.07)	1.07 (1.00, 1.14)*	27.3	1.07 (1.03, 1.11)*	1.12 (1.05, 1.19)*	28.3	1.03 (1.00, 1.07)	1.07 (1.00, 1.14)*
Noncancer mortality, 74 and younger	Low	28	1.00 (0.96, 1.05)	1.00 (0.95, 1.07)	28	0.99 (0.95, 1.03)	0.99 (0.94, 1.05)	28.1	1.05 (0.98, 1.12)	1.09 (0.96, 1.24)	27.2	1.01 (0.96, 1.08)	1.02 (0.94, 1.12)
Noncancer mortality, 74 and younger	Moderate	28	0.99 (0.96, 1.02)	0.98 (0.95, 1.02)	29.2	1.00 (0.98, 1.02)	1.00 (0.97, 1.04)	28.2	1.02 (0.98, 1.07)	1.05 (0.97, 1.13)	28.9	1.01 (0.98, 1.04)	1.02 (0.96, 1.10)
Noncancer mortality, 74 and younger	High	28	1.01 (0.97, 1.05)	1.01 (0.96, 1.07)	27.6	1.02 (0.97, 1.09)	1.04 (0.95, 1.15)	28	0.98 (0.95, 1.02)	0.98 (0.93, 1.03)	28	1.01 (0.97, 1.05)	1.02 (0.96, 1.08)
Noncancer mortality, 75 and above	Low	28	0.97 (0.94, 0.99)	0.95 (0.92, 0.99)	28	1.00 (0.98, 1.02)	1.00 (0.97, 1.03)	28	1.00 (0.98, 1.02)	1.00 (0.97, 1.03)	28	0.99 (0.97, 1.01)	0.99 (0.96, 1.02)
Noncancer mortality, 75 and above	Moderate	28.1	1.03 (1.00, 1.06)	1.06 (1.00, 1.11)*	27.7	1.03 (1.00, 1.06)	1.06 (1.00, 1.12)*	28.8	1.03 (1.00, 1.06)	1.08 (1.01, 1.14)*	28	1.03 (1.00, 1.06)*	1.05 (1.00, 1.10)*
Noncancer mortality, 75 and above	High	27.4	1.06 (1.02, 1.11)*	1.12 (1.04, 1.20)*	28.3	1.03 (0.99, 1.07)	1.06 (0.99, 1.13)	27	1.06 (1.02, 1.11)*	1.10 (1.03, 1.18)*	28.5	1.03 (0.99, 1.07)	1.07 (0.99, 1.14)

* Indicates statistical significance of $p \leq 0.05$. Each model was adjusted for day of study, day of year, day of week and public holidays.

3.4. Sensitivity analyses

When adjusted for pollutants individually, the overall findings and trends were retained in the extreme heat (2D3N) scenario analyses (Table 5). Among the elderly 75 and above, the 99th percentile RR of non-cancer mortality was no longer significant for those living in Moderate UHIdh_EH and there was a slight decrease in RR for those living in High UHIdh_EH when adjusted for PM2.5 lag 0–1 or ozone lag 0–1. Overall, the difference between Low, Moderate and High UHIdh_EH remained consistent when adjusted for pollutants.

When analyzing the associations by different age groups, no significant associations were found for those 64 and younger, and those 65 to 74 (Appendix A, Table A.2).

4. Discussion

Our study found that when classified by the urban heat island effect during the extreme heat scenario (UHIdh_EH), areas of Moderate and High UHIdh_EH found a significant increase of mortality risk in hot temperatures, while Low UHIdh_EH areas found no temperature-mortality association. High UHIdh_EH areas demonstrated almost double the risk of Moderate UHIdh_EH areas, with the mortality risk also starting earlier at a lower minimum mortality threshold (High vs. Moderate UHIdh_EH: MMT 27.7 °C vs. 28.4 °C). Other non-extreme heat scenarios, which considered different variations or the absence of extreme heat days, did not demonstrate as large a difference between Moderate and High UHIdh levels as the extreme heat scenario. These findings demonstrate the importance of considering the urban heat island effect not just for the overall summer, but specifically during extreme heat events. Not only is the urban heat island effect intensified during periods of extreme heat, but also the spatial distribution of this UHI intensification may vary. As identified in Section 3.1, the extreme heat scenario accounted for several "new towns" in more suburban areas of the city that were not included in the other non-extreme heat scenarios. This study used the weather station at the Hong Kong Observatory Headquarters located in the city center to conduct the analysis and compare differences in mortality risk between UHIdh levels. Our findings demonstrate that the temperature data at the city center serves as a strong predictor of heat-health risk particularly for moderate and high UHI areas, but less so for low UHI areas. Moreover, under the extreme heat scenario, the location of the weather station was assigned to the moderate UHIdh level, due to weighting of UHIdh by cumulative mortality counts. This demonstrates that a further mortality risk is uncovered when accounting for population exposure and vulnerability to heatwaves.

Although the intensification of UHI during heatwaves has been acknowledged and addressed in numerous UHI studies (An et al., 2020), but few studies have translated this knowledge into heat-related mortality studies. Previous studies on the UHI effect on mortality have assessed the excess mortality of singular exceptional heatwave events (Heaviside et al., 2016) or the UHI of the overall summer season (Goggins et al., 2012; Smargiassi et al., 2009). Our findings correspond to the previous 2001–2009 UHI study in Hong Kong, which found that temperature was not associated with mortality in cool UHI areas but associated with 4.1 % increase in mortality in hot UHI areas per 1 °C in temperatures above 29 °C (Goggins et al., 2012). Acclimatization and/or adaptation, such as increased air conditioning usage (Electrical and Mechanical Services Department, 2013, 2021), may have contributed to the mortality risk difference in the past decade, as a separate analysis found that the mortality association in 2010–2019 was not as prominent as that of 2000–2009 (analysis not shown). In a previous study in London, Milojevic et al. (2016) suggested an acclimatization of the UHI effect in hot temperatures, as high UHI levels did not demonstrate a multiplied risk of heat-related deaths. Their UHI understanding was based on annual mean of daily excess temperatures. On the other hand, our study findings seem to demonstrate an added influence of UHI effect in hot temperatures when having formulated a UHI understanding from extreme heat events. Future studies should also assess the temperature-mortality association and other heat-health outcomes using an UHI understanding derived from extreme heat events.

Table 5
Sensitivity analysis: mortality risk adjusted for pollutants.

Outcomes	UHIdh_EH level	Extreme Heat (2D3N)		PM25 Lag 0–1		Ozone Lag 0–1		NO2 Lag 0–1	
		MMT	99th	MMT	99th	MMT	99th	MMT	99th
Overall mortality (non-external)	Low	28	0.98 (0.96, 1.00)	28	0.98 (0.96, 1.00)	28	0.98 (0.96, 1.00)	28	0.98 (0.96, 1.00)
Overall mortality (non-external)	Moderate	28.4	1.05 (1.01, 1.09)*	28.4	1.05 (1.01, 1.10)*	28.4	1.05 (1.01, 1.09)*	28.5	1.05 (1.01, 1.10)*
Overall mortality (non-external)	High	27.7	1.08 (1.03, 1.14)*	27.6	1.08 (1.03, 1.13)*	27.5	1.07 (1.02, 1.13)*	27.6	1.08 (1.03, 1.14)*
Noncancer mortality	Low	28	0.97 (0.93, 1.00)	28	0.97 (0.93, 1.00)	28	0.97 (0.93, 1.00)	28	0.97 (0.94, 1.00)
Noncancer mortality	Moderate	28.3	1.06 (1.01, 1.11)*	28.3	1.06 (1.01, 1.12)*	28.3	1.05 (1.00, 1.10)*	28.4	1.06 (1.01, 1.12)*
Noncancer mortality	High	28.1	1.11 (1.04, 1.19)*	28.1	1.11 (1.03, 1.19)*	28	1.09 (1.02, 1.17)*	28.2	1.13 (1.05, 1.21)*
Overall mortality, 74 and younger	Low	28	0.99 (0.95, 1.03)	28	0.99 (0.95, 1.02)	28	0.99 (0.95, 1.03)	28	0.98 (0.95, 1.02)
Overall mortality, 74 and younger	Moderate	28	1.00 (0.97, 1.03)	28	1.00 (0.97, 1.03)	28	1.00 (0.97, 1.03)	28	1.00 (0.97, 1.03)
Overall mortality, 74 and younger	High	28	1.00 (0.96, 1.04)	28	1.00 (0.97, 1.04)	28	1.00 (0.97, 1.04)	28	1.00 (0.97, 1.04)
Overall mortality, 75 and above	Low	28	0.97 (0.94, 1.00)	28	0.97 (0.94, 1.00)	28	0.97 (0.94, 1.00)	28	0.97 (0.94, 1.00)
Overall mortality, 75 and above	Moderate	28.2	1.07 (1.02, 1.12)*	28.2	1.07 (1.02, 1.12)*	28.2	1.05 (1.01, 1.11)*	28.3	1.07 (1.02, 1.13)*
Overall mortality, 75 and above	High	27.3	1.12 (1.05, 1.20)*	27.3	1.12 (1.05, 1.19)*	27.3	1.11 (1.04, 1.18)*	27.3	1.12 (1.05, 1.19)*
Noncancer mortality, 74 and younger	Low	28	1.00 (0.95, 1.07)	28	1.00 (0.95, 1.07)	28	1.01 (0.95, 1.07)	28	1.00 (0.95, 1.06)
Noncancer mortality, 74 and younger	Moderate	28	0.98 (0.95, 1.02)	28.9	1.02 (0.95, 1.08)	28.6	1.03 (0.95, 1.10)	28.8	1.02 (0.95, 1.09)
Noncancer mortality, 74 and younger	High	28	1.01 (0.96, 1.07)	28	1.02 (0.95, 1.09)	28	1.01 (0.95, 1.07)	27.3	1.02 (0.95, 1.11)
Noncancer mortality, 75 and above	Low	28	0.95 (0.92, 0.99)	28	0.95 (0.92, 0.99)	28	0.95 (0.92, 0.99)	28	0.96 (0.92, 0.99)
Noncancer mortality, 75 and above	Moderate	28.1	1.06 (1.00, 1.11)*	28.1	1.05 (1.00, 1.11)	27.9	1.04 (0.99, 1.10)	28.2	1.06 (1.00, 1.12)*
Noncancer mortality, 75 and above	High	27.4	1.12 (1.04, 1.20)*	27.4	1.11 (1.03, 1.19)*	27.4	1.07 (1.02, 1.12)*	27.4	1.12 (1.04, 1.21)*

* Indicates statistical significance of $p \leq 0.05$. Each model was adjusted for day of study, day of year, day of week and public holidays.

Our study findings suggest that the UHI and temperature-mortality impact was mainly from the elderly population above 75. The elderly mortality was non-significant in low UHIdh areas but was more exacerbated in High UHIdh compared to Moderate UHIdh areas. This was similar to other temperature-mortality studies, where elderly were found to be more vulnerable to hot temperatures (Astrom et al., 2011; Bunker et al., 2016). However, to our knowledge, no UHI studies have previously compared the UHI effect between the elderly and general population, but only focused on the elderly. Previously, Laaidi et al. (2012) examined the impact of the 2003 heatwave among the elderly population in Paris and found minimum temperatures associated with higher mortality risk. On the same event, Vandentorren et al. (2006) identified risk factors among the elderly such as chronic diseases, lack of mobility, living in areas with high UHI effects, in buildings without insulation, and in bedrooms in the top floor. Macintyre et al. (2018) further found that care homes and locations where elderly reside were more likely in hotter areas of a UK city. In terms of our study, further work is needed to assess the locations within High UHIdh areas where elderly and residential care homes reside. Particularly in an ageing society where the proportion of older people is increasing, preventive heat measures are crucial to support age-friendly environments for the elderly (World Health Organization, 2020).

4.1. Implications for urban heat management

4.1.1. Factoring the UHI effect into the assessment of heat-health impact

As discussed in the beginning of this paper, the urban heat island effect is often not comprehensively accounted for in analyses of heat-health outcomes. Identifying the intra-urban variation may be influential in revealing elevated heat risks and greater health impacts (WMO-WHO, 2015). Our study findings further demonstrate the need to generate a UHI understanding of a city based on extreme heat events, especially for high-density cities, since not only does the intensity of UHI change during a heatwave, but also the spatial variation of the UHI effect (WMO-WHO, 2015). Future heat-health assessments should include the UHI effect of extreme heat events in their analysis.

4.1.2. Developing tailor-made heat-health warning system

It would be necessary to develop a tailor-made heat-health warning system to address the UHI-induced heat risks, as impacts of urban heat are not evenly distributed within cities (United Nations Environment Programme, 2021). This could look like a heat advisory alert or a warning system specifically targeting "hot spots" caused by high UHI areas that would experience additionally hotter temperatures resulting in a higher health impact. In Seoul Korea, an intra-urban heat-health warning system was developed using independent mortality algorithms for five meteorologically homogeneous areas, whereby the authorities can alert each section of the city separately (WMO-WHO, 2015). Although the climatological homogeneity may not have been based on extreme heat events specifically, this model provides an example of intra-urban differentiation which identifies the vulnerable areas and supports the allocation of appropriate resources (WMO-WHO, 2015).

4.1.3. Creating community-level intervention strategies

Based on our findings, the development of heat intervention strategies should consider the UHI effect and its potential heat impact, so that different actions at the city level can be taken to reduce health risks accordingly during periods of extreme heat. Our study identified an urgent need to target those TPUs with high UHI intensity (such as TPUs of Tin Hau 151, To Kwa Wan 241–245, Choi Hung 287, Ngau Tau Kok 293–294, Kwai Chung 326, Tuen Mun 424, Tin Shui Wai 510, Yuen Long 524, Tai Po 726, Tseung Kwan O 838, etc.). Interventions could particularly be catered to areas with a large proportion of elderly residents within these TPUs. As the high risk "hot spots" emerge from the nocturnal UHI effect during heatwaves (Hua et al., 2021; Ren et al., 2021), heat shelters should be kept open during hot nights and special assistance should be tailored to the needs of the elderly, particularly those who live alone.

4.1.4. Preparing long-term initiatives for managing heatwaves and health

Heatwaves will become more severe, frequent, and intense in the near future due to global climate change (Intergovernmental Panel on Climate Change (IPCC), 2021). As our study found that 'new towns' in the suburban districts of New Territories showed greater increase of UHIdh during heatwaves compared to the conventional urban districts, more attention should be paid in those districts to develop corresponding heat mitigation measures. These can include green or cool roofs, reflective surfaces, street vegetation, and increasing ventilation via neighborhood design (United Nations Environment Programme, 2021). Furthermore, as Hong Kong continues to construct more new town developments in the New Territories, it would be critical for the town planners and policy makers to consider climate responsive design strategies to reduce heat, manage heat exposure, and create livable cooling urban environments. These include the heat mitigation measures mentioned earlier, but also expand to adapting zoning requirements and building codes to include minimum requirements of green spaces in zoning laws, policies for thermally efficient buildings and passive cooling, and minimum energy performance requirements (United Nations Environment Programme, 2021). Furthermore, public authorities and local agencies are encouraged to periodically review the distribution of existing heat shelters and cooling facilities in the community, as over time the population vulnerability may shift or require more support to protect citizens from heat stress and heat-related illnesses.

4.2. Strengths and limitations

To our knowledge, this was the first heat-health study to do a comparison between the UHI effect in extreme heat and non-extreme heat scenarios for better understanding the UHI reduced heat-health impact. A comprehensive UHI understanding was derived using UHI degree hours in the spatial mapping of a high-density city (Ren et al., 2021). A singular meteorological station from the city center was used for comparison of the temperature-mortality effect between UHIdh levels. Creating UHI scenarios at the tertiary planning unit (TPU) level of Hong Kong enables our study findings to be applied directly to the urban planning of the city. We adjusted for pollutant levels in our sensitivity analysis. However, our study was unable to adjust for other potential confounding factors, such as socio-economic status, housing conditions, air conditioning usage, and other areas of heat vulnerability or protection. A local Hong Kong telephone survey conducted in 2012 found that although 90 % of population had an air conditioner, those with low household income were likely to not turn on their AC even while feeling hot (Gao et al., 2020). Additionally, the meteorological data measured outdoor temperatures from a single station could either over- or under-estimate the actual temperature exposures experienced by the individual, depending on the UHI intensity of their immediate location and especially those indoors.

5. Conclusions

Our study found that the UHI effect under extreme heat scenarios led to an increased risk of mortality in high temperatures compared to non-extreme heat scenarios. Under the extreme heat scenario, mortality risk in High UHIdh_EH areas were almost double that of Moderate UHIdh_EH areas. This demonstrates that spatially varying UHI intensity due to extreme heat has real-world implications on heat vulnerability and adverse health outcomes of populations and more must be done to identify those high UHI areas. Similar to this study, future studies should also model the UHI effect under extreme heat scenarios when assessing for the temperature-mortality effect and other adverse health outcomes. In an era of climate change and ageing societies, strategic climate change adaptation and healthy city planning are desired to improve the living quality of residents and promote population health. For dealing with urban heat, the UHI effect under extreme heat events must be addressed in the development of preventative measures to reduce the heat-health impact in urbanized environments.

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CRediT authorship contribution statement

Janice Y. Ho: Methodology, Investigation, Formal analysis, Data curation, Writing – original draft, Visualization. **Yuan Shi:** Resources, Data curation, Writing – review & editing, Visualization. **Kevin K.L. Lau:** Writing – review & editing, Project administration. **Edward Y.Y. Ng:** Writing – review & editing, Supervision, Funding acquisition. **Chao Ren:** Conceptualization, Resources, Methodology, Writing – review & editing, Supervision. **William B. Goggins:** Conceptualization, Resources, Methodology, Writing – review & editing, Supervision, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

An, N., Dou, J., González-Cruz, J.E., Bornstein, R.D., Miao, S., Li, L., 2020. An observational case study of synergies between an intense heat wave and the urban Heat Island in Beijing. J. Appl. Meteorol. Climatol. 59 (4), 605–620. https://doi.org/10.1175/jamc-d-19-0125.1.

Anderson, G.B., Bell, M.L., 2011. Heat waves in the United States: mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities. Environ. Health Perspect. 119 (2), 210–218. https://doi.org/10.1289/ehp.1002313.

Astrom, D.O., Forsberg, B., Rocklov, J., 2011. Heat wave impact on morbidity and mortality in the elderly population: a review of recent studies. Maturitas 69 (2), 99–105. https://doi.org/10.1016/j.maturitas.2011.03.008.

Basu, R., 2009. High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. Environ. Health 8, 40. https://doi.org/10.1186/1476-069X-8-40.

Bunker, A., Wildenhain, J., Vandenbergh, A., Henschke, N., Rocklov, J., Hajat, S., Sauerborn, R., 2016. Effects of air temperature on climate-sensitive mortality and morbidity outcomes in the elderly; a systematic review and meta-analysis of epidemiological evidence. EBioMedicine 6, 258–268. https://doi.org/10.1016/j.ebiom.2016.02.034.

Chan, E.Y., Goggins, W.B., Kim, J.J., Griffiths, S.M., 2012. A study of intracity variation of temperature-related mortality and socioeconomic status among the Chinese population in Hong Kong. J. Epidemiol. Community Health 66 (4), 322–327. https://doi.org/10.1136/jech.2008.085167.

Cheng, J., Xu, Z., Bambrick, H., Su, H., Tong, S., Hu, W., 2018. Heatwave and elderly mortality: an evaluation of death burden and health costs considering short-term mortality displacement. Environ. Int. 115, 334–342. https://doi.org/10.1016/j.envint.2018.03.041.

Electrical and Mechanical Services Department, 2013. Hong Kong Energy End-use Data 2013 Retrieved from Hong Kong.

Electrical and Mechanical Services Department, 2021. Hong Kong Energy End-use Data 2021 Retrieved from Hong Kong.

Founda, D., Santamouris, M., 2017. Synergies between urban Heat Island and heat waves in Athens (Greece), during an extremely hot summer (2012). Sci. Rep. 7 (1), 10973. https://doi.org/10.1038/s41598-017-11407-6.

Gabriel, K.M., Endlicher, W.R., 2011. Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. Environ. Pollut. 159 (8-9), 2044–2050. https://doi.org/10.1016/j.envpol.2011.01.016.

Gao, Y., Chan, E.Y.Y., Lam, H.C.Y., Wang, A., 2020. Perception of potential health risk of climate change and utilization of fans and air conditioners in a representative population of Hong Kong. Int. J. Disast. Risk Sci. 11 (1), 105–118. https://doi.org/10.1007/s13753-020-00256-z.

Gasparrini, A., 2011. Distributed lag linear and non-linear models in R: the package dlnm. Retrieved from J. Stat. Softw. 43 (8), 1–20. https://doi.org/10.18637/jss.v043.i08.

Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., Armstrong, B., 2015. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. Lancet 386 (9991), 369–375. https://doi.org/10.1016/s0140-6736(14)62114-0.

Gasparrini, A., Scheipl, F., Armstrong, B., Kenward, M.G., 2017. A penalized framework for distributed lag non-linear models. Biometrics 73 (3), 938–948. https://doi.org/10.1111/biom.12645.

Goggins, W.B., Chan, E.Y., Ng, E., Ren, C., Chen, L., 2012. Effect modification of the association between short-term meteorological factors and mortality by urban heat islands in Hong Kong. PLoS One 7 (6), e38551. https://doi.org/10.1371/journal.pone.0038551.

Gosling, S.N., McGregor, G.R., Lowe, J.A., 2009. Climate change and heat-related mortality in six cities part 2: climate model evaluation and projected impacts from changes in the mean and variability of temperature with climate change. Int. J. Biometeorol. 53 (1), 31–51. https://doi.org/10.1007/s00484-008-0189-9.

Heaviside, C., Macintyre, H., Vardoulakis, S., 2017. The urban Heat Island: implications for health in a changing environment. Curr. Environ. Health Rep. 4 (3), 296–305. https://doi.org/10.1007/s40572-017-0150-3.

Heaviside, C., Vardoulakis, S., Cai, X.M., 2016. Attribution of mortality to the urban heat island during heatwaves in the West Midlands, UK. Environ. Health 15, 27. https://doi.org/10.1186/s12940-016-0100-9.
HKSAR Census and Statistics Department, 2017. 2016 Population By-census: A202 Population Density by District Council District and Year. Hong Kong Special Administrative Region: The Government of the Hong Kong Special Administrative Region. Retrieved from https://www.bycensus2016.gov.hk/en/bc-mt.html.
Hondula, D.M., Davis, R.E., Leisten, M.J., Saha, M.V., Veazey, L.M., Wegner, C.R., 2012. Fine-scale spatial variability of heat-related mortality in Philadelphia County, USA, from 1983–2008: a case-series analysis. Environ. Health 11, 16. https://doi.org/10.1186/1476-069X-11-16.
Hua, J., Zhang, X., Ren, C., Shi, Y., Lee, T.-C., 2021. Spatiotemporal assessment of extreme heat risk for high-density cities: a case study of Hong Kong from 2006 to 2016. Sustain. Cities Soc. 64. https://doi.org/10.1016/j.scs.2020.102507.
Intergovernmental Panel on Climate Change (IPCC), 2021. Climate Change 2021: The Physical Science Basis - Summary for Policymakers (AR6). IPCC, Switzerland.
Jiang, S., Lee, X., Wang, J., Wang, K., 2019. Amplified urban Heat Islands during heat wave periods. J. Geophys. Res. Atmos. 124 (14), 7797–7812. https://doi.org/10.1029/2018jd030230.
Laaidi, K., Zeghnoun, A., Dousset, B., Bretin, P., Vandentorren, S., Giraudet, E., Beaudeau, P., 2012. The impact of heat islands on mortality in Paris during the August 2003 heat wave. Environ. Health Perspect. 120 (2), 254–259. https://doi.org/10.1289/ehp.1103532.
Lee, T.C., Chan, K.Y., Ginn, W.L., 2011. Projection of extreme temperatures in Hong Kong in the 21st century. Acta Meteor. Sinica 25 (1), 1–20. https://doi.org/10.1007/s13351-011-0001-3.
Li, D., Bou-Zeid, E., 2013. Synergistic interactions between urban Heat Islands and heat waves: the impact in cities is larger than the sum of its parts. J. Appl. Meteorol. Climatol. 52 (9), 2051–2064. https://doi.org/10.1175/jamc-d-13-02.1.
Ma, W., Zeng, W., Zhou, M., Wang, L., Rutherford, S., Lin, H., Chu, C., 2015. The short-term effect of heat waves on mortality and its modifiers in China: an analysis from 66 communities. Environ. Int. 75, 103–109. https://doi.org/10.1016/j.envint.2014.11.004.
Macintyre, H.L., Heaviside, C., Taylor, J., Picetti, R., Symonds, P., Cai, X.M., Vardoulakis, S., 2018. Assessing urban population vulnerability and environmental risks across an urban area during heatwaves - implications for health protection. Sci. Total Environ. 610–611, 678–690. https://doi.org/10.1016/j.scitotenv.2017.08.062.
Milojevic, A., Armstrong, B.G., Gasparrini, A., Bohnenstengel, S.I., Barratt, B., Wilkinson, P., 2016. Methods to estimate acclimatization to urban Heat Island effects on heat- and cold-related mortality. Environ. Health Perspect. 124 (7), 1016–1022. https://doi.org/10.1289/ehp.1510109.
Oke, T., 1982. The energetic basis of the urban heat island (Symons memorial lecture, 20 may 1980). Q. J. R. Meteorol. Soc. 108, 1–24.
Ouchi, Y., Rakugi, H., Arai, H., Akishita, M., Ito, H., Toba, K., Classification of the E., 2017. Redefining the elderly as aged 75 years and older: proposal from the Joint Committee of Japan Gerontological Society and the Japan Geriatrics Society. 17 (7), 1045–1047. https://doi.org/10.1111/ggi.13118.
R Core Team, 2018. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Ren, C., Wang, K., Shi, Y., Kwok, Y.T., Morakinyo, T.E., Lee, T.C., Li, Y., 2021. Investigating the urban heat and cool island effects during extreme heat events in high-density cities: a case study of Hong Kong from 2000 to 2018. Int. J. Climatol. 41 (15), 6736–6754. https://doi.org/10.1002/joc.7222.
Sheridan, S.C., Lin, S., 2014. Assessing variability in the impacts of heat on health outcomes in New York City over time, season, and heat-wave duration. EcoHealth 11 (4), 512–525. https://doi.org/10.1007/s10393-014-0970-7.
Shi, Y., Ren, C., Cai, M., Lau, K.K., Lee, T.C., Wong, W.K., 2019. Assessing spatial variability of extreme hot weather conditions in Hong Kong: a land use regression approach. Environ. Res. 171, 403–415. https://doi.org/10.1016/j.envres.2019.01.041.
Shreevastava, A., Prasanth, S., Ramamurthy, P., Rao, P.S.C., 2021. Scale-dependent response of the urban heat island to the european heatwave of 2018. Environ. Res. Lett. 16 (10). https://doi.org/10.1088/1748-9326/ac25bb.
Smargiassi, A., Goldberg, M.S., Plante, C., Fournier, M., Baudouin, Y., Kosatsky, T., 2009. Variation of daily warm season mortality as a function of micro-urban heat islands. J. Epidemiol. Community Health 63 (8), 659–664. https://doi.org/10.1136/jech.2008.078147.
Son, J.Y., Lee, J.T., Anderson, G.B., Bell, M.L., 2012. The impact of heat waves on mortality in seven major cities in Korea. Environ. Health Perspect. 120 (4), 566–571. https://doi.org/10.1289/ehp.1103759.
Tan, J., Zheng, Y., Tang, X., Guo, C., Li, L., Song, G., Li, F., 2010. The urban heat island and its impact on heat waves and human health in Shanghai. Int. J. Biometeorol. 54 (1), 75–84. https://doi.org/10.1007/s00484-009-0256-x.
Taylor, J., Wilkinson, P., Davies, M., Armstrong, B., Chalabi, Z., Mavrogianni, A., Bohnenstengel, S.I., 2015. Mapping the effects of urban heat island, housing, and age on excess heat-related mortality in London. Urban Clim. 14, 517–528. https://doi.org/10.1016/j.uclim.2015.08.001.
United Nations Environment Programme, 2021. Beating the heat: a sustainable cooling handbook for cities. Retrieved from Nairobi.
United Nations Office of Disaster Risk Reduction (UNDRR), 2022. Heatwaves: Addressing a Sweltering Risk in Asia-Pacific Retrieved from.
Vandentorren, S., Bretin, P., Zeghnoun, A., Mandereau-Bruno, L., Croisier, A., Cochet, C., Ledrans, M., 2006. August 2003 heat wave in France: risk factors for death of elderly people living at home. Eur. J. Pub. Health 16 (6), 583–591. https://doi.org/10.1093/eurpub/ckl063.
Wang, D., Lau, K.K., Ren, C., Goggins, W.B.I., Shi, Y., Ho, H.C., Ng, E., 2019. The impact of extremely hot weather events on all-cause mortality in a highly urbanized and densely populated subtropical city: a 10-year time-series study (2006–2015). Sci. Total Environ. 690, 923–931. https://doi.org/10.1016/j.scitotenv.2019.07.039.
WMO-WHO, 2015. Heatwaves and Health: Guidance on Warning-System Development. Retrieved from Geneva, Switzerland: https://public.wmo.int/en/resources/library/heatwaves-and-health-guidance-warning-system-development.
Wood, S., 2017. Generalized Additive Models: An Introduction With R. 2nd edition. Chapman and Hall/CRC.
World Health Organization, 2020. Decade of healthy ageing 2020–2030 proposal document. Retrieved from https://www.who.int/initiatives/decade-of-healthy-ageing.
Yang, X., Li, Y., Luo, Z., Chan, P.W., 2017. The urban cool island phenomenon in a high-rise high-density city and its mechanisms. Int. J. Climatol. 37 (2), 890–904. https://doi.org/10.1002/joc.4747.
Zhou, Y., Shepherd, J.M., 2009. Atlanta's urban heat island under extreme heat conditions and potential mitigation strategies. Nat. Hazards 52 (3), 639–668. https://doi.org/10.1007/s11069-009-9406-z.