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Assessing spatial associations between thermal stress and mortality in Hong Kong: A small-area ecological study

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A B S T R A C T

Aims: Physiological equivalent temperature (PET) is a widely used index to assess thermal comfort of the human body. Evidence on how thermal stress-related health effects vary with small geographical areas is limited. The objectives of this study are (i) to explore whether there were significant patterns of geographical clustering of thermal stress as measured by PET and mortality and (ii) to assess the association between PET and mortality in small geographical areas.

Methods: A small area ecological cross-sectional study was conducted at tertiary planning units (TPUs) level. Age-standardized mortality rates (ASMR) and monthly deaths at TPUs level for 2006 were calculated for cause-specific diseases. A PET map with 100 m × 100 m resolution for the same period was derived from Hong Kong Urban Climatic Analysis Map data and the annual and monthly averages of PET for each TPU were computed. Global Moran's *I* and local indicator of spatial association (LISA) analyses were performed. A generalized linear mixed model was used to model monthly deaths against PET adjusted for socio-economic deprivation.

Results: We found positive spatial autocorrelation between PET and ASMR. There were spatial correlations between PET and ASMR, particularly in the north of Hong Kong Island, most parts of Kowloon, and across New Territories. A 1 °C change in PET was associated with an excess risk (%) of 2.99 (95% CI: 0.50–5.48) for all natural causes, 4.75 (1.14–8.36) for cardiovascular, 7.39 (4.64–10.10) for respiratory diseases in the cool season, and 4.31 (0.12 to 8.50) for cardiovascular diseases in the warm season.

Conclusions: Variations between TPUs in PET had an important influence on cause-specific mortality, especially in the cool season. PET may have an impact on the health of socio-economically deprived population groups. Our results suggest that targeting policy interventions at high-risk areas may be a feasible option for reducing PET-related mortality.

1. Introduction

There are now growing concerns and debates about the negative impact of ambient temperature on human health worldwide, which has risen over the past few decades (Parry et al., 2007; Solomon et al., 2007). It has been supported by an extensive body of epidemiological evidence showing that exposure to temperatures exceeding certain comfort limits was associated with increased risk of numerous adverse health effects, including mortality, and hospital admissions (Basu et al., 2012; Keatinge et al., 1997; Xu et al., 2013; Yan, 2000). To clarify the possible link between ambient temperature and health outcomes, a number of indicators of thermal stress have been developed (World Meteorological Organization, 2004). Air temperature and apparent temperature are the most direct indicators of the thermal stress and are widely used in epidemiological studies (Green et al., 2009; Xu et al., 2013). However, most recent studies have used complex indicators which integrated several meteorological factors affecting humans thermo-physiologically. It has been identified that effects of the thermal stress are not solely dependent on the air temperature but strongly driven by the combined effects of several environmental factors

Abbreviations: All, all natural causes; ASMR, age-standardized mortality rates; CI, confidence interval; CVD, cardiovascular diseases; E, expected value; GAMM, generalized additive mixed model; GIS, geographic information system; ICD-10, *International Classification of Diseases, 10th Revision*; km, kilometer; LISA, local indicator of spatial association; log, natural logarithm; m, meter; MTR, mass transit railway; m/s, meters per second; n, total number of units in the study; N, north; °C, degree Celsius; PET, physiological equivalent temperature in Celsius; RESP, respiratory diseases; r, Spearman's rank correlation coefficient; SDI, socio-economic deprivation index; TPU, tertiary planning unit; UC-AnMap, Urban Climatic Analysis Map; WHO, World Health Organization.

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(Blazejczyk et al., 2012; Lin et al., 2012; Muthers et al., 2010; Omonijo and Matzarakis, 2011; Planning Department, 2009). Other atmospheric environmental factors, including humidity, wind velocity, and the short- and long-wave radiation fluxes of the atmosphere, are also related to heat exchange between the human body and the environment. For example, the risk of hyperthermia would be higher with increasing humidity or in windless conditions as the capacity of sweat vaporization is associated with water pressure and wind velocity (Gaffin and Moran, 2001).

In Hong Kong, wide geographical variations in mortality have been observed over the years, which may in part be due to differences in the thermal stress, air, and noise pollution (Wong et al., 2008; Xu et al., 2013). However, it was unclear how much thermal stress in the different areas contribute to the geographical variations in mortality. We therefore set out to explore whether there were significant patterns of geographical clustering of thermal stress as measured by physiological equivalent temperature (PET) and mortality. This hypothesis was tested via spatial cluster analysis across small geographical areas. In addition, we determined the extent to which PET was associated with geographical variation in mortality after adjustment for socio-economic deprivation, using a small-area ecological cross-sectional study.

2. Materials and methods

2.1. Study area

Hong Kong is a highly densely populated urban territory in south-eastern coast of China, with over 6.8 million people in 2006 residing in an area of approximately 1,000 km^2. It is situated at 22.2°N latitude at the mouth of the Pearl River, which opens into the South China Sea. Hong Kong has a subtropical climate, with an average temperature 19 °C from October to March and 27 °C from April to September in 2006. About 20% of the population lived on Hong Kong Island, a narrow strip of flat land around Victoria Harbour. Kowloon, a peninsula on the mainland with about 30% of Hong Kong's population, is heavily populated and highly urbanized with sparse greenery areas. Most of the remaining population lives in densely populated new towns in the New Territories. High levels of greenery are found throughout the New Territories where several hiking trails are located. The demarcation of boundaries for Hong Kong Island, Kowloon, and New Territories is provided in the Supplementary Material.

2.2. Tertiary planning units

We used *tertiary planning units* (TPUs) as the units of analysis. TPU is the smallest geographical unit at which mortality, population, and socio-economic data from the census are available. There were a total of 276 TPUs in 2006. However, information about some small TPUs is regarded as incompatible with the preservation of privacy and some of the less densely populated TPUs were merged to form larger TPUs. The eventual number of TPUs included 145 for analysis.

2.3. Socio-economic deprivation index

The Census and Statistics Department of Hong Kong conducts a population census every 10 years and a by-census every intermediate 5 years. We used socio-economic deprivation index (SDI), an index adopted for the local characteristics of Hong Kong, to adjust for social-economic deprivation at TPU level using data from the 2006 by-census report. This is a standardized combination of six census variables: (i) the proportions of the residents who were unemployed; (ii) the proportion of monthly household income < US$250; (iii) the proportion of residents with no schooling; (iv) the proportion of one-person households; (v) the proportion of residents who never married; and (vi) the proportion of sub-tenancy households. A detailed description of the development of SDI is given in one of our previous studies (Wong et al., 2008).

2.4. Mortality data

The Hong Kong Census and Statistics Department provided mortality data for all registered deaths in Hong Kong in 2006, including age, sex, date of death, TPU of residence, and the code of underlying causes of death, which is classified according to the *International Classification of Diseases, 10th Revision (ICD-10)*. We aggregated monthly and annual number of deaths due to all natural causes (A00-T99; Z00-Z99), cardiovascular (I00-I99), and respiratory diseases (J00-J98). Age-standardized mortality rates (ASMR) using the WHO standard population were calculated for all TPUs with mortality, population counts by 5-year age band. Population counts were obtained from the Hong Kong 2006 by-census.

2.5. Physiological equivalent temperature

We used PET as a measure of human thermal comfort in an environment that comprises both meteorological factors of the thermal environment and physiological characteristics of the human body. It is based on a complete heat budget model of the human body, taking all mechanisms of heat exchange into account (Gulyas and Matzarakis, 2009; Lin et al., 2012; Omonijo and Matzarakis, 2011; Planning Department, 2009). We obtained information related to climatic classification in different areas of distinct local climates based on the climatic characteristics of dynamic potential and thermal load from the Urban Climatic Analysis Map (UC-AnMap). This map was created by the Hong Kong Planning Department, which combined meteorological, planning, land use, topography, and greenery information geographically with the aim to assess their inter-relationships and effects on winds and thermal comfort in Hong Kong. It included eight urban climatic classes of thermal conditions ordered from Class 1 to Class 8, each of which characterized a 100 m × 100 m resolution grid area. Each unit increase in a class is associated with 1 °C higher in PET, with Class 3 (PET = 27 °C) regarded as the neutral thermal comfort level for typical summer conditions in Hong Kong (Ng and Ren, 2010; Planning Department, 2009). For example, Class 8 areas, which represent high and compact building volumes with limited open spaces, assume a PET value of 7 °C higher than Class 1 areas. In contrast, Class 1 and Class 2 areas have lower PET than Class 3, owing to their higher altitudes, coverage of vegetation, greenery, and coastal areas (Planning Department, 2009).

To derive monthly PET estimates at TPU level, which comprises several 100 m × 100 m grids, first, we calculated monthly PETs for Class 3 by inputting data from Hong Kong Observatory including air and mean radiant temperatures, percentage of cloud cover, humidity, and wind velocity to the RayMan software (Matzarakis et al., 2007, 2010). For Class 1 to Class 2 and Class 4 to Class 8, the monthly PETs were estimated based on changes in class number from the referenced neutral Class 3 accordingly. Second, we averaged PET values of all grids within each TPU to obtain monthly PET estimates at TPU level. The monthly estimates were then averaged to annual PETs. Data on building coverage (%) and greenery coverage (%) were computed at TPU level using ArcGIS. The data acquisition from different sources and data cleaning procedures are summarized in Fig. 1.

2.6. Local indicators of spatial association analyses

Local indicators of spatial association (LISA) analyses were used to measure and to test for spatial distribution (clustered, random or dispersed) at the TPU level and used to identify locations of clusters. This method for detecting high or low PET with high ASMR took into account both geographical locations of PET and ASMR (Anselin et al., 2006).