Title: 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+

**Abstract**

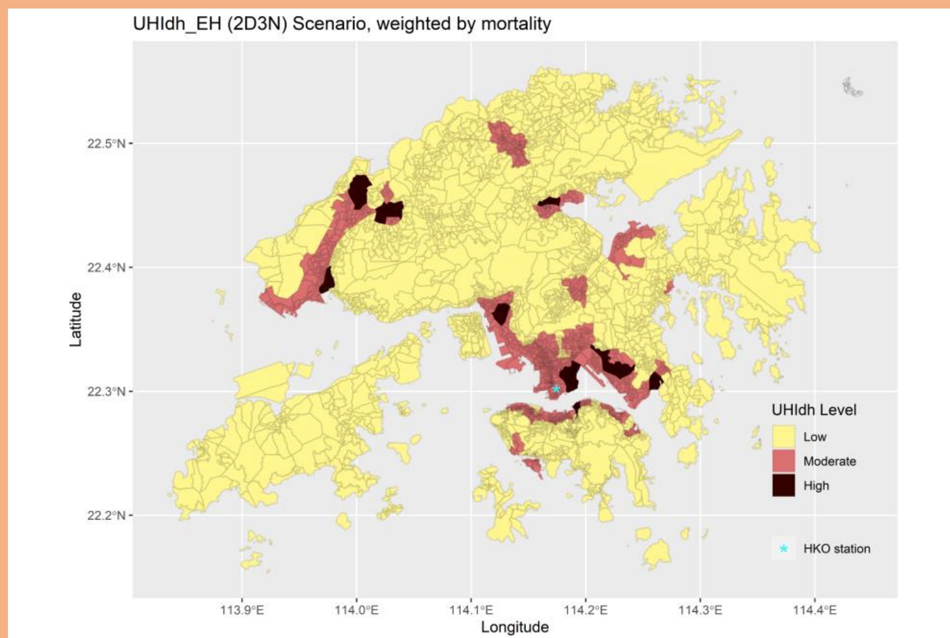
The urban heat island (UHI) effect exacerbates the adverse impact of heat on human health. However, while the UHI effect is further intensified during extreme heat events, prior studies have rarely mapped the UHI effect during extreme heat events to assess its direct temperature impact on mortality. 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 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.

Keywords: urban heat island, temperature, heatwave, elderly, heat-mortality

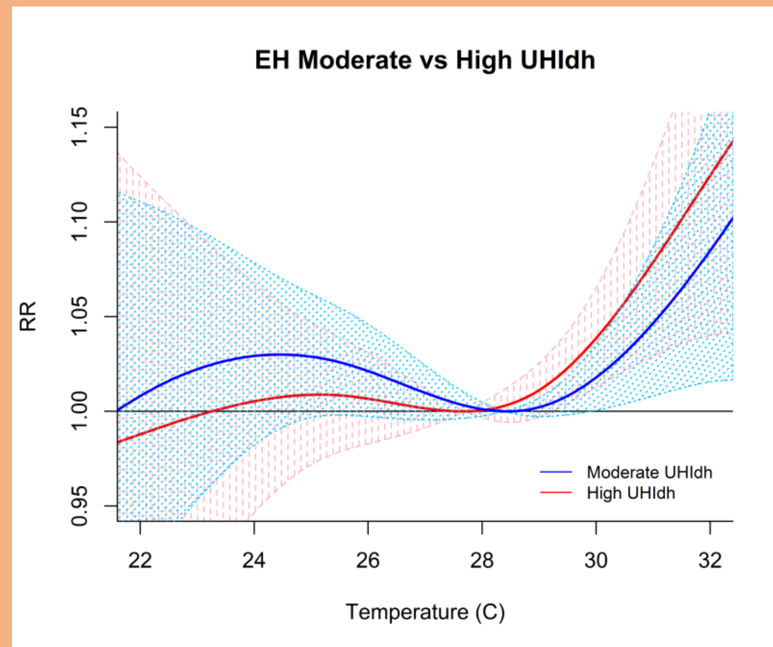
Graphical Abstract

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

Extreme heat UHI scenario, Spatial map of Hong Kong




Temperature-mortality curves under Extreme Heat UHI scenario, Hong Kong 2010-2019




**Conclusion:** Under extreme heat UHI scenario, mortality risk was greater in High UHI areas than Moderate UHI areas


Reference: Ho JY, Shi Y, Lau KKL, Ng EYY, Ren C, and Goggins WB. (2022). Urban heat island effect-related mortality under extreme heat and non-extreme heat scenarios: A 2010-2019 case study in Hong Kong. *Science of the Total Environment*

51 Abbreviations:

52 UHIdh: Urban Heat Island degree hours

53 UHIdh_EH: UHIdh under the extreme heat (2D3N) scenario

54 2D3N: three consecutive hot nights with two hot days in between

55 HDHN: Consecutive one hot day and one hot night

56 TPU: Tertiary Planning Unit

57 DLNM: Distributed Lag Non-linear Models

58 GAM: Generalized Additive Model

59 MMT: Minimum mortality temperature

60

61 # 1 Introduction

62 The climate change phenomenon has intensified in the recent years, leading to more hot extremes
63 and heatwaves among other climate impacts (Intergovernmental Panel on Climate Change (IPCC),
64 2021). While the last decade contained the hottest years on record (United Nations Office of
65 Disaster Risk Reduction (UNDRR), 2022), increasing frequency and duration of heatwaves will
66 continue in the coming decades (Intergovernmental Panel on Climate Change (IPCC), 2021). High
67 ambient temperatures have been associated with adverse health outcomes of mortality and
68 morbidity globally (Astrom et al., 2011; Basu, 2009; Gasparrini et al., 2015; Gosling et al., 2009). In
69 the subtropical city of Hong Kong, mortality was found to increase in temperatures above 28.2°C, by
70 1.8% for every 1°C increase (Chan et al., 2012). While most studies in literature have assessed the
71 overall relationship between temperature and mortality in different cities, studies have also begun
72 addressing the intra-city (within-city) variations of the temperature-mortality association throughout
73 the city.
74 The Urban Heat Island (UHI) effect is a crucial aspect where cities experience heterogeneity in their
75 temperature-mortality effect and a "threatening phenomenon" of less well-planned urbanization
76 (United Nations Office of Disaster Risk Reduction (UNDRR), 2022). Defined as where urban areas
77 experience warmer temperatures than the surrounding rural areas (Oke, 1982), the UHI effect
78 develops when built-up urban environments absorb and retain more heat than natural
79 environments, and are slower to cool down at night. The UHI effect is further intensified during
80 heatwave events, particularly in urban areas of high-density cities. The favourable conditions for
81 heatwaves correspond to the ideal conditions for high UHI (Heaviside et al., 2017).
82 However, despite the UHI phenomenon being well-documented, mortality studies on the UHI effect
83 are typically segregated into two approaches. One approach estimates the intra-city excess mortality
84 that occurs during heatwave events (Gabriel & Endlicher, 2011; Hondula et al., 2012; Tan et al.,
85 2010; Taylor et al., 2015), particularly of historically significant heat events such as the 2003
86 European heatwave (Heaviside et al., 2016; Laaidi et al., 2012; Vandentorren et al., 2006). These

87 studies report increased mortality risk during the heatwave in areas with higher UHI, with up to 50%
88 of heat mortality attributable to the UHI effect (Heaviside et al., 2016), although this may be related
89 to the coinciding spatial distribution of building types, deprivation, and vulnerable populations
90 (Hondula et al., 2012; Macintyre et al., 2018). However, these one-off extreme events are unable to
91 support the continuous monitoring of the UHI effect or trace the mortality effect at different
92 temperatures.
93 The other approach assesses the overall temperature-mortality relationship but use the overall
94 summer season as reference for their UHI intra-city variability (Goggins et al., 2012; Milojevic et al.,
95 2016; Smargiassi et al., 2009). Although heat-mortality risk was sometimes found greater in areas
96 with high UHI (Goggins et al., 2012; Smargiassi et al., 2009), these studies using overall summer UHI
97 models do not account for intensification of the UHI effect during heatwaves (Li & Bou-Zeid, 2013)
98 which occur particularly in high-density cities and coastal cities (Founda & Santamouris, 2017; Jiang
99 et al., 2019; Shreevastava et al., 2021). Furthermore, the overall summer UHI model does not
100 account for the fact that the UHI amplification during heatwaves may not be homogenous across the
101 city (Taylor et al., 2015; Zhou & Shepherd, 2009). A previous London UHI study found different
102 temperature patterns between heatwave days and overall summer season (Taylor et al., 2015).
103 However, these findings were not translated into further health-related analysis as only the spatial
104 distribution of the overall summer UHI was used in subsequent excess mortality analysis (Taylor et
105 al., 2015). Not accounting for the UHI intensification under heatwaves may have minimized and
106 underestimated the mortality effect under the UHI effect and any associated heterogeneity.
107 A UHI model considering both the UHI effects of prolonged heatwave and spatial variation of
108 heatwaves is needed in heat-risk assessment, especially temperature-mortality studies. Heatwaves
109 may affect both the spatial variation of the UHI effect, and also produce compounded effects of
110 mortality depending on the heatwave duration (Anderson & Bell, 2011; Sheridan & Lin, 2014; Son et
111 al., 2012; Wang et al., 2019). This study examined and compared the effect modification of extreme
112 heat and non-extreme heat UHI scenarios on the association between temperature and non-

113 external mortality in Hong Kong from 2010 to 2019. This study builds on the previous research in
114 Hong Kong that assessed the UHI effect during the overall summer season (Goggins et al., 2012). As
115 the last decade is the hottest years on record (United Nations Office of Disaster Risk Reduction
116 (UNDRR), 2022), the developed knowledge from this study would increase our understanding about
117 the intra-urban variation of heat-related mortality risk and support the development of city-level
118 heat action plans. The findings could be referred by other high-density cities in subtropical climate
119 regions.
120

121 # 2 Material and Methods

122 ## 2.1 Study area and data sources

123 Hong Kong is a coastal sub-tropical high-density city with hot and humid summers. Its population
124 density in 2016 had on average 6,777 persons per square kilometre, and up to 57,530 persons per
125 square kilometre in Kwun Tong area (HKSAR Census and Statistics Department, 2017).
126 Daily mean temperature and other meteorological variables were obtained for the 2010-2019 period
127 from the Hong Kong Observatory. A singular weather station from the city centre was used to be
128 representative of the temperature exposures of the city. Air pollutant data was collected from the
129 Hong Kong Environmental Protection Department for the same period from 12 general monitoring
130 stations across the city, which were averaged across the stations for each day. The pollutants of fine
131 particulate matter (PM2.5), nitrogen dioxide (NO2), and ozone (O3) were adjusted for in the
132 sensitivity analyses.
133 Mortality data in Hong Kong were obtained from the Hong Kong Census and Statistics Department
134 for the 2010-2019 period. The dataset included variables of date of death, cause of death (ICD-9 to
135 10 updated), age, sex, occupation, marital status, and Tertiary Planning Unit (TPU) of residence for
136 each decedent. TPUs are small geographical units set by the Planning Department of the Hong Kong
137 Special Administrative Region government. Each TPU was later used to assign the UHIdh level (Low,

138 Moderate, High) under different extreme heat/non-extreme heat scenarios. Non-external mortality
139 (death by natural causes) and non-cancer non-external mortality (subsequently referred to as non-
140 cancer mortality) were both examined in this analysis, since a previous study found non-cancer
141 mortality to be more sensitive to heat effects (Chan et al., 2012).

## 142 2.2 Calculations for Urban Heat Island under extreme heat and non-extreme heat 143 scenarios

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

161

162 In this study, we adopted the new concept of Urban Heat Island degree hours (UHIdh) to evaluate
163 the heat-health impact, as it comprehensively measures both the duration and difference in
164 temperature of a selected meteorological station with reference to a representative rural station
165 (Yang et al., 2017). UHIdh was calculated for 22 meteorological observation stations managed by the
166 Hong Kong Observatory across the city for the summer seasons May-Sept of 2000–2018 (Ren et al.,
167 2021). The spatial variation of UHIdh was then generated across Hong Kong using land use
168 regression, a buffering analysis and regression-based spatial mapping methodology (Shi et al., 2019).
169 Urban morphological parameters and landscape metrics were generated and analyzed as predictor
170 variables in a multiple linear regression for each extreme heat and non-extreme heat scenario.
171 Influential predictor variables of the regression modelling were then mapped and overlayed to
172 generate a composite spatial data layer, which was then aggregated to the TPU level (Shi et al.,
173 2019). This resulted in a TPU-level UHIdh value for each extreme heat and non-extreme heat
174 scenario defined in the previous paragraph. The detailed methodology of mapping UHIdh can be
175 further found in Ren et al. (2021) and Shi et al. (2019). The analysis found that "compact building
176 clusters of urban areas contribute to the increased UHIdh, especially at night during extreme heat
177 events" (Ren et al., 2021).
178 To stratify the mortality data, each TPU was initially weighted by the cumulative mortality count of
179 the study period. This weighting was used to classify the TPU-level UHIdh calculations into three
180 levels: Low (lowest 25%), Moderate (50%), and High (upper 25%). The mortality data was then
181 stratified accordingly into the three UHIdh levels and further aggregated by mortality type: non-
182 external, non-cancer; and age group: 74 and less, 75 and above (Cheng et al., 2018; Ma et al., 2015;
183 Ouchi et al., 2017). This was done separately for each of the four extreme heat/non-extreme heat
184 scenarios: EH (consecutive 2D3N), no2D3N, HDHN, and noHDHN.
185

186 ## 2.3 Analytical methods

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

201

202 $E(Daily\ non\ external\ mortality) = cb(mean\ temperature, df = 6;\ lag = 4, dflag = 5)\ +$

203 $s(day\ of\ study, k = 5)\ +\ s(day\ of year, k = 5)\ +\ factor(day\ of\ week)\ +\ factor(holiday)$

204 cb indicates the crossbasis of independent variables created using R package "dlnm" (Gasparrini, 2011)

205 df indicates the maximum degrees of freedom used in the crossbasis

206 s() indicates the smoothing function of continuous independent variables in R package "mgcv" (Wood, 2017)

207 k indicates the basis dimension for the smooth, such that k-1 is the maximum degrees of freedom

208 factor() indicates the categorical independent variables

209

210 The minimum mortality temperature (MMT) was identified for each model and used to center the
211 final outcome. Cumulative relative risk (RR) of the entire lag period was calculated in comparison to

212 the MMT, according to percentiles of the summer season analysis period (Table 1). Sensitivity
213 analyses assessed the effect of individual pollutants on the models: PM2.5, NO2, and ozone; and the
214 effect of different age groupings (64 and younger, 65 to 74, 75 and above). Statistical significance
215 level was set at $p \leq 0.05$. All analyses were conducted with the statistical software R (version 3.5.2)
216 (R Core Team, 2018), using the dlnm() (Gasparrini, 2011) and mgcv() (Wood, 2017) packages.
217

# 218 3 Results

## 219 3.1 Spatial patterns of extreme heat/non-extreme heat scenarios & other
## 220 descriptive statistics

221 The four extreme heat/non-extreme heat scenarios demonstrated different spatial patterns of
222 UHIdh heating (Ren et al., 2021), with different "hot spot" areas throughout the city [Figure 1 a-d].
223 For the extreme heat scenario UHIdh_EH (consecutive 2D3N), high UHIdh was found located in
224 several "new towns" of suburban New Territories. These included areas of Tin Shui Wai, Yuen Long,
225 Tuen Mun Town Centre, Tai Po, Kwai Chung, and Tseung Kwan O, in addition to the urban areas of
226 To Kwa Wan-Whampoa-Homantin, Tin Hau-Fortress Hill, and Choi Hung-Ngau Tau Kok. In contrast,
227 the other maps (no2D3N, HDHN, or noHDHN), high UHIdh comprised of more urban areas of
228 Kowloon and Hong Kong Island.
229 In terms of descriptive statistics, during the summer seasons (May 15-Oct 15) of 2010-2019, there
230 was a total of 162,262 non-external mortality counts and 104,073 non-cancer mortality counts.
231 Mean temperature ranged from 20.5 -32.4°C, with an average of 28.4°C (standard deviation = 1.64).
232 Table 2 shows the average daily mortality counts for each outcome according to the UHIdh level
233 (Low, Moderate, High) of the extreme heat scenario (UHIdh_EH). The mortality counts for the other
234 scenarios can be found in Appendix A, Table A.1, with the cut-offs for each scenario shown in Figure
235 A.1.
236

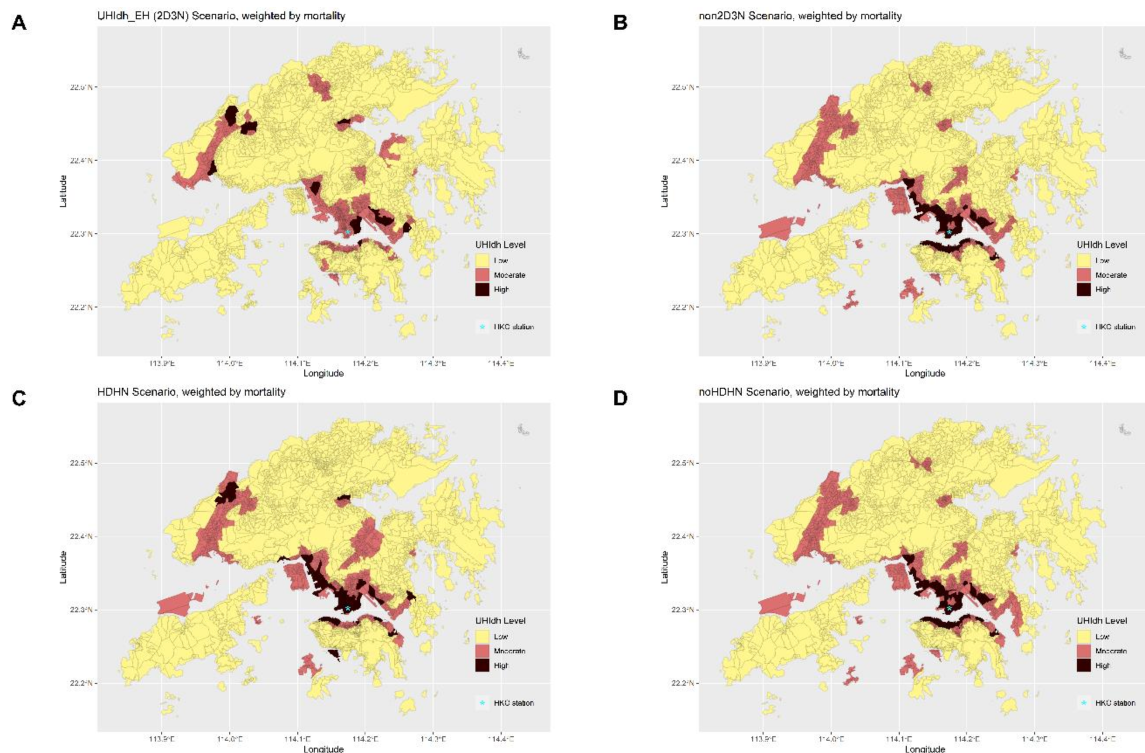



Figure 1. Spatial map of UHIdh levels for extreme heat and non-extreme heat scenarios: A) Extreme heat 2D3N, B) non2D3N, C) HDHN, and D) noHDHN. The UHIdh levels were classified by weighting each TPU with the cumulative mortality count of the study period and grouping based on: Low (lowest 25%), Moderate (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.

## 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 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 (Figure 2). Figure 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

253 UHIdh_EH areas, the 99th percentile relative risk (RR) (vs. MMT 27.7°C) was 1.08 (95%CI: 1.03, 1.14)

254 for non-external mortality. This was almost double the 99th percentile RR in Moderate UHIdh_EH (vs.

255 MMT 28.4°C) which was found at 1.05 (95% CI: 1.01, 1.09)). A consistent doubling of RR at all

256 percentiles can be seen between Moderate and High UHIdh_EH.

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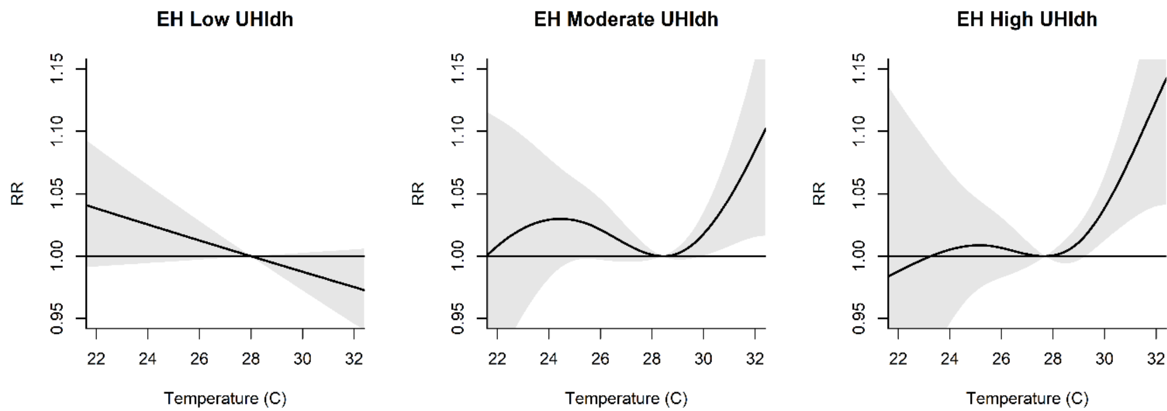


258

259 **Figure 2. Temperature-mortality associations for Low, Moderate, and High UHIdh levels under the**

260 **extreme heat scenario (EH)**

261

262

263 Stronger heat effects were found for non-cancer mortality outcomes. For those living in Moderate

264 UHIdh_EH areas, the 99th percentile RR (vs. MMT 28.3 °C) was 1.06 (95% CI: 1.01, 1.11), while the

265 99th percentile RR (vs. MMT 28.1°C) reached 1.11 (95% CI: 1.04, 1.19) for those living in High

266 UHIdh_EH areas. A steeper rate of increase was identified for non-cancer mortality in High

267 UHIdh_EH despite a higher MMT than that for non-external mortality.

268 When stratified by age, those aged 74 and younger showed no increase in mortality during hot

269 temperatures, whether for non-external or non-cancer mortality. Among those aged 75 and older,

270 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

271 Moderate and High UHIdh_EH areas, respectively (Figure 4a). The findings among elderly were

272 similar for non-cancer mortality.

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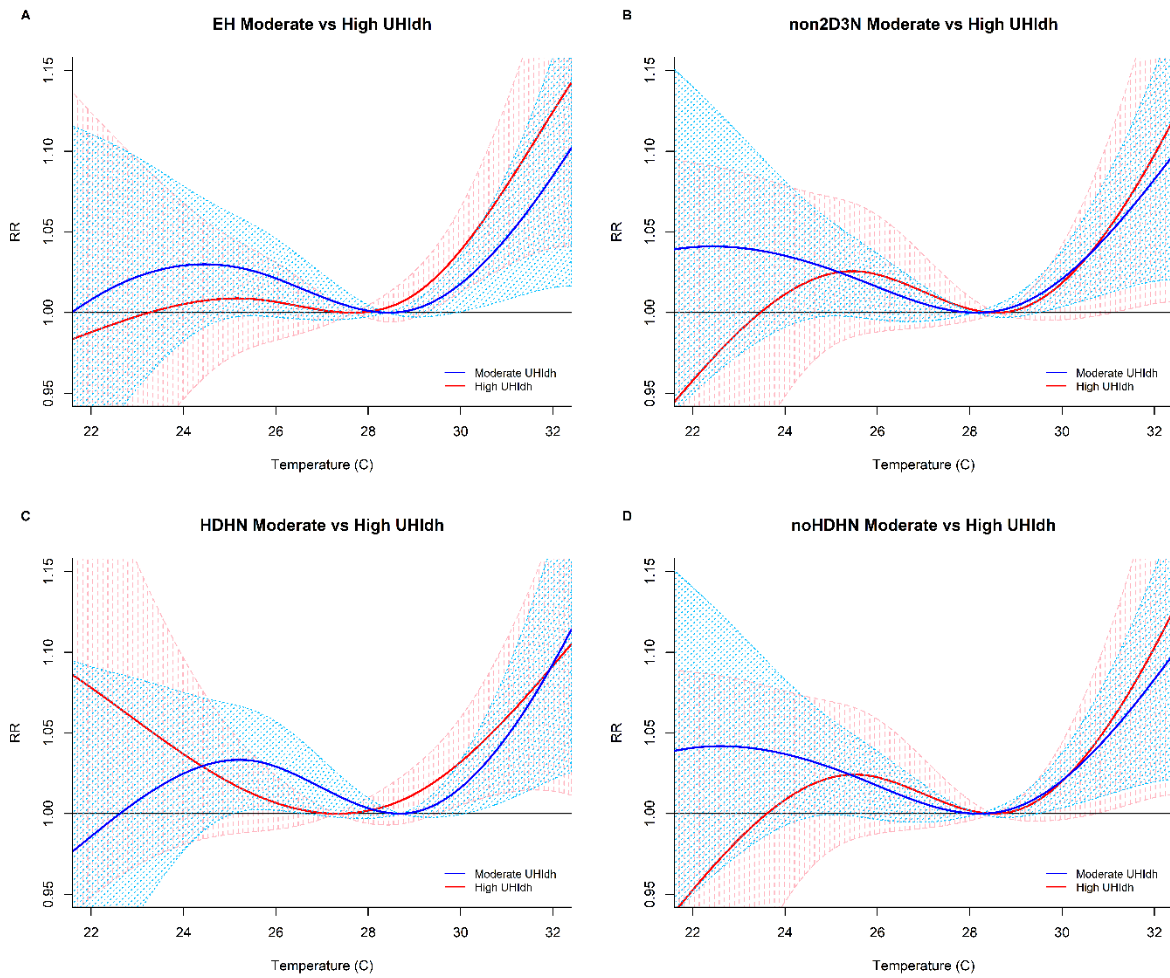


274

275 **Figure 3. Temperature-mortality associations for Moderate and High UHIdh under different**

276 **extreme heat/non-extreme heat scenarios:** A) Extreme heat 2D3N, B) non2D3N, C) HDHN, and D)

277 noHDHN

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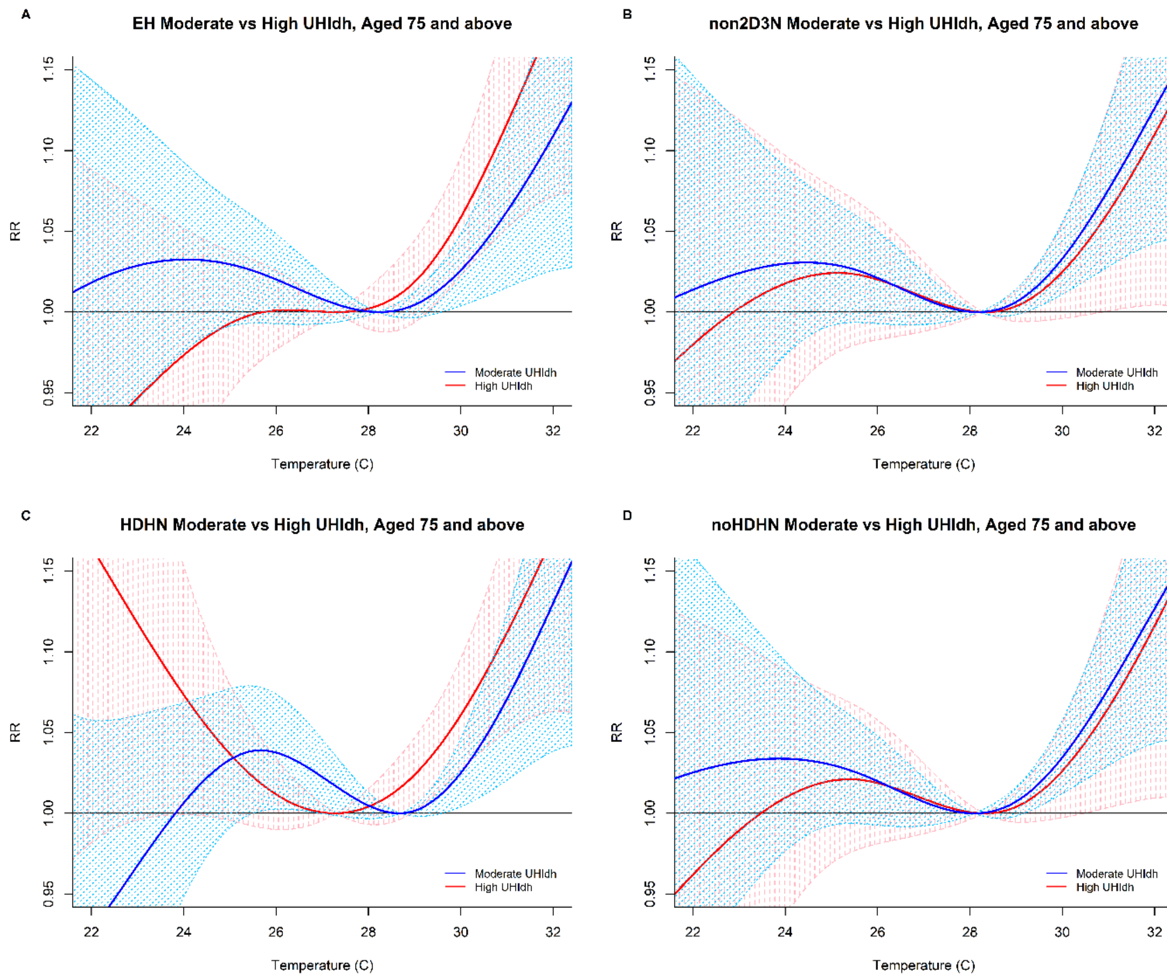


280

281 **Figure 4. Temperature-mortality associations among elderly aged 75 and above for Moderate and**

282 **High UHIdh under different extreme heat/non-extreme heat scenarios:** A) Extreme heat 2D3N, B)

283 non2D3N, C) HDHN, and D) noHDHN

284

285

286 ## 3.3 Comparisons with mortality associations under other extreme heat/non-extreme

287 heat scenarios

288 While the outcomes in the extreme heat (2D3N) scenario consistently demonstrated a near doubling

289 of relative risk between those living in Moderate and High UHIdh areas, the other three scenarios

290 did not find the same contrast. Table 4 shows the findings of 90$^{th}$ and 99$^{th}$ percentile for each

291 scenario. Figure 3 graphically demonstrate the difference between Moderate and High UHIdh areas

292 for each scenario for non-external mortality. Figure 4 illustrates the same for elderly mortality, while
293 Figures A.2 and A.3 in Appendix A show the scenarios for overall and elderly non-cancer mortality,
294 respectively. When comparing the outcomes of Moderate and High UHIdh areas, the scenarios of
295 No2D3N, HDHN, and noHDHN mostly found a difference of 0-2% relative risk. For example, the 99$^{th}$
296 percentile RR of non-external mortality was 1.05 (95% CI: 1.01, ~1.09) for Moderate but only 1.06
297 (95% CI: 1.01, ~1.11) for High areas. This was similar for other outcomes in the three scenarios. The
298 outcomes of the HDHN scenario more closely resembled our original 2D3N scenario, especially for
299 non-external mortality of 75 and above, with a 4% difference in RR between Moderate and High
300 UHIdh areas. However, this was not consistent across other outcomes. Meanwhile, the no2D3N and
301 noHDHN scenarios found a non-significant association in High UHIdh areas for the more moderate
302 90$^{th}$ percentile RR.

## 303 3.4 Sensitivity analyses

304 When adjusted for pollutants individually, the overall findings and trends were retained in the
305 extreme heat (2D3N) scenario analyses (Table 5). Among the elderly 75 and above, the 99th
306 percentile RR of non-cancer mortality was no longer significant for those living in Moderate
307 UHIdh_EH and there was a slight decrease in RR for those living in High UHIdh_EH when adjusted for
308 PM2.5 lag 0-1 or ozone lag 0-1. Overall, the difference between Low, Moderate and High UHIdh_EH
309 remained consistent when adjusted for pollutants.
310 When analyzing the associations by different age groups, no significant associations were found for
311 those 64 and younger, and those 65 to 74 (Appendix A, Table A.2).
312

# 313 4 Discussion

314 Our study found that when classified by the urban heat island effect during the extreme heat
315 scenario (UHIdh_EH), areas of Moderate and High UHIdh_EH found a significant increase of
316 mortality risk in hot temperatures, while Low UHIdh_EH areas found no temperature-mortality

317 association. High UHIdh_EH areas demonstrated almost double the risk of Moderate UHIdh_EH
318 areas, with the mortality risk also starting earlier at a lower minimum mortality threshold (High vs.
319 Moderate UHIdh_EH: MMT 27.7°C vs. 28.4°C). Other non-extreme heat scenarios, which considered
320 different variations or the absence of extreme heat days, did not demonstrate as large a difference
321 between Moderate and High UHIdh levels as the extreme heat scenario. These findings demonstrate
322 the importance of considering the urban heat island effect not just for the overall summer, but
323 specifically during extreme heat events. Not only is the urban heat island effect intensified during
324 periods of extreme heat, but also the spatial distribution of this UHI intensification may vary. As
325 identified in Section 3.1, the extreme heat scenario accounted for several "new towns" in more
326 suburban areas of the city that were not included in the other non-extreme heat scenarios. This
327 study used the weather station at the Hong Kong Observatory Headquarters located in the city
328 center to conduct the analysis and compare differences in mortality risk between UHIdh levels. Our
329 findings demonstrate that the temperature data at the city center serves as a strong predictor of
330 heat-health risk particularly for moderate and high UHI areas, but less so for low UHI areas.
331 Moreover, under the extreme heat scenario, the location of the weather station was assigned to the
332 moderate UHIdh level, due to weighting of UHIdh by cumulative mortality counts. This demonstrates
333 that a further mortality risk is uncovered when accounting for population exposure and vulnerability
334 to heatwaves.
335 Although the intensification of UHI during heatwaves has been acknowledged and addressed in
336 numerous UHI studies (An et al., 2020), but few studies have translated this knowledge into heat-
337 related mortality studies. Previous studies on the UHI effect on mortality have assessed the excess
338 mortality of singular exceptional heatwave events (Heaviside et al., 2016) or the UHI of the overall
339 summer season (Goggins et al., 2012; Smargiassi et al., 2009). Our findings correspond to the
340 previous 2001-2009 UHI study in Hong Kong, which found that temperature was not associated with
341 mortality in cool UHI areas but associated with 4.1% increase in mortality in hot UHI areas per 1°C in
342 temperatures above 29°C (Goggins et al., 2012). Acclimatization and/or adaptation, such as

343 increased air conditioning usage (Electrical & Mechanical Services Department, 2013, 2021), may
344 have contributed to the mortality risk difference in the past decade, as a separate analysis found
345 that the mortality association in 2010-2019 was not as prominent as that of 2000-2009 (analysis not
346 shown). In a previous study in London, Milojevic et al. (2016) suggested an acclimatization of the UHI
347 effect in hot temperatures, as high UHI levels did not demonstrate a multiplied risk of heat-related
348 deaths. Their UHI understanding was based on annual mean of daily excess temperatures. On the
349 other hand, our study findings seem to demonstrate an added influence of UHI effect in hot
350 temperatures when having formulated a UHI understanding from extreme heat events. Future
351 studies should also assess the temperature-mortality association and other heat-health outcomes
352 using an UHI understanding derived from extreme heat events.
353 Our study findings suggest that the UHI and temperature-mortality impact was mainly from the
354 elderly population above 75. The elderly mortality was non-significant in low UHIdh areas but was
355 more exacerbated in High UHIdh compared to Moderate UHIdh areas. This was similar to other
356 temperature-mortality studies, where elderly were found to be more vulnerable to hot
357 temperatures (Astrom et al., 2011; Bunker et al., 2016). However, to our knowledge, no UHI studies
358 have previously compared the UHI effect between the elderly and general population, but only
359 focused on the elderly. Previously, Laaidi et al. (2012) examined the impact of the 2003 heatwave
360 among the elderly population in Paris and found minimum temperatures associated with higher
361 mortality risk. On the same event, Vandentorren et al. (2006) identified risk factors among the
362 elderly such as chronic diseases, lack of mobility, living in areas with high UHI effects, in buildings
363 without insulation, and in bedrooms in the top floor. Macintyre et al. (2018) further found that care
364 homes and locations where elderly reside were more likely in hotter areas of a UK city. In terms of
365 our study, further work is needed to assess the locations within High UHIdh areas where elderly and
366 residential care homes reside. Particularly in an aging society where the proportion of older people
367 is increasing, preventive heat measures are crucial to support age-friendly environments for the
368 elderly (World Health Organization, 2020).

369

370 ## 4.1 Implications for urban heat management

371 ### 4.1.1 Factoring the UHI effect into the assessment of heat-health impact

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

379 ### 4.1.2 Developing tailor-made heat-health warning system

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

390 ### 4.1.3 Creating community-level intervention strategies

391 Based on our findings, the development of heat intervention strategies should consider the UHI
392 effect and its potential heat impact, so that different actions at the city level can be taken to reduce
393 health risks accordingly during periods of extreme heat. Our study identified an urgent need to
394 target those TPUs with high UHI intensity (such as TPUs of Tin Hau 151, To Kwa Wan 241-245, Choi
395 Hung 287, Ngau Tau Kok 293-294, Kwai Chung 326, Tuen Mun 424, Tin Shui Wai 510, Yuen Long 524,

396 Tai Po 726, Tseung Kwan O 838, etc.). Interventions could particularly be catered to areas with a
397 large proportion of elderly residents within these TPUs. As the high risk “hot spots” emerge from the
398 nocturnal UHI effect during heatwaves (Hua et al., 2021; Ren et al., 2021), heat shelters should be
399 kept open during hot nights and special assistance should be tailored to the needs of the elderly,
400 particularly those who live alone.

#### 401 4.1.4 Preparing long-term initiatives for managing heatwaves and health

402 Heatwaves will become more severe, frequent, and intense in the near future due to global climate
403 change (Intergovernmental Panel on Climate Change (IPCC), 2021). As our study found that ‘new
404 towns’ in the suburban districts of New Territories showed greater increase of UHIdh during
405 heatwaves compared to the conventional urban districts, more attention should be paid in those
406 districts to develop corresponding heat mitigation measures. These can include green or cool roofs,
407 reflective surfaces, street vegetation, and increasing ventilation via neighborhood design (United
408 Nations Environment Programme, 2021). Furthermore, as Hong Kong continues to construct more
409 new town developments in the New Territories, it would be critical for the town planners and policy
410 makers to consider climate responsive design strategies to reduce heat, manage heat exposure, and
411 create livable cooling urban environments. These include the heat mitigation measures mentioned
412 earlier, but also expand to adapting zoning requirements and building codes to include minimum
413 requirements of green spaces in zoning laws, policies for thermally efficient buildings and passive
414 cooling, and minimum energy performance requirements (United Nations Environment Programme,
415 2021). Furthermore, public authorities and local agencies are encouraged to periodically review the
416 distribution of existing heat shelters and cooling facilities in the community, as over time the
417 population vulnerability may shift or require more support to protect citizens from heat stress and
418 heat-related illnesses.

419

420 ## 4.2 Strengths and limitations

421 To our knowledge, this was the first heat-health study to do a comparison between the UHI effect in
422 extreme heat and non-extreme heat scenarios for better understanding the UHI reduced heat-health
423 impact. A comprehensive UHI understanding was derived using UHI degree hours in the spatial
424 mapping of a high-density city (Ren et al., 2021). A singular meteorological station from the city
425 center was used for comparison of the temperature-mortality effect between UHIdh levels. Creating
426 UHI scenarios at the tertiary planning unit (TPU) level of Hong Kong enables our study findings to be
427 applied directly to the urban planning of the city. We adjusted for pollutant levels in our sensitivity
428 analysis. However, our study was unable to adjust for other potential confounding factors, such as
429 socio-economic status, housing conditions, air conditioning usage, and other areas of heat
430 vulnerability or protection. A local Hong Kong telephone survey conducted in 2012 found that
431 although 90% of population had an air conditioner, those with low household income were likely to
432 not turn on their AC even while feeling hot (Gao et al., 2020). Additionally, the meteorological data
433 measured outdoor temperatures from a single station could either over- or under-estimate the
434 actual temperature exposures experienced by the individual, depending on the UHI intensity of their
435 immediate location and especially those indoors.
436

437 # 5 Conclusions

438 Our study found that the UHI effect under extreme heat scenarios led to an increased risk of
439 mortality in high temperatures compared to non-extreme heat scenarios. Under the extreme heat
440 scenario, mortality risk in High UHIdh_EH areas were almost double that of Moderate UHIdh_EH
441 areas. This demonstrates that spatially varying UHI intensity due to extreme heat has real-world
442 implications on heat vulnerability and adverse health outcomes of populations and more must be
443 done to identify those high UHI areas. Similar to this study, future studies should also model the UHI
444 effect under extreme heat scenarios when assessing for the temperature-mortality effect and other

445 adverse health outcomes. In an era of climate change and ageing societies, strategic climate change
446 adaptation and healthy city planning are desired to improve the living quality of residents and
447 promote population health. For dealing with urban heat, the UHI effect under extreme heat events
448 must be addressed in the development of preventative measures to reduce the heat-health impact
449 in urbanized environments.

450

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466 **L. Lau**: Writing - Review & Editing, Project administration; **Edward Y. Y. Ng:** Writing - Review &
467 Editing, Supervision, Funding acquisition; **Chao Ren:** Conceptualization, Resources, Methodology,
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470

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