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RESEARCH ARTICLE

Urban environmental influences on the temperature–mortality relationship associated mental disorders and cardiorespiratory diseases during normal summer days in a subtropical city

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Abstract

Temperature is associated with mortality risk across cities. However, there is lack of study investigating the summer effect on mortality associated with mental/behavioral disorders, especially in cities with subtropical climate. In addition, summer mortality in subtropical cities is different from tropical cities, and previous studies have not investigated the urban environmental inequality on heat mortality associated with mental/behavioral disorders. A register-based study was developed to estimate the temperature effects on decedents on days with 50th percentile of average daily temperature between 2007 and 2014 in Hong Kong (n = 133,359). Poisson regression was firstly applied to estimate the incidence rate ratio (IRR) from the summer temperature effects on all-cause mortality, cardiovascular mortality, respiratory mortality, and mortality associated with mental/behavioral disorders. For a 1 °C increase in average temperature on days with temperature ≥ 24.51 °C, IRRs of mortality associated with mental and behavioral disorders on lag 0 and lag 1 days were 1.033 [1.004, 1.062] and 1.030 [1.002, 1.060], while temperature effects on cardiovascular mortality and respiratory mortality during normal summer days (not extreme heat events) were not significant. A further investigation with linear regression has shown that decedents with mental/behavioral disorders on higher temperature days resided in areas with lower percentage of sky view, lower percentage of vegetation cover, higher level of neighborhood-level $PM_{2.5}$, higher level of neighborhood-level NO, and higher level of neighborhood-level black carbon (BC). In order to develop protocols for community healthcare based on the "Leaving no one behind" scheme documented in the 2016 Sustainable Development Goals report of the United Nations, it is necessary to include heat effects on mental/behavioral disorders, especially people with dementia, for community planning and healthcare development.

Keywords Temperature mortality · Summer · Mental and behavioral disorders · Dementia · Spatiotemporal · Urban environment · Community health

Introduction

Temperature has proved to be significantly associated with mortality risk across cities (Gasparrini et al. 2015; Vandentorren et al. 2004). Increasing temperatures due to climate change have been widely observed to increase the severity, frequency, and intensity of summer heat (Meehl and Tebaldi 2004). In order to mitigate disastrous risk from increased summer heat, previous studies have evaluated heat effects on mortality over time (Davis et al. 2003; Ishigami et al. 2008; Schaffer et al. 2012; Sheridan et al. 2009). Evidence of the effects of extreme heat stress on all-cause mortality and cardiorespiratory mortality has been documented from both temperate and tropical regions (Ho et al. 2017; Urban et al. 2014). Recently, there has been more research on

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the association between summer heat and other causes of death, such as mortality from stillbirth (Ha et al. 2017; Li et al. 2018).

Although heat mortality has been widely studied, the relationship between temperature and mortality associated with mental and behavioral disorders (e.g., dementia) has not been adequately documented, which is surprising as mental-related mortality is common in urban communities (Samba et al. 2016). The study of heat effects on mortality related to mental and behavioral disorders is essential, since mental illnesses can range from a short-term occurrence of anxiety and depression to various long-term conditions associated with developmental impairments and chronic diseases (Hansen et al. 2008). Several mental disorders can also be one of leading causes of a city. For example, dementia has been recognized as one of the "ten leading causes of death" in Hong Kong, with 2.1% of males and 4.0% of females were deaths from dementia.

In addition, in the context of human behavior, several studies have indicated an association between temperature and mental disorders (Cornali et al. 2004; Noelke et al. 2016). These included recent studies in both temperate and subtropical cities, which analyzed the relationship between temperature and hospital admissions associated with mental and behavioral disorders (Chan et al. 2018; Culqui et al. 2017; Linares et al. 2017; Peng et al. 2017). However, since morbidity and mortality are two levels of risks, these studies may not be able to address the impact of extreme heat on mortality associated with mental and behavioral disorders.

Due to these facts, this study has conducted a literature review, which found that only a few studies directly discussed the heat mortality associated with mental and behavioral disorders. These included a study to evaluate the effect of heat waves on mortality associated with mental disorders in Adelaide, Australia (Hansen et al. 2008); a study to analyze the impact of high ambient temperature on deaths among people with psychosis and dementia in the UK (Page et al. 2012); a brief report documenting deaths of psychiatric patients during heat waves in New York City, USA (Bark 1998); a research that investigated the heat-related mortality during a 1999 heat wave in Chicago (Naughton et al. 2002); and a study that documented heat-related death and mental illness during the 1999 Cincinnati heat wave (Kaiser et al. 2001). Since all of these represented the scenario in temperate cities, they may be unable to demonstrate the association between temperature and mortality associated with mental and behavioral disorders in subtropical cities. Therefore, it is necessary to investigate heat effects on mortality related to mental and behavioral disorders in a subtropical city, in order to improve protocols for the effectiveness of critical healthcare and public health surveillance. Such investigation is important, because population in a subtropical city may have acclimatized and adapted to the local hot weather (Lam et al. 2013), due to a continuously high thermal discomfort in summer days causing a high adaptability among the local population, compared to those in temperate cites. Therefore, heat mortality in general (e.g., all-cause mortality, cardiovascular mortality) across a subtropical city is quite different to those in temperate cites, while the impact of high temperature of a day on mortality risk can be quite low compared to the colder regions (Chan et al. 2012; Ho et al. 2017). It will be essential whether the impact of high temperature on mortality associated with mental and behavioral disorders is consistent with the "typical impact" of high temperature on the other types of mortality risk.

In terms of the effectiveness of critical healthcare and public health surveillance, recent studies have noted the effectiveness of location-based analysis for community health planning, as this can identify neighborhoods with high deprivation or health burdens for resource allocation (Schuurman et al. 2018). Therefore, current practices of heat health planning have also attempted to incorporate location-based analysis, by identifying which areas with the social or urban environment represent higher risk of mortality during extreme heat events (Harlan et al. 2012; Hattis et al. 2012; Ho et al. 2017b; Hondula et al. 2015; Johnson et al. 2009; Krstic et al. 2017; Reid et al. 2009; Rosenthal et al. 2014; Smargiassi et al. 2009). For example, several studies have applied synoptic spatial temperature datasets in heat mortality studies and have found that regions with higher local temperature may have higher mortality risk (Ho et al. 2017b; Krstic et al. 2017; Smargiassi et al. 2009). There are also studies indicating that inequality of urban environment can induce higher heat mortality (Krstic et al. 2017; Rosenthal et al. 2014). These previous studies implied that a further investigation regard to the influence of urban environment on heat mortality is necessary (Tomlinson et al. 2011), as urban environmental effects on different populations and causes of death can be varied by locations.

In this study, we hereby applied a register-based study to investigate the temperature effect on summer mortality caused by mental disorders in a subtropical city and compared it with the temperature influence on cardiorespiratory and all-cause mortality, which are the common leading disease-specific causes of death. We further evaluated the difference between urban environmental influences on mortality from mental disorders and those from cardiorespiratory diseases and from all-cause mortality. This indicates the weight to the spatial variation of neighborhood impacts on different causes of death during summer. Hong Kong was selected as the study area (Fig. 1), since it is a typical subtropical Asian city with high-density living with a large population. Based on the census data of 2011, there were approximately 7.1 million people living in approximately 1100 km^2 of land. The local population

Fig. 1 Study area (Hong Kong)

is well adapted to the subtropical summer heat, although previous studies have described mortality risk from the extreme hot weather events (Ho et al. 2017; Yi and Chan., 2015). Several local studies on socioeconomic inequality (Chan et al. 2012) or the influence of urban heat island effect (Goggins et al. 2012; Thach et al. 2015) have indicated spatial inequality in heat mortality across districts.

The results can provide implications for health policy and planning, with a multi-level framework that can better target vulnerable populations. The results of this study are aligned with the "Leaving no one behind" scheme documented in the 2016 Sustainable Development Goals report of the United Nations.

Data and methods

Mortality data

We applied a mortality dataset with information of all decedents in Hong Kong between 2007 and 2014. This dataset includes the following information: (1) date of death, (2) gender, (3) age, (4) district-level location of residence, and (5) cause of death recorded based on the 10th Revision of the International Statistical Classification of Diseases and Related Health Problems (ICD-10). The finest district-level for mortality data is based on the Tertiary Planning Unit (TPU), which is commonly used for small-district planning in Hong Kong.

Temporally varying data

We collected hourly temperature data from a weather station located at the headquarter of the Hong Kong Observatory for analyzing heat effects on mortality, and we retrieved temporally varying air pollution data from point-based air quality monitoring network of the Hong Kong Environmental Protection Department. This dataset includes the daily average records of coarse particulate matter (PM_{10}), nitrogen dioxide (NO_2), ozone (O_3), and sulfur dioxide (SO_2) from seven point-based monitoring stations (Central Western, Sham Shui Po, Sha Tin, Tai Po, Tsuen Wan, Kwai Chung, and Tap Mun), in order to minimize bias of urban/urban difference for temporal analyses.

Spatially varying data

The following six types of spatial data were also examined in order to represent the quality of the urban environment that can influence urban mortality across Hong Kong, including the following: (1) sky view factor (SVF), (2) vegetation cover, (3) neighborhood-level fine particulate matter (neighborhood $PM_{2.5}$), (4) neighborhood-level nitrogen oxide (neighborhood NO), (5) neighborhood-level NO_2 (neighborhood NO_2), and (6) neighborhood-level black carbon (neighborhood BC).

SVF is a ratio with values from 0 to 1 and represents the amount of visible sky from the ground (Hodul et al. 2016). SVF is also a building morphological factor that is strongly associated with air ventilation and local air temperature (Ho et al. 2014). In this study, the SVF map from Yang et al. (2015) derived from LiDAR data and building GIS data with a highly-accurate method (Zakšek et al. 2011) was applied to represent the density of urban environment across Hong Kong (Fig. 2). Higher SVF indicates areas with lower density and more open spaces while lower SVF represents a compact and high-density environment. We multiplied all values by 100 in order to retrieve the potential percentage of sky view for further analysis.

Vegetation cover has been found to be an important factor in reducing urban heat, and the spatial datasets associated with urban vegetation have been widely used in heat health analyses (Krstic et al. 2017). Therefore, a vegetation map derived from land use and land cover information obtained from the Hong Kong Planning Department was used (Fig. 3).

In this study, we used synoptic spatial datasets of air quality to represent the typical spatial distributions of neighborhood $PM_{2.5}$, neighborhood NO, neighborhood NO_2, and neighborhood BC across Hong Kong (Figs. 4, 5, 6, and 7). Fine particulate matter has been recognized as a major dust-related urban pollutant. Nitrogen oxides can be mixture of regional and traffic-related air pollutions. Black carbon is a type of aerosol primarily generated from anthropogenic activities (e.g., fuel combustion) and is highly associated with traffic-related pollution. These air pollutants have been found to be strongly associated with community health risk. Therefore, air pollution maps were estimated based on land use regressions and the HK2D sampling campaign with the use of air quality data from the Hong Kong Environmental Protection Department (Barratt et al. 2018; Lee et al. 2017). In details, HK2D sampling campaign was conducted based on two field measurements across Hong Kong to measure air quality in two different seasons, one from April to May and another one from November to January. Land use regression was built based on potential geospatial predictor variables to measure a typical scenario of territory-wide distribution of air quality.

Baseline mortality caused by increase in temperature

The first part of this register-based study is to conduct a cross-sectional analysis to estimate the baseline mortality caused by increase in temperature, based on group-based mortality data aggregated by date. To reduce the bias of a cross-sectional analysis, we first applied a list-wise deletion to exclude records with missing dates of death and location of residences from the mortality dataset. To design the cross-sectional analysis specifically for summer, we then further stratified the data to all decedents for days with an average temperature equal to or higher than (≥) 50^{th} percentile between 2007 and 2014.

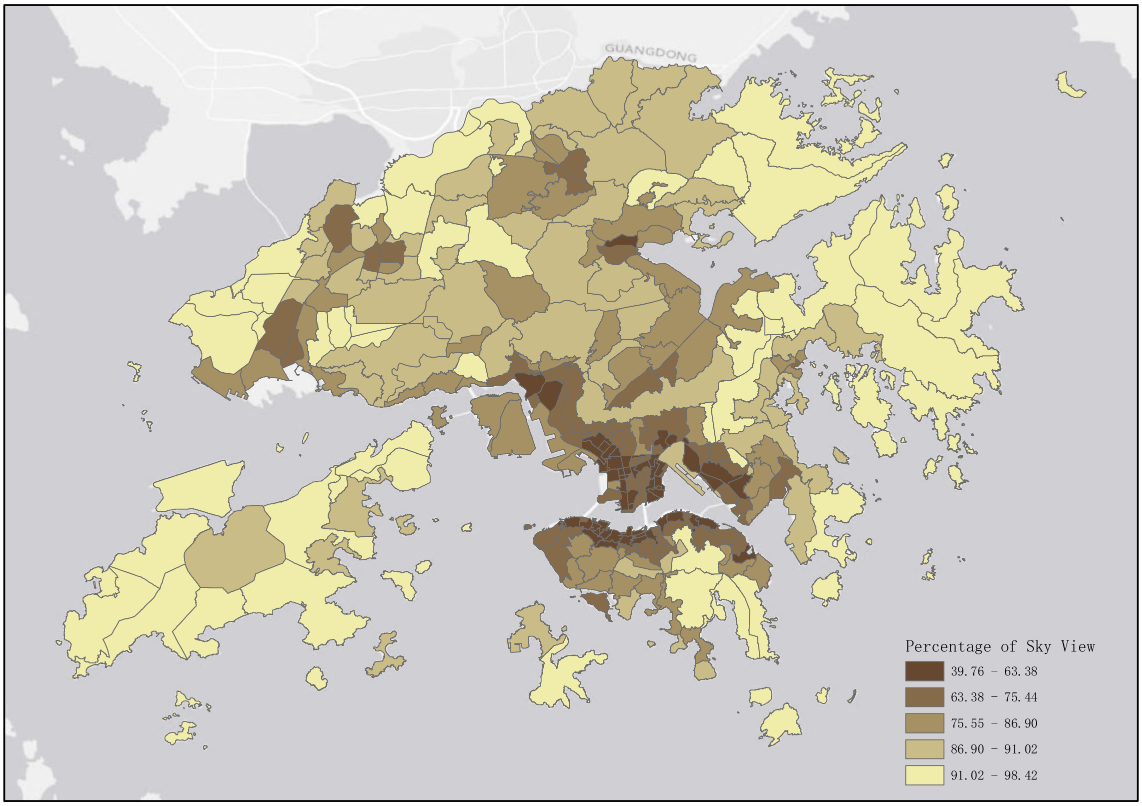

Fig. 2 Average of sky view percentage of each TPU in Hong Kong

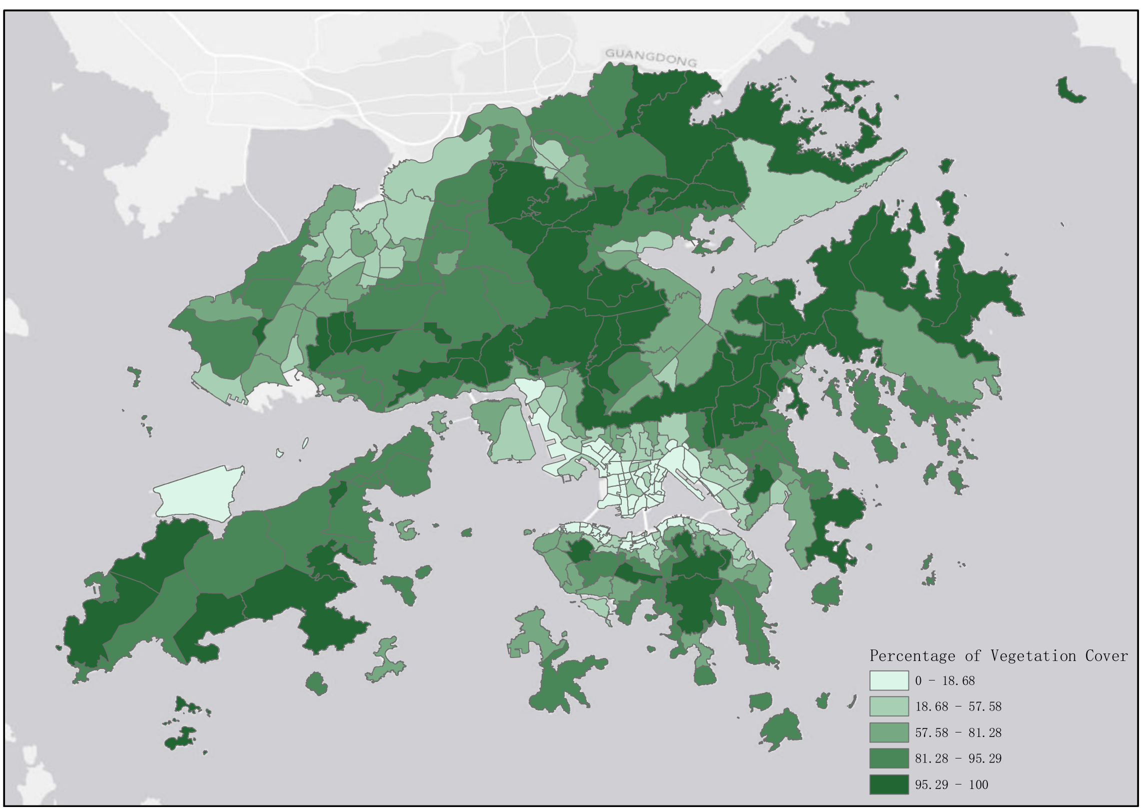

Fig. 3 Percentage of vegetation cover of each TPU in Hong Kong

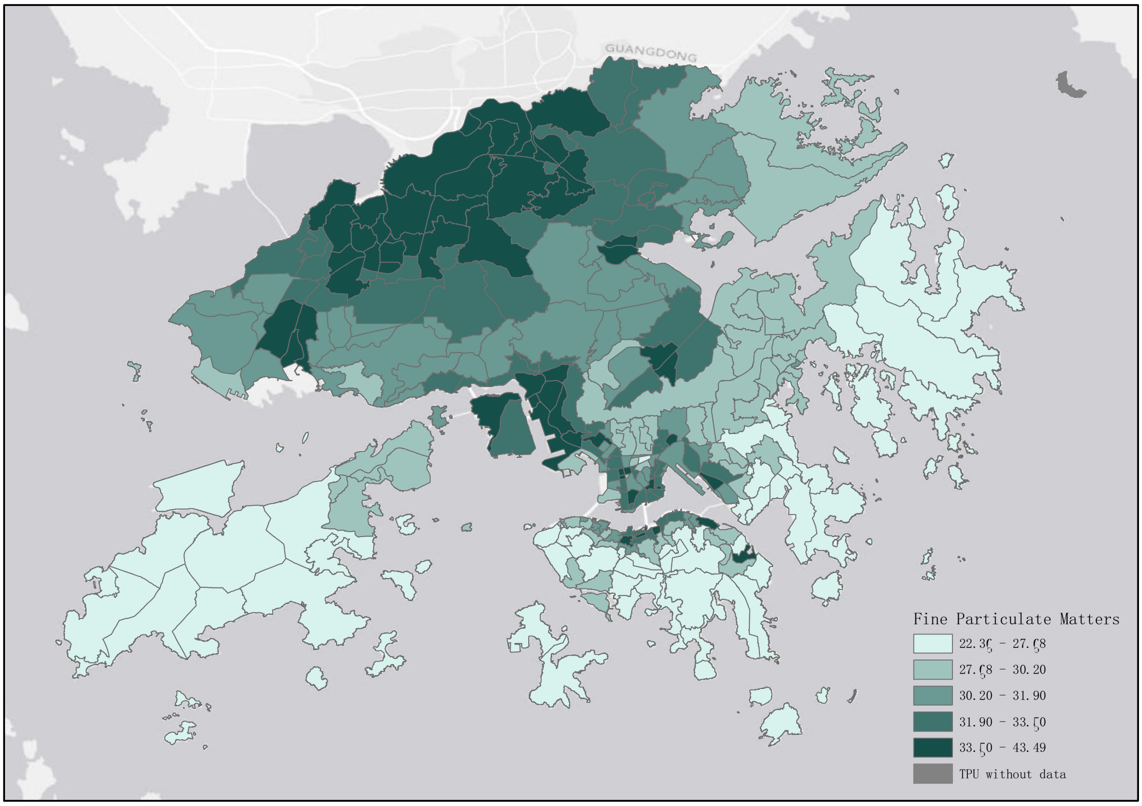

Fig. 4 Average level of fine particulate matters of each TPU in Hong Kong

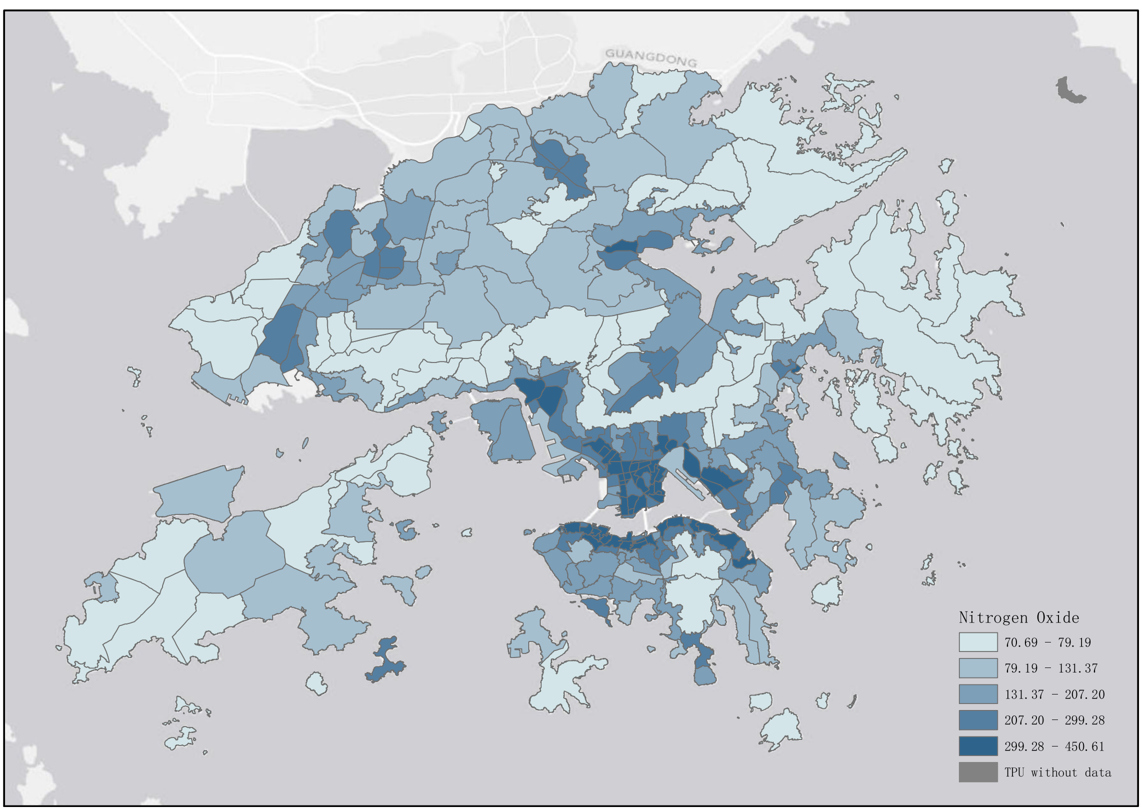

Fig. 5 Average level of nitrogen oxide of each TPU in Hong Kong

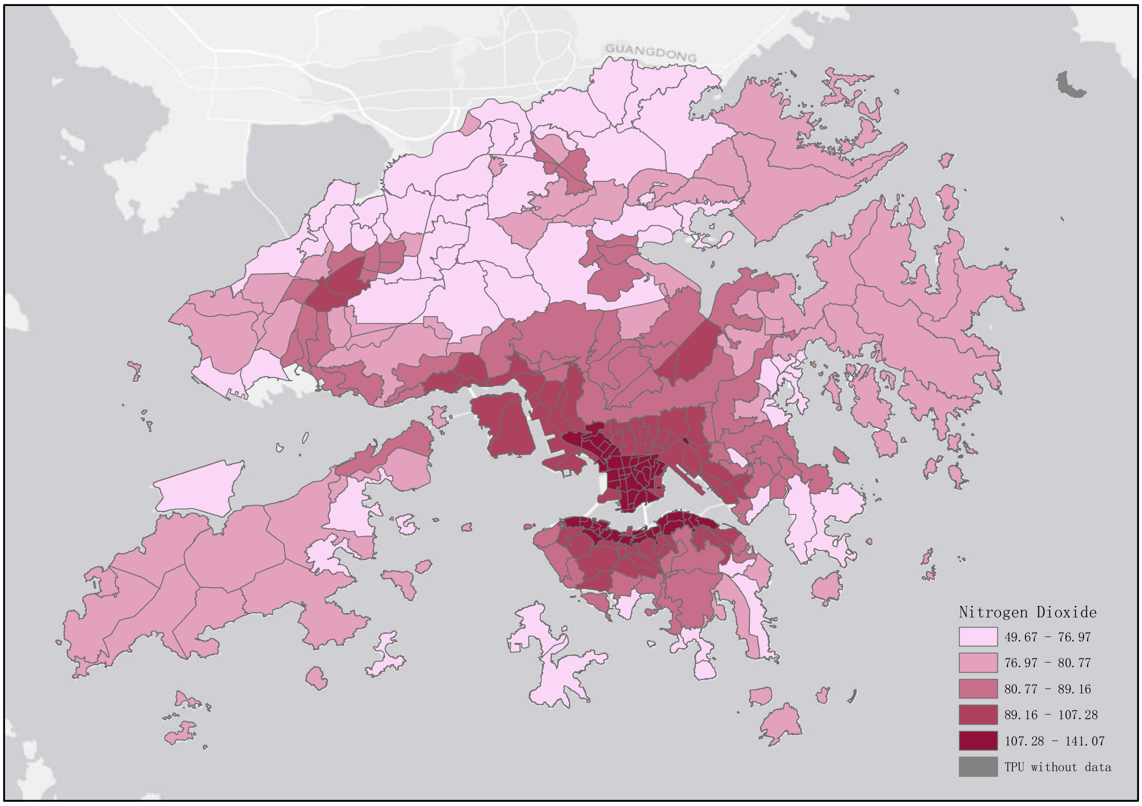

Fig. 6 Average level of nitrogen dioxide of each TPU in Hong Kong

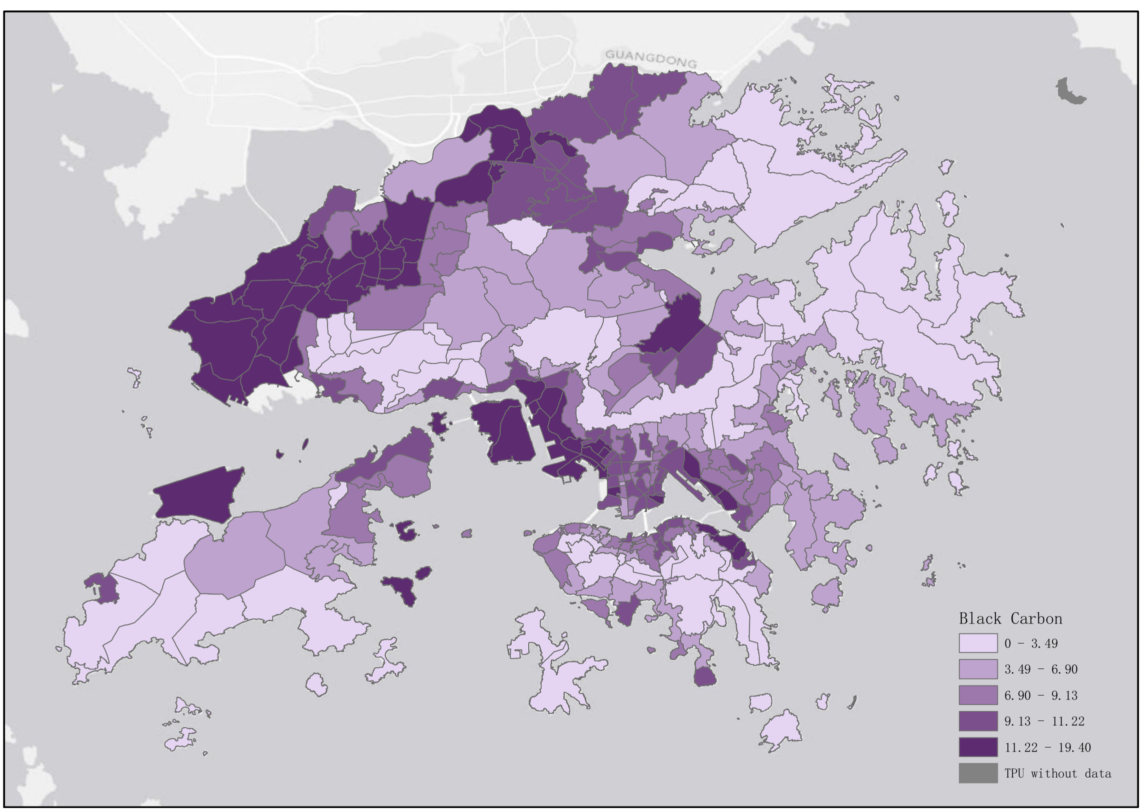

Fig. 7 Average level of black carbon of each TPU in Hong Kong

Based on this analytic subset, we examined the association between increase in temperature and daily mortality, with a Poisson regression and the "glm2" package of R software:

$$LogE(D_t) = \beta_0 + \beta_1 tmean_{(t)} + \beta_2 \mathrm{RH}_{(t)} + \beta_3 \mathrm{PM}_{10(t)} + \beta_4 \mathrm{O}_{3(t)} + \beta_5 \mathrm{NO}_{2(t)} + \beta_6 \mathrm{SO}_{2(t)} + \beta_7 \mathrm{DOW}_{(t)} + \beta_8 Month_{(t)}$$

where D_t represents the number of cause-specific deaths in a day, tmean indicates the average temperature of the corresponding day, RH indicates the daily average relative humidity, PM_{10} indicates the daily average PM_{10}, O_3 indicates the daily average O_3, NO_2 indicates the daily average NO_2, SO_2 indicates the daily average SO_2, DOW is a category variable of the day of the week, and Month is a continuous variable of the month (n: 1, ..., 96) counted from Jan 2007 to Dec 2014. Note that air conditioning was commonly overused in Hong Kong even among population with low socioeconomic status. Therefore, prevalence of air conditioning and variables related to low socioeconomic status were not used as confounders of this study.

The regression above was applied to four types of mortality: (1) all-cause mortality, (2) cardiovascular mortality (ICD codes I00–I99), (3) respiratory mortality (ICD codes J00–J99), and (4) mortality associated with mental and behavioral disorders (ICD codes F00–F99). Incidence rate ratio (IRR) and the 95% confidence intervals (CI) estimated by the β_1 were used to estimate the independent effect of increasing temperature on cause-specific mortality. RH, PM_{10}, O_3, NO_2, and SO_2 were the confounders controlling the baseline influences of weather and air quality; DOW a confounder for the weekday–weekend effect; and Month to control the seasonality effect and to adjust the temporal influence from previous months. We consider the scenarios of lag 0–3 days, in order to comprehensively evaluate the daily temperature effect on short-term mortality.

Effect modification: spatial influences of urban environment on cause-specific mortality

The second part of this register-based study to further evaluate the modifying effect caused by spatial influences of urban environment on cause-specific mortality, based on individual-level mortality data, in which every decedent was a single case. To analyze whether the cause-specific deaths lived in neighborhoods with lower environmental quality, we aggregated the spatial datasets into TPU-level based on averaging all pixels within a TPU. After averaging, six urban environmental factors were calculated: (1) average percentage of sky view (%SV), (2) percentage of vegetation cover (%veg), (3) neighborhood-level $PM_{2.5}$, (4) neighborhood-level NO, (5) neighborhood-level NO_2, and (6) neighborhood-level BC. Based on the conceptual model of (Kosatsky et al. 2012), we then further estimated the effect modification of these six environmental factors on heat mortality with the following linear regression:

$$Environment = \beta_0 + \beta_1 tmean + \beta_2 \mathrm{RH} + \beta_3 \mathrm{PM}_{10} + \beta_4 \mathrm{O}_3 + \beta_5 \mathrm{NO}_2 + \beta_6 \mathrm{SO}_2 + \beta_7 \mathrm{DOW} + \beta_8 Month + \beta_9 Gender + \beta_{10} \mathrm{Age}$$

where Environment is the urban environmental factor (e.g., percentage of vegetation cover) of the location of residence of a decedent in TPU, Gender is a category variable of gender for all decedents, and Age is a continuous variable of age for all decedents.

Note that the use of a linear regression was to include all decedents as individual cases, in order to develop a model more appropriate for individual-level, at the same time providing an alternative approach to bypass the problem of spatial clustering caused by the group-level data. Such approach may be useful because 70% of the lands across Hong Kong are restricted for land development; therefore, population distribution cannot be simply explained by a function of spatial lag. In addition, this regression controls the effects of demographic factors and air quality on mortality as well as the occupational and seasonal effects. As a result, the β_1 of this model is an independent effect that can represent whether a decedent who died on a day with one degree higher temperature lived in an area with lower environmental quality. This regression was repeated for each environmental factor and for each specific cause of death, and β_1 (deviation) and the 95% CI have been reported for each analysis.

Results

Data summary

The 50th percentile of average daily temperature within the study period was 24.51 °C. Based on the mortality dataset, there were 133,359 decedents on days with temperature equal to or higher than the 50th percentile. A total of 26,736 of these decedents died from cardiovascular diseases, 28,703 of them died from respiratory diseases, and 2653 of them died from mental and behavioral disorders. For the decedents with mental and behavioral disorders, approximately 98.9% of them (2623 decedents) were cases of dementia.

A t test based on the individual-level mortality dataset was conducted to summarize the data. Based on the average values of urban environmental factors obtained from pooling the subsets of decedents, there was no major difference between the urban environmental factors for all specific cause of deaths. Except for one decedent who resided in a remote area with no

Table 1 Baseline mortality caused by 1 °C increase in temperature. Asterisk indicates significant result

Cause of death	Lag 0 day	Lag 1 day	Lag 2 days	Lag 3 days
All causes	0.997 [0.993, 1.001]	0.999 [0.995, 1.003]	1.001 [0.997, 1.005]	1.000 [0.996, 1.004]
Cardiovascular diseases (ICD codes: I00-I99)	0.991 [0.982, 1.000]	0.9901[0.983, 1.000]	0.988 [0.979, 0.997]	0.990 [0.981, 0.999]
Respiratory diseases (ICD codes: J00-J99)	0.990 [0.982, 0.999]	0.994 [0.985, 1.002]	0.999 [0.991, 1.008]	0.994 [0.986, 1.003]
Mental and behavioral disoders (ICD codes: F00-F99)	1.033 [1.004, 1.062]*	1.030 [1.002, 1.060]*	1.012 [0.984, 1.040]	1.023 [0.995, 1.052]

environmental information obtainable, for the other 133,358 decedents who died on days with temperature ≥ 24.51 °C, the average %SV and average %veg of their residential neighborhood were 67.4% and 45.2%, respectively. These people were exposed to long-term high NO and high NO_2 from the residential environment, with averages of 262.8 μg/m^3 and 95.6 μg/m^3. Note that the current "World Health Organization (WHO) Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide" has stated that annual mean of NO_2 should not be exceed 40 μg/m^3 annual mean. There were also long-term exposed to 32.4 μg/m^3 of $PM_{2.5}$ and 9.2 μg/m^3 of BC. The decedents with mental and behavioral disorders lived in neighborhoods with average %SV of 67.4%, average %veg of 42.5%, average NO of 271.1 μg/m^3, average NO_2 was 95.7 μg/m^3, average $PM_{2.5}$ of 33.0 μg/m^3, and average BC of 9.7 μg/m^3. Since there was not a great spatial difference of environmental exposures between different groups of decedents, the spatial inequality of cause-specific mortality may be a combining effect from the spatiotemporal influence of daily temperature and urban environment.

Estimation of baseline mortality

In general, summer temperature had insignificant association with all-cause mortality (Table 1), probably because weanalyzed heat effects on all days with average daily temperature ≥ 50th percentile in modeling, but not only considering the impacts of extreme heat events (temperature ≥ 95th percentile) as conducted in previous studies (Ho et al. 2017; Goggins et al. 2012). For a 1 °C increase in average temperature, incidence rate ratios (IRRs) of all-cause mortality of lag 2 and 3 days were 1.001 [0.997, 1.005] and 1.000 [0.996, 1.004].

In addition, unlike the results from extreme heat events with temperature higher than the 95th percentile, a normal summer day with average temperature ≥ 50th percentile had a negative association with respiratory and cardiovascular mortality. These results possibly aligned with previous studies that cold effect on mortality was much stronger than that of extreme heat in Hong Kong (Yi and Chan 2015). This is partially because of the cultural practices in Hong Kong, in which local people did not use heater in colder seasons but they have been overused air conditioning in hotter days even it may not be extremely hot (e.g., average temperature ≥ 50th percentile). During a hotter day, local population may stay indoors to prevent thermal discomfort; as a result, they have less mortality risk caused by cardiorespiratory diseases during a normal (but not extremely hot) summer day.

In comparison, the temporal relationship between daily temperature and mortality associated with mental and behavioral disorders in a normal summer day was considerably strong. After controlling seasonal and weekday/weekend effects, as well as the influence from air quality, a 1 °C increase in average temperature on a normal summer day shows a significant relationship with mortality associated with mental and behavioral disorders for lag 0 and lag 1 days. The corresponding IRRs for these days were 1.033 [1.004, 1.062] and 1.030 [1.002, 1.060].

Effect modification of neighborhood characteristics on heat mortality

Considering the location-based characteristics from the residential districts of all decedents, we found that only the %SV has modifying effects on temperature and all-cause mortality in summer (Table 2). For decedents died on lag 0 day with

Table 2 Influences of urban environmental factors on temperature-mortality relationship among all-cause mortality decedents. Asterisk indicates significant result

Urban environmental factors	Lag 0 day	Lag 1 day	Lag 2 days	Lag 3 days
sky view (%)	− 0.04 [− 0.08, − 0.00]*	− 0.04 [− 0.08, 0.03]	− 0.03 [− 0.07, 0.01]	− 0.02 [− 0.06. 0.02]
vegetation cover (%)	− 0.09 [− 0.20, 0.02]	− 0.08 [− 0.19, 0.03]	− 0.04 [− 0.15, 0.06]	− 0.09 [− 0.20, 0.02]
$PM_{2.5}$ (μg/m^3)	0.00 [− 0.01, 0.02]	0.00 [− 0.01, 0.02]	0.00 [− 0.01, 0.02]	0.01 [− 0.00, 0.03]
NO (μg/m^3)	0.25 [− 0.11, 0.61]	0.23 [− 0.12, 0.60]	0.20 [− 0.16, 0.56]	0.19 [− 0.16, 0.55]
NO_2 (μg/m^3)	0.01 [− 0.04, 0.07]	0.00 [− 0.05, 0.06]	− 0.00 [− 0.60, 0.06]	− 0.02 [− 0.08, 0.04]
BC (μg/m^3)	0.00 [− 0.01, 0.01]	− 0.00 [− 0.01, 0.02]	0.01 [− 0.01, 0.02]	0.01 [− 0.00, 0.02]

Table 3 Influences of urban environmental factors on temperature-mortality relationship among respiratory mortality decedents. Asterisk indicates significant result

Urban environmental factors	Lag 0 day	Lag 1 day	Lag 2 days	Lag 3 days
sky view (%)	− 0.08 [− 0.17, 0.01]	− 0.04 [− 0.13, 0.05]	− 0.03 [− 0.12, 0.07]	− 0.03 [− 0.10, 0.09]
vegetation cover (%)	− 0.19 [− 0.43, 0.05]	− 0.04 [− 0.28, 0.19]	− 0.05 [− 0.29, 0.19]	− 0.09 [− 0.33, 0.15]
$PM_{2.5}$ (μg/m^3)	0.01 [− 0.02, 0.04]	− 0.01 [− 0.04, 0.02]	− 0.00 [− 0.03, 0.03]	0.03 [− 0.00, 0.06]
NO (μg/m^3)	0.37 [− 0.41, 1.16]	0.06 [− 0.72, 0.85]	0.19 [− 0.61, 0.98]	− 0.03 [− 0.82, 0.76]
NO_2 (μg/m^3)	0.02 [− 0.11, 0.14]	− 0.03 [− 0.15, 0.10]	− 0.03 [− 0.16, 0.09]	− 0.06 [− 0.19, 0.06]
BC (μg/m^3)	− 0.00 [− 0.03, 0.03]	− 0.01 [− 0.04, 0.01]	− 0.00 [− 0.03, 0.03]	0.02 [− 0.01, 0.05]

1 °C higher average temperature, they were more likely to live in a TPU with 0.04% lower sky view (deviation: − 0.04 [− 0.08, − 0.00]). In addition, we did not find any effect modification between daily temperature and respiratory mortality in this study (Table 3).

Overall, neighborhood characteristics have a much stronger modifying effect on the relationship between cardiovascular mortality and high temperature (Table 4).

On a lag 0 day with 1 °C higher average temperature, a decedent with cardiovascular disease is likely to reside in a district with 0.15 μg/m^3 higher neighborhood-level NO_2 (deviation: 0.15 [0.03, 0.28]), and on a lag 1 day with 1 °C higher average temperature, a decedent with cardiovascular disease is likely to reside in a district with 0.11% lower sky view (deviation: − 0.11 [− 0.21, − 0.02]) and 0.15 μg/m^3 higher neighborhood-level NO_2 (deviation: 0.15 [0.02, 5.28]). Furthermore, on a lag 3 days with 1 °C higher average temperature, a decedent with cardiovascular disease is likely to reside in a TPU with 0.04 μg/m^3 higher neighborhood-level NO_2 (deviation: 0.04 [0.01, 0.06]).

In addition, neighborhood characteristics have the strongest modifying effect on the relationship between mortality associated with mental and behavioral disorders and high temperature (Table 5). On a lag 0 day with 1 °C higher average temperature, a decedent with mental and behavioral disorders is likely to reside in a district with 2.60 μg/m^3 higher neighborhood-level NO (deviation: 2.60 [0.01, 5.52]); on a lag 1 day, a decedent with mental and behavioral disorders is likely to reside in a district with 0.09 μg/m^3 higher neighborhood-level BC (deviation: 0.09 [0.01, 0.18]); and on a lag 3 days, a decedent with mental and behavioral disorders is likely to reside in a district with 0.36% lower sky view (deviation: − 0.36 [− 0.66, − 0.05]), 0.94% lower vegetation cover (deviation: − 0.94 [− 1.72, − 0.16]), 0.10 μg/m^3 higher neighborhood-level $PM_{2.5}$ (deviation: 0.10 [0.00, 0.20]), and 3.27 μg/m^3 higher neighborhood-level NO (deviation: 3.27 [0.67, 5.87]). The modifying effect of urban environmental factors above also implied a spatial inequality of heat mortality across the city. In details, even short-term heat mortality risk associated with mental and behavioral disorders induced by temporal change of temperature has been dropped to insignificant, spatiotemporal influence caused by both daily temperature and urban environmental effect can still be found in particular deprived districts across the city during the latter day (lag 3).

Discussion

Implications from cross-sectional analysis

In this study, we have examined the temperature-mortality relationship duringnormal summer days in Hong Kong, and we have analyzed the spatiotemporal relationship between heat mortality and the urban environment. The results indicate that mortality associated with mental and behavioral disorders was the major cause-of-death associated with daily temperature on all days with average temperature ≥ 24.51 °C. On the

Table 4 Influences of urban environmental factors on temperature-mortality relationship among cardiovascular mortality decedents. Asterisk indicates significant result

Urban environmental factors	Lag 0 day	Lag 1 day	Lag 2 days	Lag 3 days
sky view (%)	− 0.09 [− 0.18, 0.00]	− 0.11 [− 0.21, − 0.02]*	− 0.08 [− 0.17, 0.01]	− 0.05 [− 0.14, 0.05]
vegetation cover (%)	− 0.16 [− 0.40, 0.08]	− 0.22 [− 0.47, 0.02]	− 0.14 [− 0.38, 0.10]	− 0.07 [− 0.31, 0.18]
$PM_{2.5}$ (μg/m^3)	− 0.00 [− 0.03, 0.03]	− 0.00 [− 0.03, 0.03]	0.01 [− 0.02, 0.05]	0.02 [− 0.01, 0.05]
NO (μg/m^3)	0.44 [− 0.36, 1.24]	0.79 [− 0.01, 1.60]	0.44 [− 0.36, 1.24]	0.33 [− 0.47, 1.14]
NO_2 (μg/m^3)	0.15 [0.03, 0.28]*	0.15 [0.02, 0.28]*	0.13 [− 0.00, 0.26]	0.06 [− 0.07, 0.19]
BC (μg/m^3)	0.01 [− 0.02, 0.04]	0.02 [− 0.01, 0.05]	0.03 [− 0.00, 0.06]	0.04 [0.01, 0.06]*

Table 5 Influences of urban environmental factors on temperature-mortality relationship among decedents with mental and behavioral disorders. Asterisk indicates significant result

Urban environmental factors	Lag 0 day	Lag 1 day	Lag 2 days	Lag 3 days
sky view (%)	− 0.22 [− 0.53, 0.08]	− 0.20 [− 0.51, 0.11]	− 0.23 [− 0.54, 0.08]	− 0.36 [− 0.66, − 0.05]*
vegetation cover (%)	− 0.75 [− 1.53, 0.03]	− 0.64 [− 1.43, 0.15]	− 0.49 [− 1.26, 0.29]	− 0.94 [− 1.72, − 0.16]*
$PM_{2.5}$ (μg/m^3)	0.07 [− 0.03, 0.17]	0.04 [− 0.07, 0.14]	0.06 [− 0.03, 0.16]	0.10 [0.00, 0.20]*
NO (μg/m^3)	2.60 [0.01, 5.20]*	2.18 [− 0.45, 4.80]	1.68 [− 0.92, 4.27]	3.27 [0.67, 5.87]*
NO_2 (μg/m^3)	0.31 [− 0.10, 0.72]	0.31 [− 0.11, 0.73]	0.07 [− 0.34, 0.49]	0.23 [− 0.18, 0.65]
BC (μg/m^3)	0.06 [− 0.03, 0.14]	0.09 [0.01, 0.18]*	0.06 [− 0.03, 0.14]	0.08 [− 0.00, 0.16]

other hand, we observed that the association between daily temperature and cardiorespiratory mortality duringnormal summer days was weak. These results are aligned with previous local studies and provide an improved understanding of the effects of hot weather on mortality associated with mental and behavioral disorders.

Previous research, especially local studies that have pointed to an association between summer temperature and cardiorespiratory mortality, concentrated on extreme heat events (Ho et al. 2017; Goggins et al. 2012). Indeed, there are more studies indicating that cold stress has a much stronger influence than heat stress on cardiorespiratory mortality in subtropical region (Leung et al. 2008; Xie et al. 2013). The previous studies observed that the increase in cardiorespiratory mortality was only found on days with extremely high temperature (e.g., a day with temperature higher than 95th percentile of a year). They also hypothesized that unless an extreme heat event accelerated the disastrous risk to a level higher than the resilience and adaptation of the local population, the elevated mortality risk caused by temperature would not likely to occur (Leung et al. 2008; Xie et al. 2013). Based on this fact, several studies have pointed out that heat mortality in subtropical region may not be driven by daily temperature; instead, this is more likely to be influenced by a prolonged heat event (Ho et al. 2017).

In contrast to previous studies, we pooled the decedents based on the 50th percentile of average temperature in a subtropical city for our analysis. This cross-sectional design provides greater flexibility in self-controlling all cases who died on summer and near-summer days. This design can also provide an alternative approach for the healthcare community. The result based on this alternative approach may inspire an increase in the awareness of the general public, in which summer temperature may contribute to mortality associated with mental and behavioral disorders, even if the daily temperature is not necessarily extremely high.

This result is essential. While the temperature threshold of this study is much lower than previous studies (Hansen et al. 2008; Kaiser et al. 2001; Page et al. 2012), our results are still aligned with their findings. For example, Hansen et al. (2008) attempted to link the mortality associated with mental and behavioral disorders to heat waves. This study in Australia has found that a heat wave could potential cause 2.4-fold increase in deaths among the older people. Specifically, a heat wave can be resulted to approximately 5.1-fold increase in dementia-related deaths among older people and 12.7-fold increase in dementia-related deaths among young adults in Adelaide, Australia. Results from an earlier study for the 1999 Cincinnati Heat Wave also found that 47.1% of the heat-related deaths were associated with mental illness (Kaiser et al. 2001). In addition, for the British study using a temperature threshold of the 93th percentile which is barely lower than the common extreme scenario, the authors still found that 4.9% increase in mental-related deaths per 1° increase in temperature (Page et al. 2012). These results were comparable with our study that temperature effect on mortality associated with mental and behavioral disorders can be much more extreme than the effect on other diseases such as cardiorespiratory problems.

Based on these facts, we conclude that critical healthcare is necessary for population with mental and behavioral disorders, especially for people with dementia. It has been well documented that community care is necessary for people with dementia, due to their sensitivities to a changing environment (Culqui et al. 2017; Linares et al. 2017). These populations have a lower ability to adapt changes, as their self-preparation for any environmental impact on their health is low. Therefore, community support in locations near their residential area is required, as these groups may have lower mobility and walkability. Critical nursing care may also be necessary to target this group of people, especially live-in services during summer, as this population may not be able to take care of themselves in at-risk scenarios.

In addition, examining the spatial relationship between urban environment and daily mortality has shown that neighborhoods can modify the temperature–mortality relationship, even if the cause-specific mortality itself is not sensitive to high temperatures. For example, cardiovascular mortality is not associated with increasing in average temperature in this subtropical city; however, we could still find more cardiovascular deaths residing in areas with lower % SV and higher concentrations of local air pollutants (e.g., black carbon, NO_2) on days with higher temperatures. This implies that understanding the neighborhood characteristics and its relationship with cause-specific mortality is necessary, and a multi-level framework should be put in for (1) identifying specific characteristics of neighborhoods for particular vulnerable groups, (2) mapping higher-risk neighborhoods based on the specific characteristics of this group of vulnerable population, and (3) allocating specific community care to the high-risk areas for long-term care and short-term emergency response. Different sets of multi-level frameworks should be designed for population with different underlying diseases, as our results show that modifying effects of environmental factors associated with temperature mortality were different for various causes of death. Specifically, improving occupational and environmental hygiene is the key to community care, since vegetation, urban density, and regional air quality have found spatial associations with temperature-related mortality.

Limitations and further investigation

In this study, we analyzed the temperature–mortality relationship based on a governmental mortality dataset with limited variables. While such datasets have been used in other studies (Goggins et al. 2012; Thach et al. 2015; Yi and Chan 2015), there are limitations due to the fact that they are unable to comprehensively represent the underlying processes inducing mortality. Future studies can be conducted based on the use of a retrospective cohort dataset, which has been commonly used in temperature-related health studies (Ha et al. 2017). However, cohort design is limited by sample size, making it difficult to determine whether the result from a cohort study is a significant result or a statistical bias due to the sample size.

Another limitation of this study is the use of synoptic spatial data as a reference. Thus, the hypothesis that the geophysical environment has not changed much over the 8 years of the study may be inappropriate. In order to improve the analysis, further studies could apply a time series with remotely sensed data as a substitute. However, this approach is dependent on obtaining cloud-free summer satellite images which is difficult in a subtropical city such as Hong Kong. In addition, estimation of the relationship between the data signal of satellite images and ground-level environmental information is always a challenge. For the purpose of this study, synoptic spatial data are still applicable.

In this study, we have not included suicide as a type of mental and behavioral disorders. Note that several studies have also attempted to investigate the relationship between temperature and suicide (Dixon et al. 2014; Page et al. 2007). However, since suicide is an external cause of death, it may not be directly associated with mental and behavioral disorders. Instead, it may be more related to marginalized mental health issues such as stress from social events or emotional outbursts from daily lives. It will be important to conduct a separate study to compare suicide and mental disorders to evaluate the different in impacts on mortality risk.

Finally, the repeated analyses for spatial assessment in this study were somewhat following the method of spatial delineation published in previous studies (Ho et al. 2017; Kosatsky et al. 2012; Krstic et al. 2017; Ho et al. 2018). However, this repeated assessment may also be involved with the type I error related to random error. In order to minimize this bias, alternative method can be used to follow traditional models to aggregate individual-level data to district level for the applications of spatial regression (Rosenthal et al. 2014; Thach et al. 2015; Wong et al. 2017). However, the aggregation of data may also reduce the power of modeling and induce problems related to spatial autocorrelation. In order to maximize the advantage of a dataset with large sample size, the use of repeated analyses for individual-level data may still be appropriate in this study.

Conclusions

In this study, the effect of increasing temperature on cause-specific mortality and the potential interaction between the urban environment and daily temperature on cause-specific mortality were examined. Our results indicated that normal summer days (without extreme heat events) did not contribute to cardiovascular or respiratory mortality, but they were shown to greatly influence mortality associated with mental and behavioral disorders. We also found that the urban environment was associated with heat-related mortality. For decedents with mental disorders who died on days with higher temperature, they were more likely to reside in areas with lower sky view, lower vegetation, higher $PM_{2.5}$, higher NO, and higher BC. In conclusion, community care should be targeted specifically to populations with dementia, in order to minimize mortality from high temperature in this population group. Community planning should also be undertaken, to improve environmental sanitation, in order to minimize the effects on temperature–mortality relationships from long-term exposure to poor environmental quality.

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