Int J Biometeorol
DOI 10.1007/s00484-017-1383-4

ORIGINAL PAPER

Characterizing prolonged heat effects on mortality in a sub-tropical high-density city, Hong Kong

Hung Chak Ho[1,2] · **Kevin Ka-Lun Lau**[1,3,4] · **Chao Ren**[1,3,5] · **Edward Ng**[1,3,4,5]

Received: 26 November 2016 / Revised: 10 April 2017 / Accepted: 15 May 2017

Abstract Extreme hot weather events are likely to increase under future climate change, and it is exacerbated in urban areas due to the complex urban settings. It causes excess mortality due to prolonged exposure to such extreme heat. However, there is lack of universal definition of prolonged heat or heat wave, which leads to inadequacies of associated risk preparedness. Previous studies focused on estimating temperature-mortality relationship based on temperature thresholds for assessing heat-related health risks but only several studies investigated the association between types of prolonged heat and excess mortality. However, most studies focused on one or a few isolated heat waves, which cannot demonstrate typical scenarios that population has experienced. In addition, there are limited studies on the difference between daytime and nighttime temperature, resulting in insufficiency to conclude the effect of prolonged heat. In sub-tropical high-density cities where prolonged heat is common in summer, it is important to obtain a comprehensive understanding of prolonged heat for a complete assessment of heat-related health risks. In this study, six types of prolonged heat were examined by using a time-stratified analysis. We found that more consecutive hot nights contribute to higher mortality risk while the number of consecutive hot days does not have significant association with excess mortality. For a day after five consecutive hot nights, there were 7.99% [7.64%, 8.35%], 7.74% [6.93%, 8.55%], and 8.14% [7.38%, 8.88%] increases in all-cause, cardiovascular, and respiratory mortality, respectively. Non-consecutive hot days or nights are also found to contribute to short-term mortality risk. For a 7-day-period with at least five non-consecutive hot days and nights, there was 15.61% [14.52%, 16.70%] increase in all-cause mortality at lag 0–1, but only −2.00% [−2.83%, −1.17%] at lag 2–3. Differences in the temperature-mortality relationship caused by hot days and hot nights imply the need to categorize prolonged heat for public health surveillance. Findings also contribute to potential improvement to existing heat-health warning system.

Keywords Prolonged heat · Temperature-mortality relationship · Heat wave definition · Sub-tropical high-density cities · Short-term mortality risk

Introduction

Excess mortality due to prolonged heat was widely observed in urban environment, including cities from tropical and sub-tropical areas and temperate regions (Bell et al. 2008; Chan et al. 2012; Curriero et al. 2002; Dang et al. 2016; Filleul et al. 2006; Goggins et al. 2012; Guo et al. 2012; Hajat et al. 2005; Ho et al. 2017; Huang et al. 2010; Kaiser et al. 2007; Kosatsky et al. 2012; Lin et al. 2011; Semenza et al. 1996; Seposo et al. 2016; Smargiassi et al. 2009; Tam et al. 2009; Wu et al. 2013). It is attributed to the accumulated heat during such extreme hot weather and exacerbated by the compact urban settings. Climate change has also increased the severity, intensity, and frequency of extreme hot weather, resulting in increases in

---

✉ Hung Chak Ho
derrick.hc.ho@polyu.edu.hk

[1] Institute of Environment, Energy, and Sustainability, The Chinese University of Hong Kong, Sha Tin, Hong Kong

[2] Department of Land Surveying and Geo-Informatics, Hong Kong Polytechnic University, Kowloon, Hong Kong

[3] Institute of Future Cities, The Chinese University of Hong Kong, Sha Tin, Hong Kong

[4] CUHK Jockey Club Institute of Ageing, The Chinese University of Hong Kong, Sha Tin, Hong Kong

[5] School of Architecture, The Chinese University of Hong Kong, Sha Tin, Hong Kong

excess mortality (Meehl and Tebaldi 2004; Reid et al. 2009), and controlled by the mitigation to extreme hot weather such as heat warning system and community resilience (Burkart et al. 2016; Chau et al. 2009; Petkova et al. 2014). However, as there are no universal definition of prolonged heat or heat wave, it is important to consider the characteristics of local meteorological conditions and living environment in the impact assessment of extreme hot weather (Gao et al. 2015; Xu et al. 2016), in order to implement and improve the heat warning system for enhancing the climate resilience of a city (Petkova et al. 2014).

Previous studies extensively found excess mortality above a temperature threshold in different climatic regions, and this temperature threshold was commonly used to represent severity and intensity of extreme heat to human health (Ma et al. 2014; McMichael et al. 2008). Several recent studies have focused on studying prolonged heat or heat wave to mortality (Lin et al. 2011; Gasparrini and Armstrong 2011; Zeng et al. 2014). In order to quantify the relationship between prolonged heat and mortality risk, previous studies generally isolated a period of "heat wave" to examine the elevated mortality risk (Fouillet et al. 2006; Gabriel and Endlicher 2011; Kosatsky et al. 2012; Smoyer 1998). There were also studies to analyze temperature-mortality relationship based on decedents died on a day after consecutive days with average temperature above certain thresholds (Anderson and Bell 2011; Gasparrini and Armstrong 2011; Lin et al. 2011, Revich and Shaposhnikov 2008; Zeng et al. 2014). These two methods have been widely used to address the excess mortality associated with prolonged and abnormally high temperature.

Despite of the common use of the above methods, the nature of model settings may lead to potential bias to the results. For example, studies isolating a period of "heat wave" were typically conducted by pre-selecting one or a few 7- or 14-day-periods with multiple days of extreme heat as "periods of heat wave," then compared these "periods of heat wave" to the periods with less hot days (Fouillet et al. 2006; Gabriel and Endlicher 2011; Kosatsky et al. 2012). While this method is useful to predict mortality shift during one or a few specific heat waves, these results cannot represent the temperature-mortality relationship during prolonged heat because these specific heat waves are isolated events or very extreme cases.

In comparison with isolating a period of "heat wave," analyzing temperature-mortality relationship based on a temperature threshold is more promising because it generally involves multiple periods of extreme hot weather in a prediction model, which enhances the model ability to estimate the mortality risk during a prolonged period of extreme hot weather (Anderson and Bell 2011; Revich and Shaposhnikov 2008; Zeng et al. 2014). However, there were missing elements in term of integrating the characteristics of prolonged heat into previous studies, including the lack of consideration for periods with multiple non-consecutive hot days and the diurnal difference in temperature. Failure to include such characteristics of prolonged heat in previous models is likely the reason for the lack of significantly additional effect of consecutive hot days quantified by average temperature on excess mortality (Gasparrini and Armstrong 2011; Lin et al. 2011; Zeng et al. 2014).

In contrast to the common use of daytime temperature to quantify the temporal characteristics of temperature-mortality relationship, several studies suggested that urban nighttime temperature or diurnal temperature range had more significant association with thermal health issues (Cheng et al. 2014; Giridharan et al. 2005; Kan et al. 2007; Laaidi et al. 2012; Lim et al. 2012; Tam et al. 2009; Wang et al. 2013; Yang et al. 2013). It is therefore important to associate different characteristics of prolonged heat, such as consecutive hot days and consecutive hot nights, with the temperature-mortality relationship in order to appropriately predict excess mortality from different types of heat waves for public health planning.

In order to investigate the characteristics of prolonged heat to temperature-mortality relationship, we hereby developed a time-stratified analysis to compare different types of prolonged heat and their influences on excess mortality. Time-stratified analyses have been used to assess the influence of weather and air pollution on mortality, especially to examine the sensitivity of mortality risk to extreme heat across multiple cities, or to study mortality shift based on isolating a specific hot weather event in a defined geographic region (Bell et al. 2008; Ho et al. 2017; Johnston et al. 2011; Kosatsky et al. 2012; Medina-Ramón and Schwartz 2007; Smargiassi et al. 2009; Stafoggia et al. 2008). Time-stratified analysis can also simplify data analysis and reduce seasonal effects, for the purpose of directly differentiating excess mortality of cases from controls (e.g., hot periods vs non-hot periods). In this study, we applied time-stratified analysis to Hong Kong because the extremely dense urban environment and extensive building coverage highly influence the urban climate, resulting in distinctive diurnal temperature pattern which significantly affects mortality risk in Hong Kong (Tam et al. 2009). We examined the heat mortality between 2007 and 2014 for the purpose of removing potential bias before/after the first issue of heat warning system in 2000 (Chau et al. 2009); for the potential of improving current heat warning system that should be revised every 5 years (Hess and Ebi 2016); and for keeping the location of residence of each decedent under the same "Tertiary Planning Unit" (a neighborhood-level boundary in Hong Kong) issued in 2006. The objectives of our study include (1) to estimate the temperature-mortality relationship of each type of prolonged heat (e.g., consecutive hot days and consecutive hot nights) in Hong Kong, (2) to compare the difference in excess mortality of each type of prolonged heat, and (3) to identify the type of prolonged heat with higher contribution to short-term excess mortality.

Study area

Hong Kong is a high-density city with a population of approximately 7.1 million residing in an area of slightly more than 1000 km^2 (Thach et al. 2015). It is located in the sub-tropical region with a summer mean temperature of 28.6 °C during the period of 2007–2014. In addition, there are 480 days with daily mean temperature over 29 °C in the study period and daily maximum temperature can reach up to 34.8 °C. Due to the terrain and natural reserve, the population is resided in about 30% of the land, resulting in an extreme separation between urban and rural areas. Such an extremely high population density also results in highly compacted and high-rise urban form and a significant spatiotemporal difference in temperature (Nichol 2005). Although the heat warning system issued in 2000 could reduce 1.3 deaths from ischemic heart disease and 0.97 deaths from stroke of the elderly in Hong Kong (Chau et al. 2009); in the downtown area, due to strong urban heat island effect and reduced air ventilation, there is still a 5.7% excess mortality on hot summer days after 2000 (Goggins et al. 2012).

Materials and methods

We used mortality data from 2007 to 2014 to conduct this time-stratified analysis. This dataset was obtained from the Census and Statistics Department and consists of 284,477 mortality records with information of age, gender, occupation, date, location of residence, and underlying cause of death coded according to the 10th Revision of the International Classification of Diseases (ICD-10). We also used temperature between 7:00 a.m. and 7:00 p.m. to represent the daytime temperature and temperature between 7:00 p.m. and 7:00 a.m. to represent the nighttime temperature. Both daytime and nighttime temperature were retrieved based on hourly air temperature data recorded at the Hong Kong Observatory Headquarter during the study period. We also retrieved daily average concentration of air pollutants, including CO, NO_2, NO_x, O_3, SO_2, and PM_{10}, from the Environmental Protection Department for model adjustment.

In this study, cases were identified as the decedents who died on the days classified as hot days, and controls were the decedents on the same weekdays of 4 weeks before the date of death in order to minimize the weekday-weekend bias (Kosatsky et al. 2012). Two temperature thresholds were used in this study based on the Very Hot Weather Warning of the Hong Kong Observatory, namely Very Hot Days (VHD; at least 1 h of daytime temperature ≥33 °C) and Hot Nights (HN; all hours of night temperature ≥28 °C) (Hong Kong Observatory 2008). This approach follows previous studies of heat-related health risks for examining extreme heat warning with mortality data (Chau et al. 2009; Ebi et al. 2004; Tan et al. 2007). In addition, these temperature thresholds correspond to the 95th percentiles of $T_{\max}$ (32.8 °C) and $T_{\min}$ (28.2 °C) based on the 2007–2014 temperature data in Hong Kong, which is consistent with the common method of using 95th (or above) percentile of temperature as the thresholds for defining heat waves (Bell et al. 2008; Lin et al. 2011; Revich and Shaposhnikov 2008; Smargiassi et al. 2009).

Six types of prolonged heat were applied in this study: (1) three consecutive VHDs, (2) three consecutive HNs, (3) five consecutive VHDs, (4) five consecutive HNs, (5) at least three VHDs and three HNs within a 7-day period, and (6) at least five VHDs and five HNs within a 7-day period. The results of (1) and (3) were to analyze the effect of prolonged heat on the temperature-mortality relationship based on the traditional approach of using consecutive days (Lin et al. 2011), while the results of (2) and (4) were to determine whether nighttime temperature would induce a different temperature-mortality relationship from previous understandings of prolonged heat quantified by daytime temperature. On the other hand, the results of (5) and (6) were to examine whether prolonged heat with non-consecutive hot days and nights would also contribute to excess mortality. We also included an analysis of all cases died on VHDs in our study, as a baseline scenario demonstrating temperature-mortality relationship of hot summer days in general, for the purpose of demonstrating "main" effect on heat risk. Based on the comparison with the baseline's model, the higher risks of results of the other types of prolonged heat can be acted as the "additional effect" on mortality from the heat wave.

We applied a generalized linear regression with the *glm2* package of *R* software to estimate excess mortality from prolonged heat (Marschner 2014). Gaussian model was chosen for the purpose of generating an asymptotically normal distribution for cases and controls of all types of prolonged heat in order to retrieve relative risks between 0 and 100% for all models. In brief, to explain our model, we applied $T_{\min}$ to quantify excess mortality and controlled the model by the concentration of different air pollutants (CO, NO_2, NO_x, O_3, SO_2, and PM_{10}), weekday-weekend effect, socioeconomic vulnerability (age, gender, unemployment), and adaptive capacity estimated by the neighborhood-level vegetation cover. For each case, we assigned 100% as its expected mortality influencing from heat, while we assigned 0% as the expected mortality of each control for modeling:

$$\begin{aligned}\text{Heat Mortality Risk }(0\text{–}100\%) \sim \beta_0 &+ \beta_1 T_{\min} + \beta_2 \text{CO} \\ &+ \beta_3 \text{NO}_2 + \beta_4 \text{NO}_x + \beta_5 \text{O}_3 + \beta_6 \text{SO}_2 \\ &+ \beta_7 \text{PM}_{10} + \beta_8 \text{weekend }(1,0) + \beta_9 \text{Age} \\ &+ \beta_{10} \text{Gender} + \beta_{11} \text{Unemployment} \\ &+ \beta_{12} \text{Vegetation}\end{aligned}$$

The use of $T_{\min}$ to quantify excess mortality was found to have stronger association with heat-related mortality than $T_{\max}$

in warmer southern cities in the northern hemisphere (Davis et al. 2016). Time-stratified analysis also self-controls the seasonality based on the selection of cases and controls, therefore, seasonality has not been added as a confounding factor (Bell et al. 2008). As a result, this model measures excess mortality associated with a 1 °C increase in daily minimum air temperature and the 95% confidence intervals (CI).

We first estimated excess mortality of all prolonged heat based on a lag 0–3's scenario with the following subsets of mortality data: (1) all-cause mortality except traffic accidents (excluded ICD-10 codes V01–V99), (2) cardiovascular mortality (ICD-10 codes I00–I99), and (3) respiratory mortality (ICD-10 codes J00–J99). The results aim to represent excess mortality of each type of prolonged heat in general. Based on all-cause mortality models with highest excess mortality of each type of prolonged heat, we then reported all-cause mortality results at lag 0–1, and at lag 2–3 separately for estimating short-term lagged effect of prolonged heat. We also reported the *P* values of all variables of each all-cause mortality model (lag 0–3) in order to validate the significance of each confounding factor, for the purpose of minimizing the confounding bias of a retrospective study (Cox et al. 2009).

Results

Significance of confounding factors

For all-cause mortality, the adjustment of the influence of air pollutants was required for estimating the temperature-mortality relationship (Table 1). CO, PM_{10}, and SO_2 were found to be significant (*P* value <0.05) in all models while the influences of NO_x and O_3 were significant in all models except one, and influence of NO_2 was significant in five models. Age, unemployment, and weekday-weekend effect were partially important in the model adjustment while gender and neighborhood-level vegetation covers were not a significant confounding factor in any models.

Compared to the models for predicting all-cause mortality, influence of air pollutants, occupational weekday-weekend effect, socioeconomic vulnerability, and adaptive capacity estimated by neighborhood-level vegetation cover were fully or partially important in the model adjustment for cardiovascular mortality (Table 2). All confounding factors were also fully or partially important in predicting respiratory mortality except unemployment (Table 3).

Characteristics of prolonged heat to temperature-mortality relationship

In general, there were five events of three consecutive VHDs; 31 events of three consecutive HNs; three events of five consecutive VHDs; 11 events of five consecutive HNs, 67 events of at least three VHDs and three HNs within a 7-day period; and 11 events of at least three VHDs and three HNs within a 7-day period between 2007 and 2014. We compared the temperature-mortality relationships of the six types of prolonged heat based on all-cause mortality and found that three consecutive VHDs and five consecutive HNs had the highest influence on mortality risk in Hong Kong (Table 4), with 7.97% [7.14%, 8.80%] and 7.99% [7.64%, 8.35%] increase in mortality in 1 °C increase in daily minimum air temperature at lag 0–3, respectively. Excess mortality under these two types of prolonged heat was greater than without considering prolonged heat effect (the baseline scenario) with an increase of 3.67% [3.53%, 3.81%].

Our results do not indicate any significant trends between excess mortality and different types of consecutive VHDs, which is consistent with previous studies in sub-tropical regions (Lin et al. 2011; Zeng et al. 2014). There was a 4.90% [3.59%, 6.21%] increase in all-cause mortality for lag 0–3 after five consecutive VHDs, which was lower than excess mortality (7.97% [7.14%, 8.80%]) after three consecutive VHDs. There was no significant increase in respiratory mortality for lag 0–3 after five consecutive VHDs compared to 7.06% [5.32%, 8.80%] excess mortality after three consecutive VHDs. This "bell-shape" increase/decrease of excess mortality associated with consecutive hot days was also reported in a previous study conducted in temperate climate (Gasparrini and Armstrong 2011) although our range of consecutive hot days is relatively shorter than this previous study.

In contrast, we found significant trends between excess mortality (all-cause, cardiovascular, and respiratory) and consecutive HNs. Excess mortality of all-cause, cardiovascular, and respiratory mortality at lag 0–3 after three consecutive HNs were 3.70, 3.54, and 3.72% higher than the baseline's result, respectively, while excess mortality after five consecutive HNs were 0.62, 0.33, and 0.87% higher than that after three consecutive HNs. These results indicate that more consecutive HNs contributed to higher risk of all-cause, cardiovascular, and respiratory mortality, against more consecutive VHDs only contributed to cardiovascular mortality but not all-cause and respiratory mortality in Hong Kong between 2007 and 2014.

Excess mortality was also found under the influence of prolonged heat with non-consecutive VHDs or HNs. For lag 0–3 days after at least three VHDs and three HNs within a 7-day period, there was only 1.46% [1.22%, 1.71%], 1.82% [1.29%, 2.36%], and 1.80% [1.28%, 2.32%] increase in all-cause, cardiovascular, and respiratory mortality, respectively. However, for lag 0–3 days after at least five VHDs and five HNs within a 7-day period, we found 5.32% [4.59%, 6.04%], 5.74% [4.18%, 7.29%], and 6.23% [4.62%, 7.85%] increase in the three types of mortality, respectively. Although excess mortality of non-consecutive VHDs or HNs was generally lower than that of the consecutive counterpart, the duration

Table 1 *P* values of confounding factors, representing the significance of confounding factors in each all-cause mortality model. Significant confounding factors are marked with *

Variables	Baseline (T_{max} ≥33 °C)	Three consecutive VHDs	Three consecutive HNs	Five consecutive VHDs	Five consecutive HNs	At least three VHDs and three HNs within a 7-day period	At least five VHDs and five HNs within a 7-day period
CO	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*
NO_2	0.14	<0.05*	0.26	<0.05*	<0.05*	<0.05*	<0.05*
NO_x	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*	0.11
O_3	<0.05*	0.32	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*
PM_{10}	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*
SO_2	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*
Weekday-weekend effect	<0.05*	0.08	<0.05*	0.24	0.86	<0.05*	<0.05*
Age	0.16	0.35	0.96	0.16	0.07	<0.05*	0.66
Gender	0.78	0.35	0.94	0.92	0.31	0.36	0.87
Unemployment	<0.05*	0.66	0.06	0.59	0.15	<0.05*	0.87
Vegetation	0.51	0.70	0.85	0.28	0.26	0.47	0.94

of non-consecutive VHDs or HNs is a factor to consider with regard to excess mortality due to prolonged heat.

Lagged effect of heat mortality (lag 0–1 and lag 2–3)

We examined the lagged effect of heat mortality of the models with the highest excess mortality: (1) three consecutive VHDs, (2) five consecutive HNs, and (3) at least five VHDs and five HNs within a 7-day period (Table 5). We found similar patterns of lagged effect of consecutive hot days and consecutive hot nights to our baseline's result as well as previous studies conducted in sub-tropical cities (Wu et al. 2013; Yang et al. 2015).

For lag 0–1 days of (1) baseline scenario, (2) three consecutive VHDs, and (3) five consecutive HNs, we found 5.91% [5.72%, 6.10%], 10.23% [9.02%, 11.45%], and 10.95% [10.48%, 11.42%] excess mortality, respectively. For lag 2–3 days, excess mortality was reduced but still significant, which we found 1.09% [0.88%, 1.30%], 6.60% [5.67%, 7.52%], and 5.24% [4.72%, 5.77%] increase in mortality, respectively, for a 1 °C increase in daily minimum air temperature.

In contrast, there was a lack of lagged effect after non-consecutive VHDs/HNs compared to other scenarios. Lag

Table 2 *P* values of confounding factors, representing the significance of confounding factors in each cardiovascular mortality model. Significant confounding factors are marked with *

Variables	Baseline (T_{max} ≥ 33 °C)	Three consecutive VHDs	Three consecutive HNs	Five consecutive VHDs	Five consecutive HNs	At least three VHDs and three HNs within a 7-day period	At least five VHDs and five HNs within a 7-day period
CO	<0.05*	0.10	<0.05*	<0.05*	0.22	<0.05*	<0.05*
NO_2	<0.05*	<0.05*	0.35	<0.05*	<0.05*	<0.05*	<0.05*
NO_x	<0.05*	0.19	<0.05*	<0.05*	<0.05*	<0.05*	0.62
O_3	<0.05*	0.36*	0.14	<0.05*	0.12	<0.05*	<0.05*
PM_{10}	<0.05*	<0.05*	<0.05*	<0.05*	0.93	<0.05*	<0.05*
SO_2	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*
Weekday-weekend effect	<0.05*	0.31	<0.05*	0.57	0.29	0.36	<0.05*
Age	0.84	0.68	0.32	0.84	0.19	<0.05*	0.31
Gender	0.15	0.19	0.83	<0.05*	0.69	<0.05*	0.20
Unemployment	0.20	0.44	0.66	0.92	0.50	<0.05*	0.73
Vegetation	0.36	0.05	0.84	<0.05*	0.94	0.41	0.84

Table 3 *P*-values of confounding factors, representing the significance of confounding factors in each respiratory mortality model. Significant confounding factors are marked with *

Variables	Baseline ($T_{max} \geq 33$ °C)	Three consecutive VHDs	Three consecutive HNs	Five consecutive VHDs	Five consecutive HNs	At least three VHDs and three HNs within a 7-day period	At least five VHDs and five HNs within a 7-day period
CO	<0.05*	<0.05*	<0.05*	<0.05*	0.07	<0.05*	<0.05*
NO_2	0.21	<0.05*	0.14	<0.05*	<0.05*	<0.05*	<0.05*
NO_X	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*	0.25
O_3	<0.05*	0.17	<0.05*	<0.05*	0.09	<0.05*	<0.05*
PM_{10}	0.21	<0.05*	<0.05*	<0.05*	0.92	<0.05*	<0.05*
SO_2	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*	<0.05*
Weekday-weekend effect	<0.05*	0.23	0.98	0.87	0.76	<0.05*	<0.05*
Age	0.29	0.59	<0.05*	0.68	0.30	0.47	0.43
Gender	0.97	0.27	0.76	0.98	0.95	<0.05*	<0.05*
Unemployment	0.08	0.14	0.37	0.48	0.91	0.55	0.66
Vegetation	0.05	0.06	0.23	<0.05*	0.56	0.11	0.58

0–1 days after at least five VHDs and five HNs within a 7-day period had an increase of 15.61% [14.52% 16.70%] in mortality for a 1 °C increase in daily minimum air temperature but excess mortality of lag 2–3 days was −2.00% [−2.83%, −1.17%].

Discussion

Comparison of heat-related health studies

In this study, we examined the temperature-mortality relationship under prolonged heat conditions from two aspects, namely baseline, and consecutive and non-consecutive hot days or hot nights. Our results indicate similar findings to previous studies that prolonged heat effect of consecutive hot days did not have significant contribution to excess mortality (Gasparrini and Armstrong 2011; Lin et al. 2011; Zeng et al. 2014) and at the same time provide new finding that prolonged heat from consecutive hot nights has an effect on excess mortality (7.99% [7.64%, 8.35%]). We also found that, although non-consecutive hot days/nights have weaker associations with excess mortality than consecutive hot days/nights at lag 0–3, an increase in non-consecutive hot days and hot nights within a 7-day period was related to increasing excess mortality. More importantly, we found significant mortality displacement after at least five VHDs and five HNs within a 7-day period, in which it induced severe increase in very short-term mortality at lag 0–1 (excess mortality 15.61% [14.52%, 16.70%]). Our results also show mortality displacement for other types of prolonged heat but it is relatively lower than the one from non-consecutive hot days/nights.

In general, our results are consistent with research studies in Hong Kong or nearby cities (Goggins et al. 2012; Thach et al. 2015; Wu et al. 2013; Yang et al. 2015; Yi and Chan 2015; Zeng et al. 2014). Our baseline's results ($T_{max} \geq 33$ °C) show that there

Table 4 Excess mortality of prolonged heat (lag 0–3). The results indicate the percentage increase in mortality in 1 °C increase in daily minimum air temperature at lag 0–3 and the corresponding 95% confidence intervals of each model. Significant results are marked with *

Model	All-cause mortality	Cardiovascular mortality	Respiratory mortality
Baseline ($T_{max} \geq 33$ °C)	3.67% [3.53%, 3.81%]*	3.87% [3.55%, 4.18%]*	3.54% [3.24%, 3.85%]*
Three consecutive VHDs	7.97% [7.14%, 8.80%]*	8.36% [6.53%, 10.19%]*	7.06% [5.32%, 8.80%]*
Three consecutive HNs	7.37% [7.14%, 7.61%]*	7.41% [6.88%, 7.94%]*	7.26% [6.77%, 7.75%]*
Five consecutive VHDs	4.90% [3.59%, 6.21%]*	9.64% [6.75%, 12.54%]*	0.78% [−2.01%, 3.56%]
Five consecutive HNs	7.99% [7.64%, 8.35%]*	7.74% [6.93%, 8.55%]*	8.13% [7.38%, 8.88%]*
At least three VHDs and three HNs within a 7-day period	1.46% [1.22%, 1.71%]*	1.82% [1.29%, 2.36%]*	1.80% [1.28%, 2.32%]*
At least five VHDs and five HNs within a 7-day period	5.32% [4.59%, 6.04%]*	5.74% [4.18%, 7.29%]*	6.23% [4.62%, 7.85%]*

Table 5 Excess mortality of prolonged heat (lag 0–1 and lag 2–3). The results indicated the percentage increase in mortality in 1 °C increase in daily minimum air temperature at lag 0–1 and lag 2–3, and the corresponding 95% confidence intervals of each model. Significant results are marked with *

Model	All-cause mortality (lag 0–1)	All-cause mortality (lag 2–3)
Baseline ($T_{\max}$ ≥33 °C)	5.91% [5.72%, 6.10%]*	1.09% [0.88%, 1.30%]*
Three consecutive VHDs	10.23% [9.02%, 11.45%]*	6.60% [5.67%, 7.52%]*
Five consecutive HNs	10.95% [10.48%, 11.42%]*	5.24% [4.72%, 5.77%]*
At least five VHDs and five HNs within a 7-day period	15.61% [14.52% 16.70%]*	−2.00% [−2.83%, −1.17%]*

was a 3.67% [3.53%, 3.81%] increase in mortality in 1 °C increase in daily minimum air temperature at lag 0–3 for the study period of 2007–2014. These results are similar to previous studies at Hong Kong that 2.1% [−0.3%, 4.6%] increase in mortality was found for a day with average temperature higher than 29 °C between 2001 and 2009 (Goggins et al. 2012) and 2.16% [−0.05%, 4.37%] excess mortality was found in the warm season in Hong Kong in 2006 (Thach et al. 2015). However, our baseline result is lower than a relatively extreme case reported by Yi and Chan (2015), with 9% [3%, 17%] higher mortality at 99th percentile of average temperature (31.5 °C) compared to 75th percentile (27.8 °C) between 2002 and 2011. In Guangzhou, sharing similar urban environment, population structure (including culture practices), and sub-tropical climate to Hong Kong, results of previous studies in this city are also comparable to our baseline result. Three to four percent increase in mortality was found in Guangzhou between 2003 and 2007 (Yang et al. 2015) and 2.9–3.7% increase was reported between 2006 and 2009 (Wu et al. 2013). It is noted that the characteristics of urban environment and population structure significantly influence heat-related mortality risks in sub-tropical cities, resulting in significant differences in temperature-mortality relationship. One example is that Zeng et al. (2014) reported a large variation of excess mortality, ranging from 4.8 to 15.4%, in four different cities in Guangdong province (Guangzhou, Zhuhai, Nanxiong, and Taishan). Therefore, our baseline results should only be consistent with the sub-tropical high-density cities with similar socioeconomic conditions.

Implications of heat wave definition

One major advantage of our study is the stratification of temperature-mortality relationship based on the characteristics of prolonged heat. Previous studies overgeneralized the definition of heat wave since there was an insufficient consideration of the type of prolonged heat and a lack of understanding about nighttime temperature (Anderson and Bell 2011; Gasparrini and Armstrong 2011; Lin et al. 2011; Revich and Shaposhnikov 2008; Zeng et al. 2014). Overgeneralizing the heat wave definition as a result in insufficiency of representing the actual prolonged heat a vulnerable person would experience. While extremes in daily temperature were widely recognized as the most important factor of heat-related mortality in both tropical/subtropical and temperate regions (Gasparrini and Armstrong 2011; Zeng et al. 2014), better understandings of additional effect of prolonged heat during nighttime will improve the analysis of excess mortality and short-term mortality displacement during a heat wave and is useful to the development of public health surveillance system for reducing the vulnerability to prolonged or extreme heat events (Wilhelmi and Hayden 2010). Therefore, analyzing the characteristics of prolonged heat with regard to the temperature-mortality relationship is essential and innovative because our method clearly classifies potential scenarios of prolonged heat in summer and is able to identify specific scenarios in need of emergency response in terms of excess mortality.

Another advantage of our study is the application of local heat warning system to a comprehensive heat-mortality assessment. Previous studies compared heat waves with or without local heat warning and found significant difference in mortality (Chau et al. 2009; Ebi et al. 2004; Fouillet et al. 2008; Petkova et al. 2014; Tan et al. 2007). These results show that the appropriate use of local heat warning system could successfully help reduce the vulnerability to prolonged or extreme heat events in the future (Wilhelmi and Hayden 2010). However, the main focus of previous studies was to predict mortality shift between two heat events, one with local warning and one without warning (Chau et al. 2009; Ebi et al. 2004; Fouillet et al. 2008; Tan et al. 2007). These research could not address excess mortality under different types of heat wave or prolonged heat conditions while understanding the effect of the nature of heat wave on excess mortality is necessary to inform potential disaster outbreaks during future heat events. Therefore, it is important to integrate local heat warning system into more comprehensive heat-mortality assessment in order to determine the practicality of local heat warning system to public health surveillance and, at the same time, provide accurate estimation of excess mortality for emergency management. The results of this study can also be used to improve the current heat warning system of Hong Kong since there is a need for review on the local heat warning system in every 5 years (Hess and Ebi 2016).

Mortality estimation with time-stratified analysis

Compared to previous studies, we did not apply time-series analysis with distributed lag linear model (DLLM) or distributed lag non-linear model (DLNM) to estimate mortality risk. While DLLM and DLNM were commonly used to develop an all-inclusive model to determine heat-related risks (Anderson and Bell 2011; Chan et al. 2012; Goggins et al. 2012; Lin et al. 2011; Seposo et al. 2016; Zeng et al. 2014), including data from all seasons in such a model, may reduce the ability to directly quantify the excess mortality of particular heat scenarios (e.g., prolonged heat with different characteristics). In this study, the use of time-stratified analysis can therefore provide valid and more relevant results since the model can directly estimate the excess mortality of different types of prolonged heat relative to other summer days in the same year.

Also, non-consecutive hot days/nights within a 7-day period were examined as scenarios of prolonged heat in this time-stratified analysis, which is different from common understandings that the effect of prolonged heat is mainly due to accumulated heat through consecutive days (Tan et al. 2007). It was reported that temperature difference between hot and non-hot days is the “main effect” for heat-related mortality while the duration of heat can be the “additional effect” (Xu et al. 2016; Zeng et al. 2014). The findings of this study implies that non-consecutive hot days/nights within a 7-day period can develop a “mixed effect” to heat-related mortality by both temperature variation and relatively longer duration of heat. It was supported by a previous study, with results indicating a significant association between temperature change of neighboring days and mortality risk in sub-tropical Chinese cities (Lin et al. 2013), matching with our results that prolonged heat with significant temperature change between neighboring days (at least five VHDs and five HNs within a 7-day period) had severe mortality increase at lag 0–1.

Limitations

One limitation of our study is that our time-stratified analysis did not consider any spatial factors. Recent studies have emerged to assert the importance of understanding the spatial variability of heat-related mortality (Goggins et al. 2012; Ho et al. 2017; Hondula et al. 2012; Laaidi et al. 2012; Smargiassi et al. 2009; Thach et al. 2015). However, these studies also reported the potential issues of using temperature and pollution maps in studies of heat-related mortality (Ho et al. 2017; Thach et al. 2015). Insufficient spatial coverage of weather stations causes ecological fallacy (Thach et al. 2015) and therefore induces a statistical bias to the prediction model. Remote sensing applications based on satellite images or land use regression models using GIS data are possible measures to improve the mapping of temperature or air pollution in fine spatial scales (Adam-Poupart et al. 2014; Dons et al. 2014; Eeftens et al. 2016; Ho et al. 2014; Ho et al. 2016; Hoek et al. 2008; Lai et al. 2016; Liu et al. 2016; Nichol et al. 2009; Shi et al. 2016; Su et al. 2008; Xu and Liu 2015). Such techniques are somewhat limited by the temporal resolution of spatial data such that there is a lack of study accurately mapping spatiotemporal variation of daily temperature or air pollution. The key of our study is to apply a time-stratified analysis to predict excess mortality on a day after prolonged heat. While integrating spatial information to our model may increase the variability of heat mortality, inappropriate use of spatial data would also significantly reduce the accuracy of our analysis. Therefore, we hereby propose a spatiotemporal analysis for future studies, given that sufficient spatial data with quality are available.

Conclusions

We developed a time-stratified analysis to determine the temperature-mortality relationship associated with six different types of prolonged heat in Hong Kong, including traditional type of prolonged heat defined by consecutive hot days or hot nights, and new types of prolonged heat categorized by non-consecutive hot days or hot nights. For the traditional type of prolonged heat, our results do not indicate associations between the number of consecutive VHDs and all-cause mortality or respiratory mortality, similar to previous studies conducted in sub-tropical high-density cities (Lin et al. 2011; Zeng et al. 2014). In contrast to VHDs commonly used in previous studies, our results indicate new findings of strong associations between the number of consecutive HNs and excess mortality (all-cause mortality, cardiovascular mortality, and respiratory mortality) in Hong Kong, with the highest mortality risks observed in the case of five consecutive HNs at lag 0–3. This relationship between the number of consecutive HNs and excess mortality has seldom been examined in previous studies. For the new type of prolonged heat categorized by non-consecutive hot days or nights, our results indicate that at least five VHDs and five HNs within a 7-day period can cause significant mortality displacement and can severely increase excess mortality at lag 0–1. Finally, our approach of integrating excess mortality of specific prolonged heat scenarios into current local heat warning system can be used to validate local heat warning and improve public health surveillance (Chau et al. 2009; Wilhelmi and Hayden 2010) by setting new heat-health alarm at days experienced prolonged heat.

Acknowledgements The authors acknowledge the Chinese University of Hong Kong for providing partial funding for this project (Vice-Chancellor Discretionary Fund).

References

Adam-Poupart A, Brand A, Fournier M, Jerrett M, Smargiassi A (2014) Spatiotemporal modeling of ozone levels in Quebec (Canada): a comparison of kriging, land-use regression (LUR), and combined Bayesian maximum entropy-LUR approaches. Environ Health Perspect 122(9):970

Anderson GB, Bell ML (2011) Heat waves in the United States: mortality risk during heat waves and effect modification by heat wave characteristics in 43 US communities. Environ Health Perspect 119(2): 210

Bell ML, O'Neill MS, Ranjit N, Borja-Aburto VH, Cifuentes LA, Gouveia NC (2008) Vulnerability to heat-related mortality in Latin America: a case-crossover study in Sao Paulo, Brazil, Santiago, Chile and Mexico City, Mexico. Int J Epidemiol 37(4):796–804

Burkart K, Meier F, Schneider A, Breitner S, Canário P, Alcoforado MJ et al (2016) Modification of heat-related mortality in an elderly urban population by vegetation (urban green) and proximity to water (urban blue): evidence from Lisbon, Portugal. Environ Health Perspect 124(7):927

Chan EYY, Goggins WB, Kim JJ, Griffiths SM (2012) A study of intracity variation of temperature-related mortality and socioeconomic status among the Chinese population in Hong Kong. J Epidemiol Community Health 66(4):322–327

Chau PH, Chan KC, Woo J (2009) Hot weather warning might help to reduce elderly mortality in Hong Kong. Int J Biometeorol 53(5): 461–468

Cheng J, Xu Z, Zhu R, Wang X, Jin L, Song J, Su H (2014) Impact of diurnal temperature range on human health: a systematic review. Int J Biometeorol 58(9):2011–2024

Cox E, Martin BC, Van Staa T, Garbe E, Siebert U, Johnson ML (2009) Good research practices for comparative effectiveness research: approaches to mitigate bias and confounding in the design of nonrandomized studies of treatment effects using secondary data sources: the International Society for Pharmacoeconomics and Outcomes Research Good Research Practices for Retrospective Database Analysis Task Force Report—part II. Value Health 12(8):1053–1061

Curriero FC, Heiner KS, Samet JM, Zeger SL, Strug L, Patz JA (2002) Temperature and mortality in 11 cities of the eastern United States. Am J Epidemiol 155(1):80–87

Dang, T. N., Seposo, X. T., Duc, N. H. C., Thang, T. B., An, D. D., Hang, L. T. M., ... & Honda, Y. (2016). Characterizing the relationship between temperature and mortality in tropical and subtropical cities: a distributed lag non-linear model analysis in Hue, Viet Nam, 2009–2013. Global health action, 9

Davis RE, Hondula DM, Patel AP (2016) Temperature observation time and type influence estimates of heat-related mortality in seven US cities. Environ Health Perspect 124(6):795

Dons E, Van Poppel M, Panis LI, De Prins S, Berghmans P, Koppen G, Matheeussen C (2014) Land use regression models as a tool for short, medium and long term exposure to traffic related air pollution. Sci Total Environ 476:378–386

Ebi KL, Teisberg TJ, Kalkstein LS, Robinson L, Weiher RF (2004) Heat watch/warning systems save lives. Bull Am Meteorol Soc 85(8): 1067

Eeftens M, Meier R, Schindler C, Aguilera I, Phuleria H, Ineichen A et al (2016) Development of land use regression models for nitrogen dioxide, ultrafine particles, lung deposited surface area, and four other markers of particulate matter pollution in the Swiss SAPALDIA regions. Environ Health 15(1):1

Filleul L, Cassadou S, Médina S, Fabres P, Lefranc A, Eilstein D et al (2006) The relation between temperature, ozone, and mortality in nine French cities during the heat wave of 2003. Environ Health Perspect 114:1344–1347

Fouillet A, Rey G, Laurent F, Pavillon G, Bellec S, Guihenneuc-Jouyaux C et al (2006) Excess mortality related to the August 2003 heat wave in France. Int Arch Occup Environ Health 80(1):16–24

Fouillet A, Rey G, Wagner V, Laaidi K, Empereur-Bissonnet P, Le Tertre A et al (2008) Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. Int J Epidemiol 37(2):309–317

Gabriel KM, Endlicher WR (2011) Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. Environ Pollut 159(8):2044–2050

Gao J, Sun Y, Liu Q, Zhou M, Lu Y, Li L (2015) Impact of extreme high temperature on mortality and regional level definition of heat wave: a multi-city study in China. Sci Total Environ 505:535–544

Gasparrini A, Armstrong B (2011) The impact of heat waves on mortality. Epidemiology 22(1):68

Giridharan R, Lau SSY, Ganesan S (2005) Nocturnal heat island effect in urban residential developments of Hong Kong. Energ Buildings 37(9):964–971

Goggins WB, Chan EY, Ng E, Ren C, Chen L (2012) Effect modification of the association between short-term meteorological factors and mortality by urban heat islands in Hong Kong. PLoS One 7(6): e38551

Guo Y, Punnasiri K, Tong S (2012) Effects of temperature on mortality in Chiang Mai city, Thailand: a time series study. Environ Health 11(1):1

Hajat S, Armstrong BG, Gouveia N, Wilkinson P (2005) Mortality displacement of heat-related deaths: a comparison of Delhi, Sao Paulo, and London. Epidemiology 16(5):613–620

Hess JJ, Ebi KL (2016) Iterative management of heat early warning systems in a changing climate. Ann N Y Acad Sci 1382(1):21–30

Ho HC, Knudby A, Sirovyak P, Xu Y, Hodul M, Henderson SB (2014) Mapping maximum urban air temperature on hot summer days. Remote Sens Environ 154:38–45

Ho HC, Knudby A, Xu Y, Hodul M, Aminipouri M (2016) A comparison of urban heat islands mapped using skin temperature, air temperature, and apparent temperature (Humidex), for the greater Vancouver area. Sci Total Environ 544:929–938

Ho HC, Knudby A, Walker BB, Henderson SB (2017) Delineation of spatial variability in the temperature-mortality relationship on extremely hot days in greater Vancouver, Canada. Environ Health Perspect 125(1):66–75

Hoek G, Beelen R, De Hoogh K, Vienneau D, Gulliver J, Fischer P, Briggs D (2008) A review of land-use regression models to assess spatial variation of outdoor air pollution. Atmos Environ 42(33): 7561–7578

Hondula DM, Davis RE, Leisten MJ, Saha MV, Veazey LM, Wegner CR (2012) Fine-scale spatial variability of heat-related mortality in Philadelphia County, USA, from 1983-2008: a case-series analysis. Environ Health 11(1):1

Hong Kong Observatory (2008) Cold and Very Hot Weather Warnings. http://www.weather.gov.hk/wservice/warning/coldhot.htm

Huang W, Kan H, Kovats S (2010) The impact of the 2003 heat wave on mortality in Shanghai, China. Sci Total Environ 408(11):2418–2420

Johnston F, Hanigan I, Henderson S, Morgan G, Bowman D (2011) Extreme air pollution events from bushfires and dust storms and their association with mortality in Sydney, Australia 1994–2007. Environ Res 111(6):811–816

Kaiser R, Le Tertre A, Schwartz J, Gotway CA, Daley WR, Rubin CH (2007) The effect of the 1995 heat wave in Chicago on all-cause and cause-specific mortality. Am J Public Health 97(Supplement_1): S158–Ssss

Kan H, London SJ, Chen H, Song G, Chen G, Jiang L et al (2007) Diurnal temperature range and daily mortality in Shanghai, China. Environ Res 103(3):424–431

Kosatsky T, Henderson SB, Pollock SL (2012) Shifts in mortality during a hot weather event in Vancouver, British Columbia: rapid assessment with case-only analysis. Am J Public Health 102(12): 2367–2371

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

Lai PC, Choi CC, Wong PP, Thach TQ, Wong MS, Cheng W et al (2016) Spatial analytical methods for deriving a historical map of physiological equivalent temperature of Hong Kong. Build Environ 99:22–28

Lim YH, Park AK, Kim H (2012) Modifiers of diurnal temperature range and mortality association in six Korean cities. Int J Biometeorol 56(1):33–42

Lin YK, Ho TJ, Wang YC (2011) Mortality risk associated with temperature and prolonged temperature extremes in elderly populations in Taiwan. Environ Res 111(8):1156–1163

Lin H, Zhang Y, Xu Y, Xu X, Liu T, Luo Y et al (2013) Temperature changes between neighboring days and mortality in summer: a distributed lag non-linear time series analysis. PLoS One 8(6):e66403

Liu C, Henderson BH, Wang D, Yang X, Peng ZR (2016) A land use regression application into assessing spatial variation of intra-urban fine particulate matter (PM 2.5) and nitrogen dioxide (NO 2) concentrations in City of Shanghai, China. Sci Total Environ 565:607–615

Ma W, Chen R, Kan H (2014) Temperature-related mortality in 17 large Chinese cities: how heat and cold affect mortality in China. Environ Res 134:127–133

Marschner (2014). glm2: Fitting Generalized Linear Models. R software

McMichael AJ, Wilkinson P, Kovats RS, Pattenden S, Hajat S, Armstrong B et al (2008) International study of temperature, heat and urban mortality: the 'ISOTHURM'project. Int J Epidemiol 37(5):1121–1131

Medina-Ramón M, Schwartz J (2007) Temperature, temperature extremes, and mortality: a study of acclimatisation and effect modification in 50 US cities. Occup Environ Med 64(12):827–833

Meehl GA, Tebaldi C (2004) More intense, more frequent, and longer lasting heat waves in the 21st century. Science 305(5686):994–997

Nichol J (2005) Remote sensing of urban heat islands by day and night. Photogramm Eng Remote Sens 71(5):613–621

Nichol JE, Fung WY, Lam KS, Wong MS (2009) Urban heat island diagnosis using ASTER satellite images and 'in situ'air temperature. Atmos Res 94(2):276–284

Petkova EP, Gasparrini A, Kinney PL (2014) Heat and mortality in New York City since the beginning of the 20th century. Epidemiology 25(4):554

Reid CE, O'Neill MS, Gronlund CJ, Brines SJ, Brown DG, Diez-Roux AV, Schwartz J (2009) Mapping community determinants of heat vulnerability. Environ Health Perspect 117(11):1730

Revich B, Shaposhnikov D (2008) Excess mortality during heat waves and cold spells in Moscow, Russia. Occup Environ Med 65(10): 691–696

Semenza JC, Rubin CH, Falter KH, Selanikio JD, Flanders WD, Howe HL, Wilhelm JL (1996) Heat-related deaths during the July 1995 heat wave in Chicago. N Engl J Med 335(2):84–90

Seposo XT, Dang TN, Honda Y (2016) Effect modification in the temperature extremes by mortality subgroups among the tropical cities of the Philippines. Glob Health Action 9

Shi Y, Lau KKL, Ng E (2016) Developing street-level PM2. 5 and PM10 land use regression models in high-density Hong Kong with urban morphological factors. Environ Sci Technol 50(15):8178–8187

Smargiassi A, Goldberg MS, Plante C, Fournier M, Baudouin Y, Kosatsky T (2009) Variation of daily warm season mortality as a function of micro-urban heat islands. J Epidemiol Community Health 63(8):659–664

Smoyer KE (1998) A comparative analysis of heat waves and associated mortality in St. Louis, Missouri—1980 and 1995. Int J Biometeorol 42(1):44–50

Stafoggia M, Forastiere F, Agostini D, Caranci N, De'Donato F, Demaria M et al (2008) Factors affecting in-hospital heat-related mortality: a multi-city case-crossover analysis. J Epidemiol Community Health 62(3):209–215

Su JG, Brauer M, Ainslie B, Steyn D, Larson T, Buzzelli M (2008) An innovative land use regression model incorporating meteorology for exposure analysis. Sci Total Environ 390(2):520–529

Tam WW, Wong TW, Chair SY, Wong AH (2009) Diurnal temperature range and daily cardiovascular mortalities among the elderly in Hong Kong. Arch Environ Occup Health 64(3):202–206

Tan J, Zheng Y, Song G, Kalkstein LS, Kalkstein AJ, Tang X (2007) Heat wave impacts on mortality in Shanghai, 1998 and 2003. Int J Biometeorol 51(3):193–200

Thach TQ, Zheng Q, Lai PC, Wong PPY, Chau PYK, Jahn HJ et al (2015) Assessing spatial associations between thermal stress and mortality in Hong Kong: a small-area ecological study. Sci Total Environ 502: 666–672

Wang MZ, Zheng S, He SL, Li B, Teng HJ, Wang SG et al (2013) The association between diurnal temperature range and emergency room admissions for cardiovascular, respiratory, digestive and genitourinary disease among the elderly: a time series study. Sci Total Environ 456:370–375

Wilhelmi OV, Hayden MH (2010) Connecting people and place: a new framework for reducing urban vulnerability to extreme heat. Environ Res Lett 5(1):014021

Wu W, Xiao Y, Li G, Zeng W, Lin H, Rutherford S et al (2013) Temperature–mortality relationship in four subtropical Chinese cities: a time-series study using a distributed lag non-linear model. Sci Total Environ 449:355–362

Xu Y, Liu Y (2015) Monitoring the near-surface urban Heat Island in Beijing, China by satellite remote sensing. Geogr Res 53(1):16–25

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 89:193–203

Yang J, Liu HZ, Ou CQ, Lin GZ, Zhou Q, Shen GC et al (2013) Global climate change: impact of diurnal temperature range on mortality in Guangzhou, China. Environ Pollut 175:131–136

Yang J, Ou CQ, Guo Y, Li L, Guo C, Chen PY et al (2015) The burden of ambient temperature on years of life lost in Guangzhou. China Sci Rep 5

Yi W, Chan AP (2015) Effects of temperature on mortality in Hong Kong: a time series analysis. Int J Biometeorol 59(7):927–936

Zeng W, Lao X, Rutherford S, Xu Y, Xu X, Lin H et al (2014) The effect of heat waves on mortality and effect modifiers in four communities of Guangdong Province, China. Sci Total Environ 482:214–221