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)

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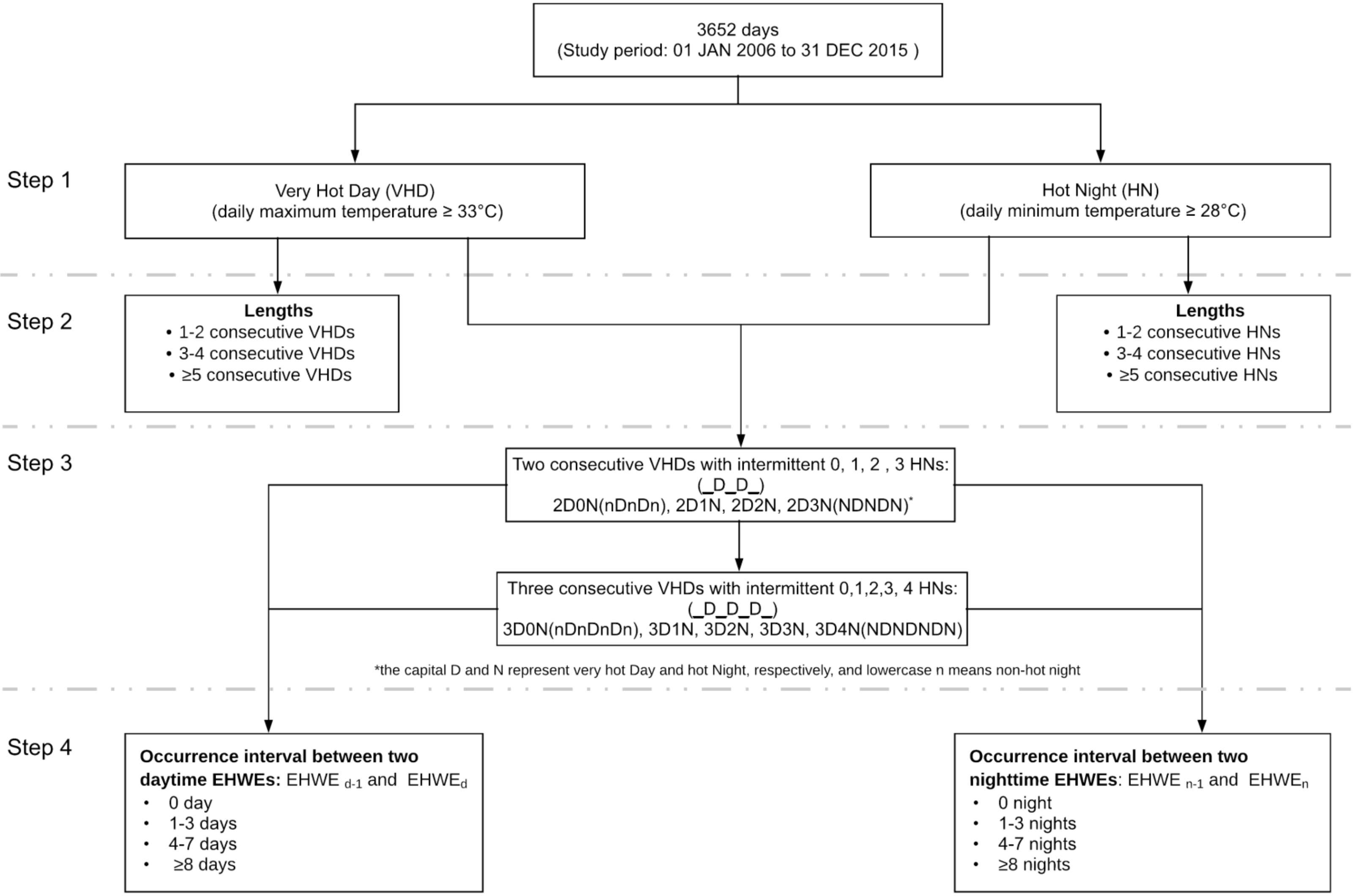
*Graphical Abstract



3652 days
(Study period: 01 JAN 2006 to 31 DEC 2015)

Step 1

Very Hot Day (VHD)
(daily maximum temperature ≥ 33°C)

Hot Night (HN)
(daily minimum temperature ≥ 28°C)

Step 2

Lengths
- 1-2 consecutive VHDs
- 3-4 consecutive VHDs
- ≥5 consecutive VHDs

Lengths
- 1-2 consecutive HNs
- 3-4 consecutive HNs
- ≥5 consecutive HNs

Step 3

Two consecutive VHDs with intermittent 0, 1, 2 , 3 HNs:
(_D_D_)
2D0N(nDnDn), 2D1N, 2D2N, 2D3N(NDNDN)*

Three consecutive VHDs with intermittent 0,1,2,3, 4 HNs:
(_D_D_D_)
3D0N(nDnDnDn), 3D1N, 3D2N, 3D3N, 3D4N(NDNDNDN)

*the capital D and N represent very hot Day and hot Night, respectively, and lowercase n means non-hot night

Step 4

Occurrence interval between two daytime EHWEs: EHWE $_{d-1}$ and EHWE$_d$
- 0 day
- 1-3 days
- 4-7 days
- ≥8 days

Occurrence interval between two nighttime EHWEs: EHWE $_{n-1}$ and EHWE$_n$
- 0 night
- 1-3 nights
- 4-7 nights
- ≥8 nights

***Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

Highlights

- Extremely hot weather event (EHWE) were categorized based on durations/intensities of very hot days and nights.
- The effect of different EHWEs on public health was investigated.
- EHWEs occurred during nighttime, with extended length, or in the pattern of consecutively two hot days and three hot nights might need superior attention for hazard prevention.
- Females and seniors were found to be the most affected populations in Hong Kong.
- Meteorologists and government officials should collaborate to decrease mortality.

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Abstract

Background

The impact of heatwaves on public health has led to an urgent need to describe extremely hot weather events (EHWEs) and evaluate their health impacts.

Methods

In Hong Kong, a very hot day (VHD) can be defined when the daily maximum temperature ≥ 33 °C, and a hot night (HN) can be identified if the daily minimum temperature ≥ 28 °C. Three lengths of time, nine combinations of VHD and HN, and four categories of occurrence intervals between two EHWEs were considered over 2006–2015. The daily relative risk (RR) of all-cause mortality was estimated using Poisson generalized additive regression models, controlling for both short-term and long-term trends in temperature as well as four air pollutants. Lagged effects of the representative EHWEs were further examined for their association with mortality. Subgroup analysis was conducted for different sex and age groups.

Results

Significant associations with raised mortality risks were observed for a single HN, while stronger associations with mortality were observed as significant for five or more consecutive VHDs/HNs. More HNs between the consecutive VHDs also significantly amplified the impact on mortality, with the strongest association observed for EHWEs characterized as 2D3N, and the effect significantly lagged for five days. Therefore, with identifiable health impacts, three thresholds (5VHDs, 5HNs, & 2D3N) were determined to be representative of identical types of EHWEs in Hong Kong. Furthermore, by taking 2 (3) consecutive VHDs (HNs) as one daytime (nighttime) EHWE event, those occurring consecutively without non-hot days (nights) in between were found to be significantly associated with excess mortality risks. Moreover, females and older adults were determined to be relatively more vulnerable to all defined EHWEs.

Conclusions

Among all the observed significant heat-mortality associations in highly urbanized cities, EHWEs that occurred during the nighttime, with extended length, consecutively without any break in between, or in the pattern of 2D3N might require the meteorological administration, healthcare providers, and urban planners to work interactively.

Keywords: extremely hot weather event, heat wave, heat health, mortality, urban heat island effect

1 Introduction

The unprecedented loss of human life during the European heat wave in 2003 (De Bono, Peduzzi, Kluser, & Giuliani, 2004) broadly increased research interests in examining the health impact of extremely hot weather events (EHWEs) (Kravchenko, Abernethy, Fawzy, & Lyerly, 2013). In the past few decades, global climate change and aggravated urban heat island effects have combined to increase the frequency, intensity, and length of EHWEs in urban areas and cities (Alexander et al., 2006; Gershunov & Douville, 2008; Heaviside, Vardoulakis, & Cai, 2016; Meehl & Tebaldi, 2004; Perkins-Kirkpatrick & Gibson, 2017), which further contributed to extensive exploration of the occurrence characteristics of EHWEs and estimation of their corresponding health impacts (Golden, Hartz, Brazel, Luber, & Phelan, 2008; Uejio et al., 2011). For example, Hajat and Kosatsky (2010) reviewed previous epidemiological studies on heat-related mortality and found that heat-related excess mortality occurs across different geographical and climatic regions as well as for individuals at all levels of socio-economic status (Hajat & Kosatky, 2010). In 2017, another study examined twelve types of heat waves in 18 countries/regions and also found that high temperatures significantly contribute to excess mortality (Guo et al., 2017). Particularly, this study found that people residing in moderately hot and moderately cold places were more likely to suffer from heat events than those living in cold and hot areas. Moreover, previous studies highlighted the difficulty in synthesizing varied heat-mortality associations and achieving an international definition of EHWEs due to the inherent heterogeneity among different study contexts, particularly in terms of diverse meteorological conditions, built-up environments, and demographic compositions, which are highly correlated with the local population’s vulnerability, acclimatization, and adaptation to heat events.

Among the broadly studied characteristics of EHWEs in previous studies, the length of the EHWE has broadly been suggested as a critical characteristic in indicating the cumulative health effect of these events, which can provide useful reference information for the weather services to issue hot weather–related warnings and minimize the potential hazards during forecast EHWEs with different lengths. A systematic review, however, suggested that heat wave intensity can play a more important role than its length in determining heat-related deaths (Z. Xu, FitzGerald, Guo, Jalaludin, & Tong, 2016). This review also suggested that city or region-specific heat health early warning systems based on identified local EHWE characteristics may be optimal for protecting people from the adverse impacts of future EHWEs. Another health-related characteristic of EHWEs that has been increasingly discussed in epidemiological studies during the past few decades is heat exposure during the nighttime, independently from daytime EHWEs or 24-hour–based EHWEs (Murage, Hajat, & Kovats, 2017; Roye, 2017). High nighttime temperatures have been found to equally or more significantly affect the wellness of the public when compared with daytime heat events or heat events defined by using 24-hour average temperatures (Laaidi et al., 2012; Murage et al., 2017), and the adverse health impacts of hot nights were found to be particularly significant for vulnerable populations such as older people and patients with chronic ischemic stroke (Murage et al., 2017), as well as those living in densely populated downtown areas who were suffering from the urban heat island effect (Agency, 2006; Hajat & Kosatky, 2010; Kalkstein & Greene, 1997).

Without non-hot nights providing significant relief from the heat exposure during the daytime, the increasing frequency of consecutive hot days and hot nights may introduce excessive health stress to cities struggling with other unfavorable environmental conditions such as the urban heat island effect and air pollution (Analitis et al., 2014; Davies, Steadman, & Oreszczyn, 2008; Heaviside et al., 2016; Laaidi et al., 2012; Mavrogianni et al., 2011; Shahmohamadi, Che-Ani, Etessam, Maulud, & Tawil, 2011). For example, studies in Hong Kong and London highlighted the noticeable mortality risk during consecutive hot nights (Ho, Lau, Ren, & Ng, 2017; Murage et al., 2017); the study conducted in London also suggested that the impact of heat exposure was highest on hot nights that were preceded by a hot day (Murage et al., 2017). Previous studies also suggested that high nighttime temperatures may greatly affect health-related behaviors such as sleep quantity and quality, which may result in severe health conditions (Obradovich, Migliorini, Mednick, & Fowler, 2017). Moreover, people are relatively more vulnerable to environmental stressors at night due to their inactive physical status resulting in a lower likelihood of making prompt adjustments to the unfavorable heat exposure. Therefore, for cities dealing with the health impacts of the increasing frequency of EHWEs, describing daytime and nighttime

EHWEs independently and interactively—in addition to the length and intensity—is necessary to accurately summarize the population’s total heat exposure and assess the corresponding health risks.

Hong Kong is located in a subtropical climate with hot and humid summers, and its maximum temperature often exceeds 31 °C in the daytime during the summer. Due to global warming and rapid urbanization, Hong Kong has experienced more frequent and intense hot weather and prolonged summers over the last two decades, as indicated by the increasing numbers of very hot days (VHDs) and hot nights (HNs)(Y.K. Leung, 2004). Moreover, under the global trend of climate change, the frequency, magnitude, and duration of extreme hot weather are projected to increase in Hong Kong in the 21st century (J. S. W. Lee, Auyeung, Leung, Kwok, & Woo, 2014). Particularly, the high-density compact urban setting in Hong Kong was found to hamper local air ventilation, which could further exacerbate the thermal environment of urban areas (Chan, Kok, & Lee, 2012; Ginn, Lee, & Chan, 2010; Peng et al., 2018; Wong, Mok, & Lee, 2011). Acknowledging that the hot and humid summer conditions together with decreasing urban ventilation may cause significant heat-related health impacts to the locals, especially for populations of older adults suffering from chronic diseases, outdoor workers, or the underprivileged who live in congested and poorly ventilated environments (Brazel, 2006; CY, 2006), the Hong Kong Observatory (HKO) has been issuing Very Hot Weather Warnings (VHWWs) to alert the public of the risk of heatstroke and sunburn due to very hot weather in Hong Kong since 2000 (HKO, 2018b). The issuing of a VHWW appears to have some effect in reducing mortality among older people in Hong Kong (Chau, Chan, & Woo, 2009). However, a definition of an EHWE that includes an extensive description of its occurrence characteristics and corresponding estimation of its health impacts is still lacking.

To address this research gap and enhance the heat stress information services to minimize the adverse health impacts caused by EHWEs, this study aimed to develop applicable thresholds for identifying EHWEs that significantly introduce excess mortality in high-density cities by accounting for daytime and nighttime heat events, respectively and interactively, as well as different lengths and intensities of EHWEs. Suggestions on thresholds for defining EHWEs with significant health impacts are made in the context of Hong Kong, which may also be applied in other highly urbanized and subtropical metropolises.

2 Methods

This study was based on all ages of the Hong Kong population during the study period from January 1, 2006 to December 31, 2015. Time-series daily datasets of all-cause mortality, temperature, and air pollutants in Hong Kong were collected.

2.1 Measures

For the study period, daily counts of all-cause deaths were obtained from the Census and Statistics Department of Hong Kong. Hourly temperatures measured at the HKO Headquarters were acquired from the HKO, and the daily average concentration of four air pollutants (CO, NO_2, $PM_{2.5}$, and O_3) were acquired from the Environmental Protection Department. Figure 1 demonstrates the definition of EHWEs in this study.

Step 1: Based on hourly temperatures obtained from HKO Headquarters, two indicators, namely VHDs (daily maximum temperature ≥ 33 °C) and HNs (daily minimum temperature ≥ 28 °C), were adopted to define a single extremely hot day and night, respectively (T.-c. Lee, Chan, & Ginn, 2011).

Step 2: Consecutive 1–2, 3–4, or ≥ 5 VHDs and HNs were observed as three different lengths of a daytime and nighttime EHWE, respectively.

Step 3: To capture the sequentially interactive effect between VHDs and HNs on the daily population mortality, four combinations were identified for every two consecutive VHDs, according to the count of HNs among a total of three nights around these two days, namely two consecutive VHDs with intermittent 0, 1, 2, or 3 HNs (2D0N, 2D1N, 2D2N, 2D3N), where 2D0N means two consecutive VHDs without a hot night within the corresponding three nights (nDnDn), whereas 2D3N means two consecutive VHDs with three HNs (NDNDN), where the capital D and N represent VHDs and HNs, respectively, and the lowercase n represents a non-hot night. Similarly, five combinations were classified for those three consecutive VHDs with intermittent 0, 1, 2, 3, or 4 HNs (3D0N, 3D1N, 3D2N, 3D3N, 3D4N), where 3D2N means two nights out of the four nights sequentially attached with the three consecutive VHDs were identified as hot (_D_D_D_), including six possible patterns, namely NDNDnDn, NDnDNDn, NDnDnDN, nDNDNDn, nDNDnDN, and nDnDNDN.

Step 4: Among the different combinations of VHDs and HNs, a representative combination xDyN would be suggested by taking into account the occurrence frequency and effect size of its association with all-cause mortality. By taking every x consecutive VHDs as one daytime EHWE and every y consecutive HNs as one nighttime EHWE, the occurrence interval between daytime (nighttime) EHWE_i and the preceding daytime (nighttime) EHWE_{i-1} were classified into one of four groups: 1) zero non-hot days (nights) in between; 2) 1–3 non-hot days (nights) in between; 3) 4–7 non-hot days (nights) in between; 4) ≥ 8 non-hot days (nights) after the daytime (nighttime) EHWE_{i-1}, which includes the first daytime (nighttime) EHWE of each year.

2.2 Statistical analysis

For different EHWEs, respectively, the daily relative risk (RR) of all-cause mortality between an EHWE and non-EHWE was estimated by adopting Poisson generalized additive regression models and adjusting for long-term trends, seasonality, day of the week, and the daily concentration of air pollutants:

$$Log[E(Y_{i})] = \alpha + s(DOY, k = 3) + s(DOS, k = 5) + \beta DOW_i + \sum_{j=1}^{n} g_j(x_{ig}) + \gamma(t_i) + \delta(EHWE_i). \quad (1)$$

The above equation (1) shows the full model used in this study, where i is the observed date, and Y_i is the death count on date i, which is assumed to follow an over-dispersed Poisson distribution, such that the quasi-Poisson link was adopted. The main effect of the EHWE is estimated by $\delta(EHWE_i)$, where $EHWE_i$ is a dummy variable indicating whether date i was observed as extremely hot according to different definitions of EHWEs, and δ is the corresponding coefficient that could be further calculated into the RR of all-cause mortality between an extremely hot day/night and a non-extremely hot day/night. α is the intercept of the full model. Seasonality and long-term (decadal) trends were controlled by fitting spline functions on the day of the year, with three knots per year and five knots on the day of the study period. Day of the week (DOW) is specified as six dummy variables, and $\sum_{j=1}^{n} g_j(x_{ig})$ is a summarized function describing the effects of four air pollutants

(CO, NO_2, $PM_{2.5}$, and O_3). All models were adjusted for the effect of the daily average temperature by adding a cross-basis quadratic B spline term, $\gamma(t_i)$, which simultaneously includes the contributions of temperature and its lag effects. The daily average temperature was centered at the 75th percentile of the yearly temperature, which was suggested as the temperature corresponding to the minimum mortality risk by a previous study (Guo et al., 2014). A maximum nine-days' lag was allowed in the model to control for the lagged effect of the average temperature and to make the model in accordance with HKO's 9-day weather forecast system. The model fit was validated by excluding autocorrelations and checking the residuals.

A representative EHWE was identified as the one that frequently occurred in Hong Kong during the study period and was most significantly associated with all-cause mortality. Furthermore, the lagged effect of the representative EHWE was examined by postponing the EHWE to 1–9 days. We then linked the postponed EHWE with the death counts on the corresponding date to examine the lagged effect of EHWEs on all-cause mortality. Lastly, the representative EHWE was prolonged until the day from which the effect on mortality becomes insignificant, so that the average impact on the mortality of the extended EHWE can be estimated.

To explore the vulnerable populations for all the analyses done for the overall study population, subgroup analyses were conducted according to sex (male and female) and age (≤18, 19–64, and 65+), respectively. All analyses were performed using the *dlnm, mgcv, gam,* and *splines* packages of the R software (version 3.3.3), with a two-tailed significance level of $p < 0.05$.

3 Results

3.1 Data summary

Table 1 shows the summary of weather conditions and all-cause mortality from January 1, 2006 to December 31, 2015. The daily mean temperature in Hong Kong ranged from 4.9 °C to 32.5 °C with a median temperature of 24.7 °C. The daytime (0600–1800 LST) median temperature was approximately 1° higher than the nighttime median temperature (25.2 °C versus 24.2 °C). A total of 359,220 deaths were recorded during the ten years. Excluding deaths without detailed information on age and sex, there were 176,368 (49.1%) male deaths and

143,089 (39.8%) female deaths, and there were 968 (0.3%), 61,552 (17.1%), and 256,937 (71.5%) deaths in the three age groups of ≤ 18, 19–64, and 65+, respectively.

Table 2 shows the daily count for different definitions of EHWE. During the ten-year period studied between 2006 and 2015 (3,652 days), 204 VHDs were observed, among which 111, 45, and 48 days were identified as belonging to EHWEs that lasted for consecutive 1–2, 3–4, and ≥ 5 VHDs, respectively. In addition, there were 230 HNs, among which 104, 70, and 56 nights were identified as belonging to the EHWEs that lasted for consecutive 1–2, 3–4, and ≥ 5 HNs, respectively. For different combinations of VHDs and HNs, there were 46 days characterized as two consecutive VHDs with three corresponding HNs (2D3N), whereas 30 days were characterized as having two consecutive VHDs with no HN occurring thereafter (2D0N). The majority of the three consecutive VHDs occurred with two (31%) or four (35%) intermittent HNs. Taking the representative EHWE (2D3N) in Hong Kong as the standard to define the daytime EHWE (2VHDs) and nighttime EHWE (3HN), respectively, the occurrence interval between every two consecutive daytime/nighttime EHWEs were classified into four groups. In total, 55 VHDs belonged to the daytime EHWE that occurred right after the preceding daytime EHWE with non-hot days in between, 10 VHDs were identified as a daytime EHWE that occurred 1–3 days after the preceding daytime EHWE, 14 VHDs occurred more than three days after the preceding daytime EHWE, and 66 VHDs occurred more than eight days later than the preceding event. For nighttime EHWEs, there were 8, 15, 30, 11, and 34 HNs that occurred immediately thereafter, 1–3 nights later, 4–7 nights later, and more than 8 nights later than the preceding nighttime EHWE, respectively.

3.2 Main effect of EHWE on mortality

The impact of EHWEs on mortality varied across different event lengths and types. Compared with non-hot nights, significant excess mortality was observed for a single HN with an increased risk of 2.43% (95% CI: 0.75%, 4.14%). No significant mortality risk was observed for a single VHD (increased risk = 1.57%, 95% CI: -0.18%, 3.35%). The strongest daily mortality risk was observed during EHWEs that lasted for more than five consecutive days or nights, with an increased daily mortality risk of 3.99% (95% CI: 0.56%, 7.53%) for the daytime EHWE and 6.66% (95% CI: 3.45%, 9.96%) for the nighttime EHWE (Table 3). Therefore, five VHDs and five HNs are considered representative thresholds for EHWEs with significant health impacts in Hong Kong.

Among nine different combinations of VHDs and HNs, more intermittent HNs between the consecutive VHDs significantly amplified the impact on all-cause mortality, with the strongest effect on daily mortality being observed for 2D3N, with an increased mortality risk of 5.32% (95% CI: 1.83–8.93%), while 4.60% (95% CI: 0.57–8.79%) was seen for a 3D4N event (Table 4). Due to the strong association with all-cause mortality (increased mortality risk of 5.32%) and the high occurrence frequency of 2D3N (Table 2), 2D3N was considered to be another suitable threshold for EHWEs in Hong Kong.

Furthermore, among different occurrence intervals between two daytime EHWEs, a 4.39% (95% CI: 1.18–7.70%) excess risk of daily mortality was found to be significant for a daytime $EHWE_d$ occurring right after a preceding daytime $EHWE_{d-1}$ without non-hot days in between, and a 7.50% (95% CI: 1.26–14.13%) increased risk of daily mortality was found for a daytime $EHWE_d$ occurring 4–7 days after the preceding event. For different occurrence intervals between two representative nighttime EHWEs, a 5.74% (95% CI: 1.81–7.70%) excess risk of daily mortality was observed for those occurring right after a preceding nighttime $EHWE_{n-1}$ without non-hot nights in between (Table 3).

For a representative 2D3N EHWE in Hong Kong, Figure 2 shows the daily increased risk of mortality and the corresponding 95% confidence interval resulting from this representative EHWE (2D3N) with 0, 1, 2, 3, 4, 5, 6, and 7 day's lag. The excess risk of daily mortality for this type of EHWE decreased from 5.32% (95% CI: 1.78%, 8.80%) to 4.05% (0.64–7.58%) in the 5th lag day, whereas it became insignificant (RR = 3.11%, 95% CI: -0.29%, 6.62%) after the 6th lag day. Therefore, we prolonged the EHWE for five days to estimate the average effect of the representative EHWE during the prolonged hot period. Compared with all the other dates, the average increased risk of daily mortality during the prolonged representative EHWE was 3.80% (95% CI: 1.35%, 6.31%).

3.3 Subgroup analysis

By conducting subgroup analyses according to sex, we found that females were more likely to be affected by a single HN, with an increased mortality risk of 2.74% (95% CI: 0.35%, 5.18%). Besides, for both males and females, a significantly increased mortality risk was observed for nighttime EHWEs lasting for more than five days/nights, whereas daytime EHWEs of the same length were only marginally (p-value = 0.05) significant in association with an increased mortality risk of 5.06% (0.75–9.75%, p-value = 0.055) among males (Table 3). A nighttime EHWE_n preceded by an EHWE_{n-1} without any break from non-hot nights in between was found to introduce higher mortality risk only among the females, with an increased risk of 6.82% (95% CI: 0.60%, 13.43%). Moreover, a daytime EHWE_d preceded by an EHWE_{d-1} with 4–7 non-hot days in between was significantly associated with an increased mortality risk of 11.29% (1.90–21.56%) for females (Table 3).

For those younger than 18 years old, a significantly increased mortality risk was only found during five or more consecutive HNs and those representative nighttime EHWEs occurring without a non-hot break in between; however, the results need to be cautiously interpreted due to the small sample size in this age group (Table 3). No significant association was found between all defined EHWEs and all-cause mortality for the adults (18–64 years old). For those aged ≥ 65, a single HN showed a significant association with an increased mortality risk of 2.53% (0.46–4.64%), whereas a single VHD did not indicate a significant effect on mortality. However, for different lengths of EHWEs, only HNs lasting for more than five nights had significant effects on all-cause mortality of those aged ≥ 65, with a daily increased mortality risk of 5.33% (1.08–9.75%). For different combinations of VHDs and HNs, EHWEs characterized by consecutive 2D3Ns only showed significant impacts for those aged ≥ 65, with a daily increased mortality risk of 5.87% (1.46–10.47%) (Table 4). In addition, representative nighttime EHWEs that occurred without any break from non-hot nights in between could potentially cause a greater risk of mortality for those aged ≥ 65, with a significant increased risk of 5.23% (95% CI: 0.20%, 10.52%) (Table 3).

4 Discussion

4.1 Significant characteristics of EHWEs

By defining different EHWEs and comparing their corresponding daily mortalities, our findings showed that the hazards from EHWEs characterized by HNs are comparable with and even greater than those from VHDs. These HN-related EHWEs include a single HN and consecutive HNs lasting for more than five nights. Moreover, consecutive VHDs occurring with more intermittent HNs in between (2D3N or 3D4N) are more likely to cause excess all-cause mortality among the general populations, females, and seniors. Compared with two consecutive daytime EHWEs in Hong Kong, two consecutive nighttime EHWEs without any break from non-hot nights in between also showed more of an increased mortality risk than those EHWEs occurring after some non-hot nights. In a similar study conducted in Australia, extreme hot weather was predominantly associated with higher mortality risk during the daytime than at nighttime (Z. W. Xu & Tong, 2017); this is in contrast to the results in the current study and findings in our previous study on HNs, which suggests that they may contribute to the population’s excess mortality more than VHDs do (Ho et al., 2017) and further indicates that variations in climate, urban settings, and demographic composition may result in considerably different extents of health impacts from EHWEs (Luber & McGeehin, 2008). During the past few decades, nighttime temperatures have been observed to increase more rapidly than the warming trend during the daytime (Agency, 2006; Davy, Esau, Chernokulsky, Outten, & Zilitinkevich, 2017). Particularly, in high-density urban settings, the urban heat island effect intensified by waste heat released from air conditioners and traffic, commuter systems, and industrial and residential lighting has progressively contributed to the increased temperature during the nights and the weakened resilient capability of the nights (Brazel, 2006; Wang, Zhou, Ng, & Xu, 2016), which may explain the enhanced heat hazards at night in highly urbanized settings (Laaidi et al., 2012). Therefore, future studies in the assessment of EHWE-related hazards should address nighttime heat events separately and in a manner equal to those for daytime or 24-hour–based heat events.

Moreover, we compared various EHWEs with different lengths of consecutive VHDs and HNs and found that the hazards from ≥ 5 consecutive VHDs / HNs were significantly greater than hazards from a single VHD or HN. In addition, by combining VHDs and HNs, we found that consecutive VHDs with more intermittent HNs are more likely to increase the mortality risk, such that 2D3N showed the greatest harmful effect on all-cause mortality, followed by 3D4N, which indicates the significant resilience capability of non-hot nights. In a comparison of different occurrence intervals between two consecutive daytime/nighttime EHWEs, a daytime/nighttime EHWE occurring right after a preceding daytime/nighttime EHWE_{i-1} without any non-hot break in between was most likely to cause excess mortality.

In summary, from the health impact and early alert perspectives, the five consecutive VHDs, five consecutive HNs, and continuous 2D3Ns are considered to be representative thresholds for identifying different types of EHWEs in Hong Kong.

4.2 Vulnerability of populations

By stratifying the study population according to gender and age, stronger effects of EHWEs on mortality were found among females and seniors aged 64+ years. Compared with males, females generally have poorer acclimation capability resulting from their late onset of sweating and lower sweat rates (Kenney, 1985); smaller body sizes, which allow for rapid heat gain; larger surface area-to-mass ratio, which results in more significant water lost in unfavorable hot weather; poorer fitness levels, which lead to lower cardiac reserves and worse tolerance to acclimation under heat exposure; and higher body fat percentages requiring higher metabolic costs for any physical task (Kenney, 1985). For the older population, the significantly deteriorated physical function and resilience capability make acclimatization to heat exposure much slower and insufficient for older populations than for younger populations (Kenny, Yardley, Brown, Sigal, & Jay, 2010). Besides, unlike working-age populations, seniors spend the vast proportion of their time indoors at residential places, so caregivers’ assistance and the household cooling system play critical roles in their wellness during EHWEs. However, there is a considerably high proportion of older individuals living alone (Victor, Scambler, Bond, & Bowling, 2001) without close caregivers and available cooling systems, which could directly result in delayed reactions to heat-related symptoms resulting in critical health outcomes such as hospital admission and mortality, particularly for those with severe morbidities. Even for healthy older adults with close caregivers, electricity expenses and the possibility of catching a cold by using air conditioning/indoor cooling systems are two major barriers for them to take effective adjustment action during EHWEs (Hansen et al., 2011). Instead of investing in or turning on air conditioning, they are more likely to stay in public areas where the air conditioning is free and is usually set at relatively low temperatures. Alternatively, it is very common among the older population to use a fan as the “cooling device,” which might not effectively cool down the indoor air temperature due to the poor natural ventilation design and the small window size of residential buildings in Hong Kong (Gao & Lee, 2011). Therefore, females and seniors are strongly suggested to be protected during EHWEs, which could be achieved by modifying their living environments, providing accessible public resources and emergency aids, and delivering sufficient education on how to scientifically and effectively live through these extreme heat events.

However, modifying effects may exist between sex and age on all-cause mortality due to the average longer life expectancy for females than for males (87.6 vs. 75.3 years in Hong Kong) (protection, 2017), which may result in a higher proportion of older individuals in the female population than in the male population, making it possible that the significant hazards of EHWEs observed in females were actually caused by the vulnerability of older adults. In our study, the proportion of older adults in the female population was 83.4%, whereas the proportion of older adults in the male population was 75.5%, which make the findings vulnerable to the unclear interaction between sex and age on mortality. Therefore, we further checked the mortality risk during all defined EHWEs for older males and older females, and we found that the association remained robustly significant for older females, which suggests that females are relatively more vulnerable than males during EHWEs. Future studies are encouraged to extensively explore the characteristics of the population such that vulnerable populations can be identified and protected.

4.3 Strengths

Firstly, based on mortality records and city-wide meteorological measurements, both the study population and study period are representative of the Hong Kong population and weather conditions during the past decade.

Secondly, nighttime heat events were classified to compare their hazards with those of daytime heat events. We further studied how HNs interacting with consecutive VHDs affect the daily mortality risk to provide evidence on the necessity of assessing health impacts of heat events for both VHD- and HN-related EHWEs. Thirdly, we used Poisson regression models to adjust for long-term, seasonal, and lag effects of the temperature on mortality; we also controlled for weekly trends and four air pollutants, such that the results are likely to approximate the independent association between extreme heat events and mortality.

For model modification, in accordance with previous studies that controlled for relative humidity as a confounding factor in estimating the association between heat stress and mortality, we conducted a sensitivity analysis by adding daily relative humidity as a covariate in our final model. Compared with the reported model (adjusted $R^2 = 0.43$), the model fit of the modified model with relative humidity did not significantly improve (adjusted $R^2 = 0.43$), and the primary results in estimating the mortality risk during the defined EHWEs remained robust. Particularly, considering the relative humidity level in Hong Kong is constantly high with very slight spatial and temporal variation and we did not observe significant time-varying pattern in relative humidity during the study period, results from the final model without relative humidity level were reported. Similarly, even though sulfur dioxide (SO_2) has not been a critical air pollutant in Hong Kong since 1997 (Department, 2018), we conducted a sensitivity analysis by adding daily concentrations of SO_2 to our final model, in accordance with previous studies that controlled for SO_2 as one of the critical air pollutants that correlates highly with temperature and mortality. However, the model fit did not change when comparing the modified model with the reported model (adjusted R^2: 0.43 vs 0.43), and the estimated primary effect of the defined EHWEs remained robust.

Therefore, our findings are more applicable in estimating the hazards from EHWEs and enhancing the heat stress information service in a local context. Particularly, unlike evidence on the RR of mortality with every one degree increase in temperature, the predicted hazards of a defined VHD/HN in an EHWE are more interpretable for relevant stakeholders and the general public to take preventive strategies when EHWEs are predicted.

4.4 Limitations

Firstly, we studied all-cause mortality risks during EHWEs without specifying mortality attributes. In fact, heat-related deaths are very hard to clarify due to the current death diagnosis practice that is primarily based on pathophysiological attributions without considering the circumstances surrounding the death. Particularly, studies in recent years have suggested that hot weather can increase the risk of accidental deaths from committing suicide (Burke et al., 2018), unintentional fatal injuries, and accidents (Kampe, Kovats, & Hajat, 2016). Therefore, we used all-cause mortality to avoid the underestimation of fatal hazards from EHWEs, but we suggest that future studies use more immediate health outcomes or early syndromes of extreme heat exposure to evaluate the early hazards of EHWEs at the stage at which hazards are more likely to be prevented. Secondly, while the temperature records at the HKO Headquarters used in this study are generally representative of the temperature in urban areas in Kowloon Peninsula, given the complex terrain and differences in local weather (e.g., cloud cover amounts, isolated showers, and wind speed/direction) in Hong Kong, the regional variation in the temperature in different parts of the territory may sometimes not be fully represented. Thirdly, acclimatization, including physical adaptations and living environment modifications (e.g., air conditioning), could be important effect modifiers for the association between high temperatures and adverse health outcomes, which we were unable to address due to unavailable data; however, in cities that allow for publicly accessible datasets, household/district income and electricity expenses at clustering levels could be useful indicators of the prevalence of air conditioning, and subgroup analysis could be further conducted to adjust for the modifying effects of human acclimatization.

5 Conclusions

Our findings suggest that not only daytime but also nighttime-related EHWEs are independently associated with the increased mortality risk among the general population residing in a high-density urban setting. In addition, length and occurrence timing are two essential characteristics of an EHWE in determining the extent of the effect on mortality risk. By introducing different thresholds of EHWEs, the five consecutive VHDs, five consecutive HNs, and continuous 2D3N events showed strong adverse effects on daily mortality. Particularly, 2D3N with its five days' lagged effect on all-cause mortality is suggested to be applicable in defining EHWEs in Hong Kong. Moreover, females and seniors are generally at a higher risk of mortality during EHWEs.

Our study highlights the importance of defining EHWEs by extensively acknowledging their characteristics in terms of different types (daytime or nighttime), lengths, intensities, and combinations across these characteristics. Through a better understanding of the nature of human exposure to EHWEs and estimating the corresponding heat health risks, heat stress information services can be further enhanced, and heat-related healthcare services can be more efficiently distributed to meet the public's needs during EHWEs.

Declarations

Ethics approval and consent to participate: Not applicable

Consent for publication: Not applicable

Availability of data and material: The meteorological data and mortality data that support the findings of this study are available respectively from the Hong Kong Observatory and Census and Statistics Department of Hong Kong but need to apply for research purpose. Results are available from the authors upon request and with permission of the project partners.

Competing interests: The authors declare that they have no competing interests

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Authors’ contribution

Dan Wang made substantial contributions to the study design, data analysis and interpretation, and drafting the article; Kevin Lau, Chao Ren made substantial contributions to data acquisition, study design, results interpretation, and involved in drafting the article; Shi Yuan participated in data acquisition and study design; William Goggins, Jean Woo and Edward Ng made considerable contributions to results interpretation and study implications. T.C. Lee and L.S. Lee contributed to the data acquisition and results interpretation. All authors revised the paper critically and approved final approval of the version to be submitted.

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References

Agency, U. S. E. P. (2006). Excessive heat events guidebook.

Alexander, L. V., Zhang, X., Peterson, T. C., Caesar, J., Gleason, B., Klein Tank, A. M. G., . . . Vazquez-Aguirre, J. L. (2006). Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research: Atmospheres, 111*(D5). doi:doi:10.1029/2005JD006290

Analitis, A., Michelozzi, P., D'Ippoliti, D., de'Donato, F., Menne, B., Matthies, F., . . . Katsouyanni, K. (2014). Effects of Heat Waves on Mortality Effect Modification and Confounding by Air Pollutants. *Epidemiology, 25*(1), 15-22. doi:10.1097/EDE.0b013e31828ac01b

Brazel, A. (2006). The encyclopedia of world climatology. *Annals of the Association of American Geographers, 96*(4), 829-830. doi:DOI 10.1111/j.1467-8306.2006.00517_1.x

Burke, M., Gonzalez, F., Bayliss, P., Heft-Neal, S., Baysan, C., Basu, S., & Hsiang, S. (2018). Higher temperatures increase suicide rates in the United States and Mexico. *Nature Climate Change, 8*(8), 723-+. doi:10.1038/s41558-018-0222-x

Chan, H. S., Kok, M. H., & Lee, T. C. (2012). Temperature trends in Hong Kong from a seasonal perspective. *Climate Research, 55*(1), 53-63. doi:10.3354/cr01133

Chau, P. H., Chan, K. C., & Woo, J. (2009). Hot weather warning might help to reduce elderly mortality in Hong Kong. *Int J Biometeorol, 53*(5), 461-468. doi:10.1007/s00484-009-0232-5

CY, L. (2006). On Climate Changes Brought About by Urban Living. *Hong Kong Meteorological Society Bulletin, 16*(Number 1/2).

Davies, M., Steadman, P., & Oreszczyn, T. (2008). Strategies for the modification of the urban climate and the consequent impact on building energy use. *Energy Policy, 36*(12), 4548-4551. doi:10.1016/j.enpol.2008.09.013

Davy, R., Esau, I., Chernokulsky, A., Outten, S., & Zilitinkevich, S. (2017). Diurnal asymmetry to the observed global warming. *International Journal of Climatology, 37*(1), 79-93. doi:10.1002/joc.4688

De Bono, A., Peduzzi, P., Kluser, S., & Giuliani, G. (2004). Impacts of summer 2003 heat wave in Europe.

Department, E. P. (2018). *Hong Kong Air Pollutant Emission Inventory - Sulphur Dioxide*. Hong Kong SAR Retrieved from https://www.epd.gov.hk/epd/english/environmentinhk/air/data/emission_inve_so2_C.html.

Gao, C. F., & Lee, W. L. (2011). Evaluating the influence of openings configuration on natural ventilation performance of residential units in Hong Kong. *Building and Environment, 46*(4), 961-969. doi:https://doi.org/10.1016/j.buildenv.2010.10.029

Gershunov, A., & Douville, H. (2008). Extensive summer hot and cold extremes under current and possible future climatic conditions: Europe and North America. *Climate Extremes and Society*, 74-98. doi:Doi 10.1017/Cbo9780511535840.008

Ginn, W. L., Lee, T. C., & Chan, K. Y. (2010). Past and Future Changes in the Climate of Hong Kong. *Acta Meteorologica Sinica, 24*(2), 163-175.

Golden, J. S., Hartz, D., Brazel, A., Luber, G., & Phelan, P. (2008). A biometeorology study of climate and heat-related morbidity in Phoenix from 2001 to 2006. *Int J Biometeorol, 52*(6), 471-480. doi:10.1007/s00484-007-0142-3

Guo, Y., Gasparrini, A., Armstrong, B., Li, S., Tawatsupa, B., Tobias, A., . . . Williams, G. (2014). Global variation in the effects of ambient temperature on mortality: a systematic evaluation. *Epidemiology, 25*(6), 781-789. doi:10.1097/EDE.0000000000000165

Guo, Y., Gasparrini, A., Armstrong, B. G., Tawatsupa, B., Tobias, A., Lavigne, E., . . . Tong, S. (2017). Heat Wave and Mortality: A Multicountry, Multicommunity Study. *Environ Health Perspect, 125*(8), 087006. doi:10.1289/EHP1026

Hajat, S., & Kosatky, T. (2010). Heat-related mortality: a review and exploration of heterogeneity. *J Epidemiol Community Health, 64*(9), 753-760. doi:10.1136/jech.2009.087999

Hansen, A., Bi, P., Nitschke, M., Pisaniello, D., Newbury, J., & Kitson, A. (2011). Perceptions of heat-susceptibility in older persons: barriers to adaptation. *Int J Environ Res Public Health, 8*(12), 4714-4728. doi:10.3390/ijerph8124714

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 Suppl 1*, 27.

HKO. (2018b). Cold and Very Hot Weather Warnings.

Ho, H. C., Lau, K. K., Ren, C., & Ng, E. (2017). Characterizing prolonged heat effects on mortality in a sub-tropical high-density city, Hong Kong. *Int J Biometeorol, 61*(11), 1935-1944. doi:10.1007/s00484-017-1383-4

Kalkstein, L. S., & Greene, J. S. (1997). An evaluation of climate/mortality relationships in large US cities and the possible impacts of a climate change. *Environmental Health Perspectives, 105*(1), 84-93. doi:DOI 10.1289/ehp.9710584

Kampe, E. O. I., Kovats, S., & Hajat, S. (2016). Impact of high ambient temperature on unintentional injuries in high-income countries: a narrative systematic literature review. *Bmj Open, 6*(2). doi:ARTN e010399

10.1136/bmjopen-2015-010399

Kenney, W. L. (1985). A review of comparative responses of men and women to heat stress. *Environmental Research, 37*(1), 1-11. doi:https://doi.org/10.1016/0013-9351(85)90044-1

Kenny, G. P., Yardley, J., Brown, C., Sigal, R. J., & Jay, O. (2010). Heat stress in older individuals and patients with common chronic diseases. *CMAJ, 182*(10), 1053-1060. doi:10.1503/cmaj.081050

Kravchenko, J., Abernethy, A. P., Fawzy, M., & Lyerly, H. K. (2013). Minimization of heatwave morbidity and mortality. *Am J Prev Med, 44*(3), 274-282. doi:10.1016/j.amepre.2012.11.015

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. doi:10.1289/ehp.1103532

Lee, J. S. W., Auyeung, T. W., Leung, J., Kwok, T., & Woo, J. (2014). Transitions in Frailty States Among Community-Living Older Adults and Their Associated Factors. *Journal of the American Medical Directors Association, 15*(4), 281-286. doi:10.1016/j.jamda.2013.12.002

Lee, T.-c., Chan, K.-y., & Ginn, W.-l. (2011). Projection of extreme temperatures in Hong Kong in the 21st century. *Acta Meteorologica Sinica, 25*(1), 1-20. doi:10.1007/s13351-011-0001-3

Luber, G., & McGeehin, M. (2008). Climate Change and Extreme Heat Events. *American Journal of Preventive Medicine, 35*(5), 429-435. doi:10.1016/j.amepre.2008.08.021

Mavrogianni, A., Davies, M., Batty, M., Belcher, S. E., Bohnenstengel, S. I., Carruthers, D., . . . Ye, Z. (2011). The comfort, energy and health implications of London's urban heat island. *Building Services Engineering Research & Technology, 32*(1), 35-52. doi:10.1177/0143624410394530

Meehl, G. A., & Tebaldi, C. (2004). More intense, more frequent, and longer lasting heat waves in the 21st century. *Science, 305*(5686), 994-997. doi:10.1126/science.1098704

Murage, P., Hajat, S., & Kovats, R. S. (2017). Effect of night-time temperatures on cause and age-specific mortality in London. *Environmental Epidemiology*, 1. doi:10.1097/ee9.0000000000000005

Obradovich, N., Migliorini, R., Mednick, S. C., & Fowler, J. H. (2017). Nighttime temperature and human sleep loss in a changing climate. *Science Advances, 3*(5).

Peng, L., Liu, J. P., Wang, Y., Chan, P. W., Lee, T. C., Peng, F., . . . Li, Y. G. (2018). Wind weakening in a dense high-rise city due to over nearly five decades of urbanization. *Building and Environment, 138*, 207-220. doi:10.1016/j.buildenv.2018.04.037

Perkins-Kirkpatrick, S. E., & Gibson, P. B. (2017). Changes in regional heatwave characteristics as a function of increasing global temperature. *Sci Rep, 7*(1), 12256. doi:10.1038/s41598-017-12520-2

protection, C. f. h. (2017). *Life Expectancy at Birth (Male and Female), 1971 - 2017*. Retrieved from https://www.chp.gov.hk/en/statistics/data/10/27/111.html.

Roye, D. (2017). The effects of hot nights on mortality in Barcelona, Spain. *Int J Biometeorol, 61*(12), 2127-2140. doi:10.1007/s00484-017-1416-z

Shahmohamadi, P., Che-Ani, A. I., Etessam, I., Maulud, K. N. A., & Tawil, N. M. (2011). Healthy Environment: The Need to Mitigate Urban Heat Island Effects on Human Health. *2nd International Building Control Conference, 20*. doi:10.1016/j.proeng.2011.11.139

Uejio, C. K., Wilhelmi, O. V., Golden, J. S., Mills, D. M., Gulino, S. P., & Samenow, J. P. (2011). Intra-urban societal vulnerability to extreme heat: the role of heat exposure and the built environment, socioeconomics, and neighborhood stability. *Health Place, 17*(2), 498-507. doi:10.1016/j.healthplace.2010.12.005

Victor, C., Scambler, S., Bond, J., & Bowling, A. (2001). Being alone in later life: loneliness, social isolation and living alone. *Reviews in Clinical Gerontology, 10*(4), 407-417. doi:undefined

Wang, W., Zhou, W., Ng, E. Y. Y., & Xu, Y. (2016). Urban heat islands in Hong Kong: statistical modeling and trend detection. *Natural Hazards, 83*(2), 885-907. doi:10.1007/s11069-016-2353-6

Wong, M. C., Mok, H. Y., & Lee, T. C. (2011). Observed changes in extreme weather indices in Hong Kong. *International Journal of Climatology, 31*(15), 2300-2311. doi:10.1002/joc.2238

Xu, Z., FitzGerald, G., Guo, Y., Jalaludin, B., & Tong, S. (2016). Impact of heatwave on mortality under different heatwave definitions: A systematic review and meta-analysis. *Environ Int, 89-90*, 193-203. doi:10.1016/j.envint.2016.02.007

Xu, Z. W., & Tong, S. L. (2017). Decompose the association between heatwave and mortality: Which type of heatwave is more detrimental? *Environmental Research, 156*, 770-774. doi:10.1016/j.envres.2017.05.005

Y.K. Leung, K. H. Y., E.W.L. Ginn and W.M. Leung (2004). Climate Change in Hong Kong. *HONG KONG OBSERVATORY*(Technical Note No. 107).

Figures

Figure 1. Definitions of extremely hot weather events in Hong Kong during January 1, 2006 to December 31, 2015

Figure 2. Lagged effect of the representative extremely hot weather event (2D3N) on daily all-cause mortality in Hong Kong

Table 1. Descriptive statistics of daily all-cause mortality, temperature, and air pollutants during the study period (2006–~~-~~2015) in Hong Kong

	Minimum	Median	75th~~e~~ percentile	Maximum
Temperature (°C~~℃~~)				
Daily mean temperature	4.9	24.7	28.1	32.5
Daily minimum temperature~~s~~	3.2	23.0	26.1	30.1
Daily maximum temperature~~s~~	7.0	26.9	30.3	36.1
Daytime average temperature	4.2	25.2	28.5	32.9
Nighttime average temperature	5.8	24.2	27.5	31.9
Daily air pollutants (μg/m^3)				
PM$_{2.5}$	5.2	29.5	44.8	139.4
O$_3$	4.5	33.4	52.1	130.9
CO (10 μg/m^3)	33.7	76.8	95.1	216.1
NO$_2$	16.4	60.9	74.6	173.7
Daily Mortality (persons)				
General population	3	97	107	162
Males	2	53	59	91
Females	5	43	48	76
~~aged~~ ≤ 18	1	1	1	4
~~aged~~ 19 ≤ Age < 64	1	18	22	37
~~aged~~ 65+	5	77	86	137

revision_Table2

Table 2. Summary of the daily~~y~~ count for different definitions of extremely hot weather events (EHWEs) during the study period (2006–~~-~~2015) in Hong Kong

	Variables	Number of days	Number of all other days except~~ing~~ for the days meeting the definition
All days	Overall study period	3,652	0
A single hot day/night	Very hot day (VHD, daily maximum temperature ≥ 33 °C)	204	3,448
	Hot night (HN, daily minimum temperature ≥ 28 °C)	230	3,422
Length ~~of~~ of a daytime EHWE	1–~~-~~2 consecutive VHDs	111	3,448
	3–~~-~~4 consecutive VHDs	45	
	≥ 5 consecutive VHDs	48	
of a nighttime EHWE	1–~~-~~2 consecutive HNs	104	3,442
	3–~~-~~4 consecutive HNs	70	
	≥ 5 consecutive HNs	56	
Occurrence interval between two daytime EHWEs (2 VHDs): EHWE$_{d-1}$ and EHWE$_d$	Continuously with zero~~0~~ non-hot days in between	55	3,507
	with 1–~~-~~3 non-hot days in between	10	
	with 4–~~-~~7 non-hot days in between	14	
	with ≥ 8 non-hot days in between	66	
Occurrence interval between two nighttime EHWEs (3 HNs): EHWE$_{n-1}$ and EHWE$_n$	Continuously with zero~~0~~ non-hot nights in between	36	3,526
	with 1–~~-~~3 non-hot nights in between	15	
	with 4–~~-~~7 non-hot nights in between	9	
	with ≥ 8 non-hot nights in between	66	
Two consecutive VHDs with different intermittent HNs (N*D*N*D*N)	0 HNs	30	3,494
	1 HN	37	
	2 HNs	44	
	3 HNs	47	
Three consecutive VHDs with different intermittent HNs (N*D*N*D*N*D*N)	0 HNs	8	3,554
	1 HN	15	
	2 HNs	30	
	3 HNs	11	
	4 HNs	34	

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Table 3.~~1.~~ Increased risks of mortality (in percentages) between extremely hot days in the defined extremely hot weather events (EHWEs)
and non-hot days, according to different lengths of EHWEs and different occurrence intervals between daytime/nighttime EHWEs.

		A single VHD/HN	Length (consecutive VHDs/H~~V~~Ns)			Occurrence interval between two daytime/nighttime EHWEs			
			1–~~-~~2 VHDs/HNs	3–~~-~~4 VHDs/HNs	≥ 5 V~~E~~HDs/HNs	0 days/nights	1–~~-~~3 days/nights	4–~~-~~7 days/nights	≥ 8 days/nights
All study cases (n = 359,220)	Day	1.60 (-0.15, 3.39)	0.50 (-1.77, 2.81)	1.80 (-1.67, 5.38)	**3.99** **(0.56, 7.53)**	**4.39** **(1.18, 7.70)**	-1.11 (-7.97, 6.26)	7.50 (1.26, 14.13)	0.30 (-2.58, 3.26)
	Night	**2.43** **(0.75, 4.14)**	0.56 (-1.35, 3.40)	1.18 (-1.66, 4.10)	**6.66** **(3.45, 9.96)**	**5.74** **(1.81, 9.82)**	1.32 (-4.63, 7.64)	3.33 (-4.32, 11.58)	2.86 (-0.05, 5.86)
Male (n = 176,368, 49.1%)	Day	0.95 (-1.26, 3.22)	0.13 (-2.75, 3.10)	-0.10 (-4.47, 4.47)	**5.16** **(0.76, 9.75)**	3.96 (-0.14, 8.22)	-3.92 (-12.5, 5.52)	4.92 (-2.92, 13.38)	-0.31 (-3.97, 3.49)
	Night	1.28 (-0.86, 3.47)	0.29 (-2.69, 3.36)	0.00 (-3.60, 3.73)	**4.70** **(0.65, 8.90)**	1.82 (-3.09, 6.97)	2.00 (-5.58, 10.19)	0.77 (-8.80, 11.35)	2.40 (-1.31, 6.24)
Female (n = 143,089, 39.8%)	Day	2.10 (-0.53, 4.81)	1.17 (-1.96, 4.39)	4.06 (-1.03, 9.41)	2.49 (-3.13, 8.44)	4.92 (-0.1, 10.19)	5.34 (-4.59, 16.30)	**11.29** **(1.90, 21.56)**	0.60 (-34.82, 55.26)
	Night	**2.74** **(0.35, 5.18)**	1.51 (-2.01, 5.16)	5.43 (-1.70, 6.73)	**6.06** **(0.79, 11.60)**	**6.82** **(0.6, 13.43)**	2.33 (-6.93, 12.51)	4.08 (-8.85, 18.85)	2.33 (-1.99, 6.84)
Age ≤ 18 (n = 968, 0.3%)	Day	2.10 (-8.51,13.95)	1.39 (-11.6, 16.30)	4.08 (-16.1, 29.12)	5.13 (-16.9, 33.00)	3.77 (-13.5, 24.5)	5.65 (-24.4, 47.72)	-11.57 (-57.68, 84.77)	-7.69 (-24.56, 12.96)
	Night	0.30 (-9.60, 11.28)	-5.73 (-19.4, 10.27)	-3.3 (-15.7, 10.87)	26.24 (1.76, 56.61)	**28.92** **(0.7, 65.03)**	18.53 (-9.9, 55.96)	-17.30 (-50.81, 39.01)	-3.92 (-18.82, 13.72)
19 ≤ Age ≤ 64 (n = 61,552, 17.1%)	Day	-0.02 (-3.67, 3.77)	-1.00 (-5.54, 3.77)	1.01 (-6.06, 8.60)	2.02 (-5.67, 10.34)	4.8 (-2.3, 12.47)	-6.76 (-20.1, 8.85)	11.40 (-1.92, 26.54)	-1.00 (-7.01, 5.41)
	Night	-0.60 (-4.04, 2.97)	0.99 (-1.35, 3.40)	1.18 (-1.66, 4.10)	6.66 (3.45, 9.96)	-1.00 (-9.35, 8.13)	-8.61 (-20.6, 5.24)	-0.90 (-18.38, 20.33)	2.81 (-3.38, 9.40)
Age ≥ 65 (n = 256,937, 71.5%)	Day	1.71 (-0.42, 3.89)	0.90 (-1.63, 3.51)	1.82 (-2.29, 6.09)	4.29 (-0.35, 9.14)	4.08 (-0.02, 8.35)	2.84 (-5.18, 11.53)	6.79 (-0.80, 14.96)	0.19 (-3.27, 3.76)
	Night	**2.53** **(0.46, 4.64)**	1.11 (-1.63, 3.92)	2.74 (-0.63, 6.22)	**5.33** **(1.08, 9.75)**	**5.23** **(0.2, 10.52)**	7.08 (-0.61, 15.36)	0.94 (-9.50, 12.59)	2.40 (-0.96, 5.87)

Note~~s~~: Significant effects at the significance level of 0.05 are marked as bold numbers.

revision_Table4

Table 4~~3.2~~. Increased risks of mortality (in percentages) between extremely hot days in the defined ~~extremely hot weather event~~ extremely hot weather events (EHWEs) and non-hot days, according to different combinations of very hot days (VHDs) and hot nights (HNs).

	Two~~2~~ consecutive VHDs with:				Three~~3~~ consecutive VHDs with:				
	0 HNs	1 HN	2 HNs	3 HNs	0 HNs	1 HN	2 HNs	3 HNs	4 HNs
All study populations (n = 359,220)	0.56 (-3.63, 4.92)	2.28 (-1.52, 6.22)	-0.03 (-3.52, 3.59)	**5.32** **(1.83, 8.93)**	4.63 (-3.39, 13.30)	2.30 (-3.56, 8.52)	0.54 (-3.60, 4.87)	-1.15 (-8.00, 6.20)	**4.60** **(0.57, 8.79)**
Male (n = 176,368, 49.1%)	-0.48 (-5.77, 5.11)	1.25 (-3.56, 6.29)	0.13 (-4.17, 4.62)	3.25 (-1.14, 7.84)	3.32 (-6.78, 14.52)	2.22 (-5.21, 10.24)	1.4 (-3.9, 6.99)	-3.73 (-12.25, 5.62)	3.54 (-1.56, 8.91)
Female (n = 143,089, 39.8%)	1.44 (-4.30, 7.52)	3.77 (-1.44, 9.26)	-0.45 (-5.14, 4.47)	**7.57** **(2.11, 13.33)**	10.49 (-2.65, 25.41)	2.4 (-5.99, 11.5)	-2.27 (-8.74, 4.65)	1.77 (-7.79, 12.33)	4.60 (-1.94, 11.59)
Age ≤ 18 (n = 968, 0.3%)	-3.92 (-25.09, 23.23)	-5.8 (-25.5, 19.1)	-2.57 (-25.36, 27.20)	-0.9 (-18.85, 21.0)	30.87 (-14.4, 102.3)	3.1 (-23.7, 39.4)	-14.79 (-41.17, 23.42)	29.82 (-15.32, 99.03)	2.33 (-24.33, 38.38)
19 ≤ Age ≤ 64 (n = 61,552, 17.1%)	-0.80 (-9.35, 8.56)	2.84 (-5.1, 11.44)	-3.44 (-10.90, 4.64)	3.67 (-3.77, 11.68)	-17.22 (-33.01, 2.29)	11.6 (-0.7, 25.56)	-1.59 (-10.77, 8.55)	-1.98 (-14.55, 12.43)	3.67 (-4.15, 12.12)
Age ≥ 65 (n = 256,937, 71.5%)	1.61 (-3.25, 6.72)	2.07 (-2.43, 6.78)	-0.90 (-5.26, 3.67)	**5.87** **(1.46, 10.47)**	**15.95** **(5.13, 27.89)**	0.05 (-6.69,7.28)	-0.70 (-6.00, 4.90)	-1.19 (-8.88, 7.14)	4.81 (-0.53, 10.44)

Note~~s~~: Significant effects at the significance level of 0.05 are marked as bold numbers.

Formatted Table

Figure1

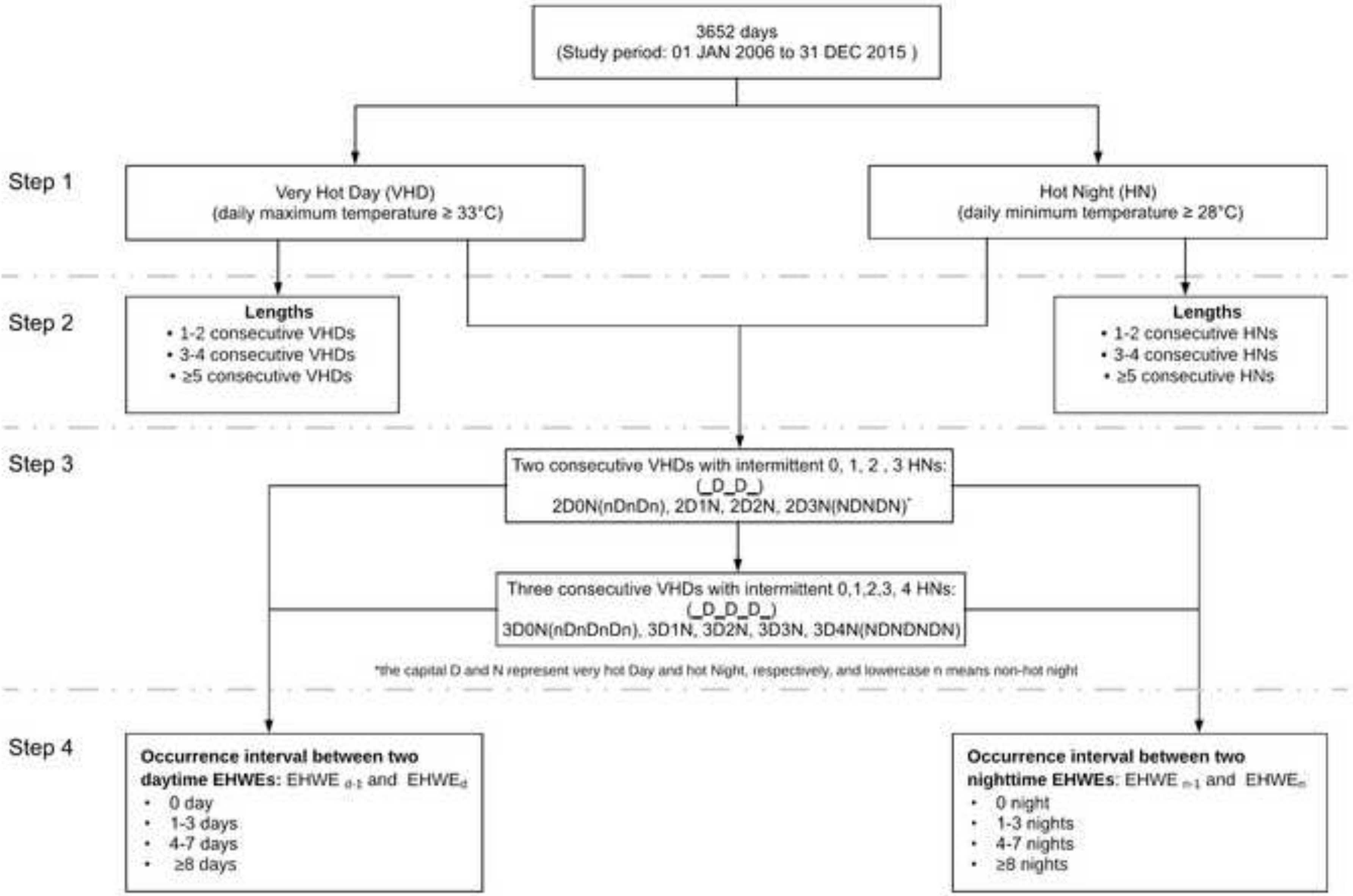
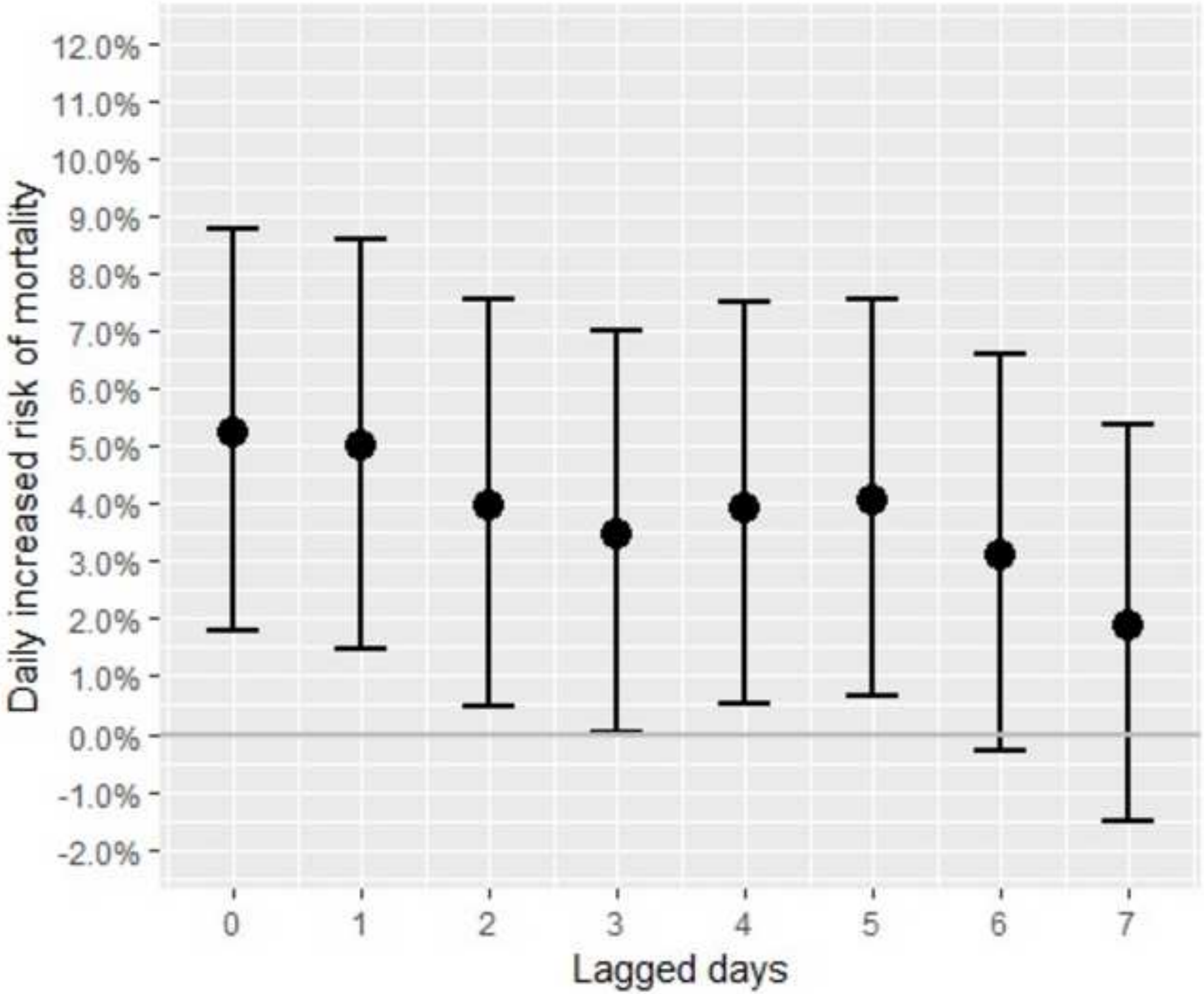

3652 days
(Study period: 01 JAN 2006 to 31 DEC 2015)
Step 1
Very Hot Day (VHD)
(daily maximum temperature ≥ 33°C)
Hot Night (HN)
(daily minimum temperature ≥ 28°C)
Step 2
Lengths
• 1-2 consecutive VHDs
• 3-4 consecutive VHDs
• ≥5 consecutive VHDs
Lengths
• 1-2 consecutive HNs
• 3-4 consecutive HNs
• ≥5 consecutive HNs
Step 3
Two consecutive VHDs with intermittent 0, 1, 2 , 3 HNs:
(_D_D_)
2D0N(nDnDn), 2D1N, 2D2N, 2D3N(NDNDN)*
Three consecutive VHDs with intermittent 0,1,2,3, 4 HNs:
(_D_D_D_)
3D0N(nDnDnDn), 3D1N, 3D2N, 3D3N, 3D4N(NDNDNDN)
*the capital D and N represent very hot Day and hot Night, respectively, and lowercase n means non-hot night
Step 4
Occurrence interval between two daytime EHWEs: EHWE $_{d-1}$ and EHWE$_d$
• 0 day
• 1-3 days
• 4-7 days
• ≥8 days
Occurrence interval between two nighttime EHWEs: EHWE $_{n-1}$ and EHWE$_n$
• 0 night
• 1-3 nights
• 4-7 nights
• ≥8 nights

Figure2



Daily increased risk of mortality
12.0%
11.0%
10.0%
9.0%
8.0%
7.0%
6.0%
5.0%
4.0%
3.0%
2.0%
1.0%
0.0%
-1.0%
-2.0%
0
1
2
3
4
5
6
7
Lagged days