Ambient temperature and intentional homicide: A multi-city case-crossover study in the US

Rongbin Xu\textsuperscript{a,b}, Xiuxin Xiong\textsuperscript{c}, Michael J. Abramson\textsuperscript{b}, Shanshan Li\textsuperscript{b,x}, Yuming Guo\textsuperscript{a,b,x}

\textsuperscript{a} School of Public Health and Management, Binzhou Medical University, Yantai, Shandong, China
\textsuperscript{b} Department of Epidemiology and Preventive Medicine, School of Public Health and Preventive Medicine, Monash University, Melbourne, Victoria 3004, Australia
\textsuperscript{c} Centre for Health Policy, Melbourne School of Population and Global Health, The University of Melbourne, Melbourne, Victoria 3010, Australia

A R T I C L E   I N F O

Handling Editor: Shoji Nakayama
Keywords:
Ambient temperature
Climate change
Inter-personal violence
Homicide
Case-crossover study

A B S T R A C T

Background: There has been an increasing interest in the association between ambient temperature and violence and crime, in the context of global warming. We aimed to evaluate the association between daily ambient temperature and intentional homicide—a proxy for overall inter-personal violence.

Methods: We collected daily weather and crime data from 9 large US cities (Chicago, Detroit, Fort Worth, Kansas City, Los Angeles, Louisville, New York, Tucson and Virginia Beach) from 2007 to 2017. A time-stratified case-crossover design was used. The associations were quantified by conditional logistic regression with distributed lag models, adjusting for relative humidity, precipitation and effects of public holidays. City-specific odds ratios (OR) were used to calculate the attributable fractions in each city.

Results: Based on 19,523 intentional homicide cases, we found a linear temperature-homicide association. Every 5 °C increase in daily mean temperature was associated with a 9.5% [95% confidence interval (CI): 4.3–15.0%] and 8.8% (95% CI: 1.5–16.6%) increase in intentional homicide over lag 0–7 days in Chicago and New York, respectively. The association was not statistically significant in the other seven cities and seemed to be stronger for cases that happened during the hot season, at night (18:00–06:00) and on the street. During the study period, 8.7% (95% CI: 4.3–12.7%) and 7.1% (95% CI: 1.4–12.0%) intentional homicide cases could be attributed to temperatures above city-specific median temperatures, corresponding to 488 and 316 excess cases in Chicago and New York, respectively.

Conclusions: Our study suggests that the interpersonal violence might increase with temperature in some US cities. We also provide some insights into the mechanisms and targeted prevention strategies for heat-related violence.

1. Introduction

Violence and crime remain big threats in the modern society. More than 400,000 people were killed by interpersonal violence in 2017 worldwide (GBD Causes of Death Collaborators, 2018). The intentional homicide rate is considered as a proxy for overall interpersonal violence, as it is one of the most accurately reported and internationally comparable crime indicators (UNODC 2014). The intentional homicide rate in the United States (US) fluctuated around 5.0/100,000 during 2007–2016, corresponding to about 16,000 victims per year (UNODC 2018).

In the context of global warming, there is an increasing interest in whether the rising temperatures could affect crime (Hsiang et al., 2011; Hsiang et al., 2013; Ranson, 2014). The potential pathway could be that warmer temperatures increase aggressive behaviour (Craig et al., 2016; Cruz et al., 2020; Rule et al., 1987), or make more people stay outside and thus increase conflicts due to a larger pool of potential victims, offenders and unattended properties (Dell et al., 2014; Tiihonen et al., 2017). According to our bibliographic search, the earliest scientific literature on this topic was published in 1927 (Ishii, 1927). This study found a clear seasonal pattern of the homicide rate in Japan, with highest rates in hottest months (July to September) and lowest in coldest months (November to January) (Ishii 1927). The seasonal pattern in homicide was confirmed by later observations in other countries, and was thought to be mainly driven by seasonal fluctuation in temperature (Ceccato, 2005; Hipp et al., 2004; Simister and Cooper, 2005; Tiihonen et al., 1997).

To explain the seasonal pattern, many studies have investigated the

\textsuperscript{*} Corresponding authors at: Department of Epidemiology and Preventive Medicine, School of Public Health and Preventive Medicine, Monash University. Level 2, 553 St Kilda Road, Melbourne, VIC 3004, Australia.

E-mail addresses: shanshan.li@monash.edu (S. Li), yuming.guo@monash.edu (Y. Guo).

https://doi.org/10.1016/j.envint.2020.105992

Received 20 March 2020; Received in revised form 30 June 2020; Accepted 16 July 2020

0160-4120/©2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/BY-NC-ND/4.0/).
association between temperature and homicide especially in the last three decades. They could be categorized into three types in terms of design: (1) cross-sectional studies based on annual homicide counts or rates (Anderson, 1987; Coccia, 2017; Lester, 1986, 1988, 1991; Rotton and Cohn, 2003); (2) longitudinal or panel studies based on annual or monthly homicide data (Mares, 2013; Ranson, 2014; Takahashi, 2017; Tiihonen et al., 2017; Yan, 2000); or (3) time-series analyses in one specific city based on daily homicide data (Anderson and Anderson, 1984; Cheatwood, 1995; Gamble and Hess, 2012; Schutte and Breetzke, 2018; Talaei et al., 2014).

None of these three types of study design showed consistent findings. For each specific design, it was the case that, some studies found a significant and positive association between ambient temperature and homicide (Anderson and Anderson, 1984; Anderson, 1987; Cheatwood, 1995; Gamble and Hess, 2012; Lester, 1986, 1991; Ranson, 2014; Takahashi, 2017; Tiihonen et al., 2017; Yan, 2000) while others found no association (Coccia, 2017; Cohn, 1990; Lester, 1988; Mares, 2013; Rotton and Cohn, 2003; Talaei et al., 2014; Yan, 2000). The cross-sectional studies could not account for many regional confounding factors, such as socioeconomic inequality, political context, and culture (Anderson, 1987; Coccia, 2017; Lester, 1986, 1988, 1991; Rotton and Cohn, 2003). Studies based on monthly or annual crime data of studies were unable to consider variations within a month, making it impossible to evaluate shorter-term effects of temperature on homicide (Mares, 2013; Ranson, 2014; Takahashi, 2017; Tiihonen et al., 2017) while others found no association (Coccia, 2017; Cohn, 1990; Lester, 1988; Mares, 2013; Rotton and Cohn, 2003; Talaei et al., 2014; Yan, 2000). In addition, none of them have accounted for lagged effects of temperature within several days (Anderson and Anderson, 1984; Cheatwood, 1995; Gamble and Hess, 2012; Schutte and Breetzke, 2018; Talaei et al., 2014). Furthermore, most studies were based on single cities (Anderson and Anderson, 1984; Ceccato, 2005; Cheatwood, 1995; Gamble and Hess, 2012; Mares, 2013; Schutte and Breetzke, 2018; Talaei et al., 2014; Yan, 2000). The temperature-homicide association might vary by city, where population structure, social context and law systems are different. This limits the generalizability of the findings.

Two recent studies have overcome some limitations mentioned above by using daily crime data from multiple places, and both of them found a linear and positive association between daily temperature and violent crime on the current day (Berman et al., 2019; Gates et al., 2019). The South African study further evaluated the lagged impacts of temperature on homicide and found the temperature on the current day was also positively associated with homicide in the next day i.e. with 1 day lag (Gates et al., 2019). However, this study did not explore possible impacts with longer lags. It is possible the conflicts associated with temperature rise do not cause homicide immediately, but increase homicide risk in the following days e.g. out of revenge. Including longer lags would also be helpful to capture the potential temporal homicide displacement (Zanobetti et al., 2002), i.e. some homicides were displaced to earlier days due to temperature rise. Another limitation of the South African study was using homicide data from death registry rather than police department (Gates et al., 2019). In South Africa, the law discourages pathologists from reporting violent death as homicide to avoid prejudicing potential investigations, thus in death registry many homicides tend to be misclassified as deaths due to other causes such as accidents (Prinsloo et al., 2017).

Although these two recent studies (Berman et al., 2019; Gates et al., 2019) based on multiple places have better generalizability than previous single-city based studies, they did not evaluate inter-city heterogeneity of the temperature-homicide association. It is possible that different cities with different urban criminogenic environments and social contexts may show different temperature-homicide associations. Previous studies suggest that homicides within a city often show clear spatial pattern (e.g., have several hot spots) and temporal pattern (e.g., more likely to happen on summer, weekends, time around midnight) (Ceccato, 2005; Taylor, 2015). Therefore, whether the temperature-homicide association varies by space and time also warrants further investigations.

In the present study, we aimed to quantify the association between daily ambient temperature and intentional homicide in nine large US cities with sufficient consideration of the potential lag impacts, and to evaluate whether the associations varied by location, season, and time of homicide.
2. Methods

2.1. Data collection

2.1.1. Intentional homicide data

Data on intentional homicide were obtained from the Crime Open Database (CODE), a project combining harmonized open-accessed crime data from large US cities, as described in detail in (Ashby, 2019). When we started our analyses, the CODE project synthesized open crime data collected and released by police department of 10 large US cities. Details about the city-specific data sources and data cleaning process could be found at https://osf.io/zyaqn/. In the present study, we only included 9 cities (Chicago, Detroit, Fort Worth, Kansas City, Los Angeles, Louisville, New York, Tucson and Virginia Beach) where homicide data were available (Fig. 1). The study period of the nine cities started from 2007 to 2013 and all ended at 2017.

The CODE also collected detailed information of each crime case such as where (longitude, latitude, location type) and when (date and exact time to minutes) the crime happened. Only crime cases with location information (i.e., longitude and latitude) and the location was within each city’s officially defined boundary were included in the CODE dataset (Ashby, 2019). Intentional homicide was originally coded as murder and nonnegligent manslaughter in the CODE dataset using the offense definitions published by the Federal Bureau of Investigation (FBI). The FBI’s definition of murder and nonnegligent manslaughter is the willful (nonnegligent) killing of one human being by another, which is close to the definition of intentional homicide (unlawful death purposefully inflicted on a person by another person) by the United Nations Office on Drugs and Crime (UNODC) (UNODC, 2014). We excluded negligent manslaughter, another kind of homicide, from the analyses for two reasons: 1) negligent manslaughter is not included as an international comparable indicator of crime by UNODC; 2) this type of homicide has a very small sample size (only 158 cases, accounting for 0.8% of all homicide cases).

2.1.2. Weather data

The daily weather data were obtained from a national meteorological dataset (4 km × 4 km resolution) created by Parameter–Elevation Regressions on Independent Slopes Model (PRISM) (PRISM Climate Group, 2018). City-specific weather were represented by the average weather data from all grids covered by the city’s officially defined boundary according to US Census Bureau (US Census Bureau, 2019). Daily mean temperature (Tmean), daily minimum temperature (Tmin), daily mean dewpoint temperature and daily precipitation during the study period were downloaded from the PRISM website (http://prism.oregonstate.edu/explorer/). The average error of Tmean from PRISM compared to meteorological station records was less than 0.2 °C, and the precipitation and daily mean dewpoint temperature were also highly consistent with weather station records (Di Luzio et al., 2008). The daily mean relative humidity was calculated from Tmean, and daily dewpoint temperature using the R package “humidity” (Cai, 2018). As PRISMA did not provide data on daily barometric pressure, we collected these data from weather stations from US Environmental Protection Agency (EPA) (downloaded from https://aqs.epa.gov/aqsweb/airdata/download_files.html#Daily). City-specific barometric pressure was represented by the average observation of all available stations within city boundary. However, daily barometric pressure from weather stations was not available for Fort Worth and Tucson, and was incomplete in other seven cities.

2.1.3. Demographic and socioeconomic data

The city-specific population data in each year during the study period were downloaded from the US Census Bureau (https://www.census.gov/). Population density was then calculated as the mean population during the study period divided by the area size of each city. We collected data on several other important city-level demographic and socioeconomic indicators from the 5-year (2013–2017 average) estimates of American Community Survey (US Census Bureau, 2020). These indicators included median age, proportion of males, ethnic composition (proportions of white/black or African/Hispanic or Latino/Asian people), poverty rate, median household income, Gini index of income inequality, unemployment rate, educational attainment (proportion of people with high school/bachelor degree or higher among those aged 25 years or above). Finally, we obtained data on the rank of state gun law strength in 2017 among 50 states in US from (Giffords Law Center, 2018).

2.2. Statistical analyses

2.2.1. Assessing the temperature-intentional homicide association

The association between ambient temperature and intentional homicide was evaluated by a time-stratified case-crossover design (Levy et al., 2001; Li et al., 2016; Xu et al., 2019a, 2019b). For each intentional homicide case, the daily mean temperatures during the risk period were compared with those during control periods in the same city. Control periods were the same days of the week in the same calendar month and year and in the same city for each intentional homicide case. In this design, each case had 3 or 4 control periods. This design could adjust for time-dependent confounders (e.g., temporal trend and day of the week) and time-constant confounders e.g., type, location and cause of the intentional homicide cases, city-level social context (Janes et al., 2005a, b).

The relationship between intentional homicide and temperature was fitted by a conditional logistic regression model. In this regression model, the dependent variable is a binary variable indicating whether an observation is a case or control (1 = case, 0 = control). Tmean was added to the model as an independent variable using a cross-basis function (Guo 2017). Our initial analyses showed that the association is linear (see supplementary material, Fig. S1) and lasted for 7 days. The Bayesian information criterion (BIC) value of the linear model was also lower than that of non-linear model (56,379 versus 56,405), suggesting that a linear model performed better than a non-linear model. Thus, we used a linear function for the exposure–response dimension and a natural cubic spline with three degrees of freedom (df) for the lag-response dimension (lag 0–7 days). In the lag-response dimension, the knots were placed at equally-spaced values in the log scale by using the “logknots” function in “dlnm” package, with number of knots equal to df minus 2 (Gasparini, 2011). The holiday effect was controlled by adding a dichotomous variable (whether that date was a public holiday) to the model. We also adjusted for the daily relative humidity and daily precipitation in lag 0–7 days by adding them to the model as cross-basis functions, using natural cubic spline with three df for both exposure–response and lag-response dimension (lag 0–7 days) to control for their potential non-linear impacts.

Stratified analyses were conducted by city, time (00:00–05:59, 06:00–11:59, 12:00–17:59, and 18:00–23:59), day of week (weekday versus weekend), location type (street, residence, open space, vehicle or transportation, and other), and season (hot, cold or moderate). The hot and cold seasons were defined by the hottest and coldest four months for each city, respectively. The other four months were coded as a moderate season (Guo et al., 2016). To test whether the daytime (06:00–17:59) or nighttime (18:00–05:59) difference varied by weekday and weekend, we performed a more detailed subgroup analyses stratified as weekday daytime, weekday nighttime, weekend daytime and weekend nighttime.

For intentional homicide cases happening during nighttime, the immediate exposure to ambient temperature tended to be better represented by Tmin rather than Tmean. However, as we were evaluating the cumulative temperature-homicide association over lag 0–7 days, Tmean was still better than Tmin to assess cumulative exposure over days. Also, Tmean and Tmin were highly correlated (Pearson correlation coefficient = 0.98). Therefore, we used Tmean rather than Tmin as the
exposure variable for cases happening during nighttime in our main analyses, which could make the results for nighttime and daytime more comparable.

The temperature-intentional homicide association was presented as the odds ratio (OR) and its 95% confidence interval (CI) of an intentional homicide occurrence for every 5 °C increase in daily mean temperature. ORs from a time-stratified case-crossover analysis could be interpreted as relative risks (RRs), because the selection of control periods is based on density sampling which makes the exposure during control periods represent the average exposure in the study population (Greenland and Thomas, 1982; Hogue et al., 1983; Xu et al., 2019b). Meta-regression was applied to check the statistical differences in the ORs between subgroups. Briefly, the effect estimates of different subgroups (e.g., nine city-specific effect estimates; three season-specific effect estimates) were modelled against the meta-predictors (e.g., city as a categorical variable with nine levels; season as a categorical variable with three levels), then the meta-regression model would provide p-values for difference that tested the inter-subgroup (e.g., inter-city) difference in effect estimates with a likelihood ratio test (Guo, 2017; Xu et al., 2019a, 2019b; Zhang et al., 2020). The p-value for difference could be interpreted as the likelihood that the inter-subgroup difference in effect estimates was due to chance.

To preliminarily evaluate whether the temperature-homicide could be modified by city-level demographic and socioeconomic factors, and gun law strength, we stratified the nine cities into high (> median, with 4 cities) and low (≤ median, with 5 cities) group according to each city-level factor. Then we performed case-crossover analyses based on pooled data of either high or low group of each indicator. We then compared effect estimates from high and low group to give some implications for the potential modifying effect of city-level indicators.

We conducted sensitivity analyses to check the robustness of our results, including: changing maximum lag of daily mean temperature from 7 days to both shorter (6 days) and longer (8–10 days) days; changing the df of lag days from 3 to 4 or 5; removing precipitation and/or relative humidity from the model; and using Tmin rather than Tmean for intentional homicide cases happening during nighttime. In a subsample of 14,438 (74% of total cases) intentional homicide cases with data on barometric pressure available, we performed sensitivity analyses by further adjusting for barometric pressure and/or barometric pressure difference from the previous day. We used meta-regression mentioned above (treating different model as different subgroups) to test whether results from sensitivity models were statistically different from those from the primary model (Guo, 2017; Xu et al., 2019a, 2019b; Zhang et al., 2020).

2.2.2. Calculating the attributable fraction of intentional homicide due to temperature

We estimated the attributable fractions (AFs) for the two cities (Chicago and New York) where the temperature-homicide association were statistically significant. For each city, three steps were used to calculate AF and its 95%CI. First, the city-specific median temperatures during the study period were chosen as reference temperatures for each city. Although the city-specific minimum Tmean was the temperature with lowest intentional homicide risk based on a linear relationship, we did not choose it as the reference, because it could be easily affected by extreme observations. AFs relative to median Tmean tended to be more robust than AF relative to minimum Tmean. Second, the attributable number of intentional homicide cases associated with temperature on day i (ACi, i.e., attributable cases on day i) was calculated using the formula ACi = Ci × (ORi − 1)/ORi, with ORi being the city-specific overall cumulative OR over lag 0–7 days associated with the increase in temperature above reference temperatures on day i, and Ci the city-specific averages of intentional homicide cases from day i to day i + 7 (Gasparrini and Leone, 2014; Hu et al., 2018; Xu et al., 2019a, 2019b). Total AC was calculated by summing the ACi during the study period.

Finally, the AFs were calculated by dividing the total AC by city-specific total intentional homicide cases. We also calculated the attributable annual intentional homicide rate by dividing the total AC by the city-specific mean population and the number of years covered by the study period. The 95%CI of AC, AF and attributable rates were calculated by applying the 95%CI of city-specific OR to the above algorithms following the same procedure. We only calculated the AC and AF for Chicago and New York, where the association between temperature and intentional homicide was statistically significant.

We used R software (version 3.3.2) to perform all data analyses. The packages “survival”, “dlnm” and “mvmeta” were used to fit conditional logistic regression, distributed lag linear or non-linear model, and meta-
regression, respectively. A two-side \( p \) value less than 0.05 was considered to be statistically significant.

3. Results

Nine cities were included, and they were located in nine different US states widely spread across the nation (Fig. 2). The study periods started from 2007 to 2013, but all ended at 2017. The average (± standard deviation) \( T_{\text{mean}} \) was 15.2 ± 10.2 °C during the study period in the nine cities, ranging from 10.4 ± 10.7 °C in Detroit to 21.3 ± 7.8 °C in Tucson. A total of 19,523 intentional homicide cases were recorded in the nine cities during the study period. The mean annual intentional homicide rate ranged from 4.0/100,000 in Fort Worth to 47.6/100,000 in Detroit (Table 1). The intentional homicide cases showed clear seasonal, within-week, intra-day, and geographical distributions: intentional homicide cases were more likely to happen in hot months (June to September), on weekends, during nighttime hours (18:00–23:59) and on the street (supplementary material, Fig. S2).

The linear association between intentional homicide rate and ambient temperature was significant and positive (odds ratio, \( OR > 1 \)) in lag 0–1 days, then diminished and followed by a harvesting effect or temporal displacement until lag 7 days. In other words, there were some cases that might have happened in lag 3–7 days but actually happened in advance at lag0–1 days due to the heat exposure in lag 0 day (Fig. 3). The cumulative effect of temperature on intentional homicide over lag 0–7 days is shown in Fig. 4. Based on pooled data from nine cities, every 5 °C increase in daily mean temperature was associated with a 4.2% (95% CI:1.1–7.3% ; \( OR = 1.042, \) 95%CI: 1.011–1.073) increase in intentional homicide cases for lag 0–7 days.

This overall effect estimate represented an average temperature-homicide association based all data available in our study, but it should be interpreted with caution when applied to any specific city. When performing city-specific analyses, the associations varied by city and were only significant in Chicago (\( OR = 1.095, \) 95%CI: 1.043–1.150) and New York (\( OR = 1.088, \) 95%CI: 1.015–1.166). The associations in Tucson and Virginia Beach showed trends towards positive, while no association was found in other cities despite the large samples in Los Angeles and Detroit. The inter-city variation in effect estimates were not likely to be solely due to chance, as the \( p \) values for difference for Detroit, Los Angeles and Louisville compared to Chicago were less than or close to 0.05.

The association seemed to be stronger in the hot season (\( OR = 1.095, \) 95%CI: 1.026–1.169) compared to cold and moderate seasons (Fig. 5). Also, intentional homicides occurring on the street showed a stronger association with temperature (\( OR:1.092 \) 95%CI: 1.030–1.157). Interestingly, only intentional homicide cases happening in the evening (18:00–23:59) (\( OR: 1.070 \) 95%CI: 1.016–1.126) and early morning (00:00–05:59) (\( OR: 1.082 \) 95%CI: 1.023–1.145) were significantly associated with temperature. The daytime (06:00–17:59) and nighttime (18:00–05:59) difference in the association was only significant on weekdays (\( p \)-value for difference = 0.010), but not on weekends (\( p \)-value for difference = 0.569).

According to analyses stratified by city-level factors, the temperature-homicide association seemed to be stronger in cities with high population density, younger median age, lower proportions of males, lower proportions of white people, high proportions of other ethnic groups (black or African, Asian, Hispanic or Latino), low proportions with high school degree, high proportions with a bachelor degree, high income inequality (i.e., high Gini index), and strong gun law strength (Fig. 6). The modifying effects of median household income, poverty rate and unemployment rate were minimal.

During the study period, 8.7% (95%CI: 4.3–12.7%) and 7.1% (95% CI: 1.4–12.0%) intentional homicide cases could be attributed to temperatures above city-specific median temperatures, corresponding to 488 and 316 excess cases in Chicago and New York, respectively (Table 2).

Sensitivity analyses indicated that the results were robust to changing the maximum lag of daily mean temperature and degrees of freedom (df) of lag days, or removing precipitation and relative humidity from the model, or further adjusting for barometric pressure (Tables S2 and S3). The effect estimates for homicide cases happening during nighttime changed minimally when replacing \( T_{\text{mean}} \) with \( T_{\text{min}} \) (Table S4).

4. Discussion

This study evaluated the association between ambient temperature and intentional homicide using a time-stratified case-crossover design based on multi-city daily crime data. We observed a significant inter-city variation in the temperature-homicide association. The associations were positive and significant only in Chicago and New York, and showed trends towards positive in Tucson and Virginia Beach. However, no association was found in Detroit, Fort Worth, Kansas City, Los Angeles, Louisville, although Detroit and Los Angeles have many intentional homicide cases. The associations were stronger for the cases that happened during hot seasons, on the street and during nighttime hours. The day-night difference in the association seemed to be only significant on weekdays, but not on weekends. In Chicago 8.7% and in New York 7.1% of intentional homicides could be attributed to temperatures above city-specific median temperatures.

There are two main theories that could explain an association between ambient temperature and intentional homicide: the biological theory, and the routine activity theory (Agnew, 2012; Cohn, 1990; Rotton and Cohn, 2003). The biological theory, also called temperature theory, and the routine activity theory (Agnew, 2012; Cohn, 1990; Rotton and Cohn, 2003).
aggression theory, postulates that high temperatures increase an individual’s discomfort and frustration levels and thus increase aggression (Hipp et al., 2004; Kenrick and Macfarlane, 1986). An association between high temperature and aggression has been observed in both animals (Olczak et al., 2015; Takeshita et al., 2018) and humans (Craig et al., 2016; Cruz et al., 2020; Rule et al., 1987). For example, one experimental study, (Rule et al., 1987) found that people exposure to higher temperature (33 °C versus 21 °C) were more likely to generate aggressive thoughts. Ambient temperature has also been positively associated with aggressive penalties in National Football League (NFL) football games (Craig et al., 2016).

However, the underlying biological mechanisms linking high temperature and aggression remain unclear. The aggression might be a side effect of the release of adrenaline in response to heat exposure (Simister and Cooper, 2005). Temperature rise may inhibit 5-hydroxytryptamine (5-HT) function in human beings (Tiihonen et al., 2017). 5-HT is known to be related to happiness and well-being (Canli and Lesch, 2007), thus reduced 5-HT may contribute to higher impulsivity and aggression. High ambient temperature may also cause sleep deprivation and sleep disturbance (Obradovich et al., 2017; Rifkin et al., 2018), while poor sleep is an important causal factor of aggression and violence (Kamphuis et al., 2012).

The routine activity theory focuses on that warmer weather could simply alter people’s routine activity patterns and lead to conflicts and violence (Rotton and Cohn, 2003). For example, during warm weather, people are more likely to go outside (Spinney and Millward, 2011; Timmermans et al., 2016), leading to social-interactions that may cause conflicts, or increasing the likelihood that motivated offenders encounter victims (Cohn, 1990). This theory is more suitable than temperature aggression theory to explain the increased homicide associated with temperature rise from cold to moderate range, as such temperature rise would not be likely to cause uncomfortable feelings. Also, it is possible that people may consume more alcohol on hot days (Hagstrom et al., 2019), which is strongly related to violent behaviour (Stockwell et al., 2015).

It would be consistent with our results, that biological response might provide the basis, while the routine activity changes might actually play a more dominant role in the association between temperature and intentional homicide. The day-night difference in the temperature-homicide association during the weekdays could be well explained by people’s routine activities, because most people usually have to work at daytime on weekdays (Ceccato, 2005). In comparison, on weekends, people’s activities at both nighttime and daytime are more flexible and thus sensitive to temperature change. This could
explain why the day-night difference in the temperature-homicide association was not significant on weekends. Finally, the routine activity mechanism could also explain the stronger association identified for intentional homicide cases that happened on the street and during hot seasons. People typically go outdoors more often during hot seasons, and most social interactions or the encounters between offenders and victims happen on the street.

The lagged impacts of daily temperature on homicides are relatively new apart from (Gates et al., 2019). Both our study and (Gates et al., 2019) have found that the daily temperature was associated with increased homicide in both current day (lag0) and the next day (lag1). The effects with a 1 day lag might be explained by both the temperature aggression and routine activity theories. For the first theory, temperature rise on the current day may cause sleep disturbance and increase the aggression level in the next day. For the second theory, temperature rise on the current day may increase outdoor activity or alcohol use and thus increase the conflict between victims and offenders, then those conflicts may result in homicide the next day (possibly out of revenge).

The significant harvesting effect or temporal displacement of homicide in lag 3–5 days suggests that there are some homicides that would happen anyway, and temperature rise is just a triggering factor to make them happen several days earlier. A potential example of such homicides is intimate partner homicide which accounts for about 15% of all homicides worldwide (Stockley et al., 2013). Some intimate partner homicides have been largely predetermined by factors such as broken relationship, arguments, sexual jealousy and romantic triangles (Eriksson and Mazeroni, 2013), while high temperature might just trigger those homicides happening earlier by increasing aggression level or alcohol use. However, more studies are needed to confirm our findings and the potential explanations.

We found that the temperature-homicide association varied by city, suggesting the association might be modified by city-level factors related to homicide. According to our preliminary analyses, such factors might include but are not limited to population density, age, sex and ethnic structure, educational levels, income inequality, and gun control laws. Higher population density, younger age, being minority ethnicity, low educational levels, and high income inequality were known risk factors for homicide (CDC, 2013; Daly et al., 2001; Lo et al., 2013; Stickley et al., 2012; Taylor, 2015; Trussler, 2012). Therefore, these factors would also be expected to increase the risk of temperature-induced homicide (i.e., boost the temperature-homicide association) as we observed in Fig. 6. For example, higher population density could increase the chances that offenders encounter victims when people increase outdoor activity due to rising temperatures.

The results that the temperature-homicide association was stronger in cities with strong gun laws, high proportions of people with bachelor’s degrees and low proportions of males were unexpected. In US in 2010, two in three homicides were committed with firearms and more than half of victims (77.4%) and offenders (66.1%) of homicides were male (Taylor, 2015). High educational level, low proportions of males and strict gun control tend to supress homicide associated with temperature (CDC, 2013; Daly et al., 2001; Lee et al., 2017; Stickley et al., 2012). The unexpected results may simply because of the fact that cities (e.g., Chicago and New York) with these three advantages also have other disadvantages such as high population density and high income inequality (see Table S1 in supplement). Therefore, our preliminary analyses on the modifying factors (Fig. 6) is definitely limited by the small number of cities included, and further studies with more cities are warranted.

Knowledge gained from our study could have important social implications, especially in the context of global warming. A significant proportion of intentional homicides were attributable to temperatures higher than city-specific median temperatures in Chicago and New York based on our estimates. This proportion might increase in the future...
given the global warming trend. It is estimated that the global mean temperature will rise by 2.7 °C by the end of this century even under full implementation of all proposed mitigation actions by national governments (International Energy Agency, 2015). Despite this worrying trend, our study also provides some useful information for targeted prevention of temperature induced intentional homicide, particularly for cities where the temperature-homicide association is significant. For example, when temperature rises, police departments in Chicago and New York should reinforce their workforce and activities e.g. security patrols, camera surveillance, that could deter criminals (Cohn, 1990). More attention should be paid to streets, nighttime and weekends.

5. Strengths and limitations

Compared to previous studies (Anderson and Anderson, 1984; Anderson, 1987; Cheatwood, 1995; Gamble and Hess, 2012; Lester 1986, 1991; Takahashi, 2017; Tiihonen et al., 2017), our study has several strengths. Firstly, to our best knowledge, apart from (Gates et al., 2019), this is one of the first studies using time-stratified case-crossover design to evaluate the relationship between weather and crime. The design could adjust for most inter-city, time-constant and time-varying confounders without any statistical adjustment. Secondly, our study has accounted for the lagged effects which have been largely neglected by previous studies based on daily data (Anderson and Anderson, 1984; Cheatwood 1995; Gamble and Hess, 2012; Schutte and Breetzke, 2018; Talaei et al., 2014). Compared to (Gates et al., 2019) which only included a 1 day lag, our analysis has fully account for the harvesting effect by including longer lags up to 7 days. If we did not capture the harvesting effect, the total effect of daily temperature on intentional homicide would have been overestimated. Thirdly, this analysis was based on multi-city data spanning for 10 years, so the generalizability and robustness tend to be better than previous single-city studies (Anderson and Anderson, 1984; Cheatwood, 1995; Gamble and Hess, 2012; Schutte and Breetzke, 2018; Talaei et al., 2014). For the first time we reported an inter-city variation of temperature-homicide association (Berman et al., 2019; Gates et al., 2019). Finally, our analyses stratified by season, location and time were novel, which could provide new information for mechanisms and targeted preventions of temperature related homicide.

However, there are also several limitations. Firstly, the cities

Table 2
The number, fraction and annual rate of intentional homicide that could be attributed to temperatures above the city-specific median temperature during the study period in Chicago and New York.

<table>
<thead>
<tr>
<th>City</th>
<th>Reference temperature (°C)</th>
<th>Attributable cases (95%CI)</th>
<th>Attributable fraction (95%CI), %</th>
<th>Attributable annual rate (95%CI), /100,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago</td>
<td>11.9</td>
<td>488 (240, 710)</td>
<td>8.7 (4.3, 12.7)</td>
<td>1.61 (0.79, 0.79)</td>
</tr>
<tr>
<td>New York</td>
<td>13.9</td>
<td>316 (62, 537)</td>
<td>7.1 (1.4, 12.0)</td>
<td>0.35 (0.07, 0.07)</td>
</tr>
</tbody>
</table>

Note: city-specific median temperatures were selected as the reference temperatures. We did not estimate the attributable cases for other seven cities, as they did not show significant temperature-homicide associations.
included in the present study are all in the US, which may not apply to other countries. Low- and middle-income countries (e.g., China, Brazil and India) have much higher population densities, but much less effective strategies to deal with heat exposure. They may suffer even more from heat-related violence. Meanwhile, some high-income countries (e.g., Australia) with much stricter gun controls compared to US might show different temperature-homicide associations. Secondly, potential missing homicide data e.g., unreported, undiscovered or misclassified as suicide, were likely to cause the underestimation of the temperature-homicide association. However, if some suicides were misclassified as homicide (Rockett et al., 2006), the association might also be overestimated, because suicide is strongly associated with daily temperature (Kim et al., 2019). Using the city average daily temperature to represent individuals’ heat exposure could also lead to underestimation of the association. However, since we would never know who were the potential offenders or criminals in this population, it would be impossible to get the individual level exposure. Finally, as the crime data were open-access for each city, detailed information on the offenders and victims (e.g., sex, age, occupation, and offender-victim relationship) was not reported in order to protect victims’ privacy (Ashby, 2019). This limited our ability to evaluate whether the homicide-temperature association could be modified by offenders’ or victims’ characteristics. A recent study in South Africa found that the temperature-homicide association did not vary by sex and age of the victims (Gates et al., 2019).

6. Conclusions

Ambient temperature was positively associated with intentional homicide, but only in some cities. The association tended to be stronger for intentional homicide cases that happened during hot seasons, at nighttime hours, or on the street. Our study suggests a potential increase in interpersonal violence under global warming in certain locations and also provides some useful information for targeted prevention of heat related homicide.

CRediT authorship contribution statement

Rongbin Xu: Conceptualization, Data curation, Methodology, Formal analysis, Visualization, Software, Writing - original draft. Xiuqin Xiong: Data curation, Visualization, Writing - review & editing. Michael J. Abramson: Writing - review & editing. Shanshan Li: Writing - review & editing. Yuming Guo: Supervision, Resources, Methodology, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michael Abramson holds investigator initiated grants from Pfizer and Boehringer-Ingelheim for unrelated research. He has also undertaken an unrelated consultancy for Sanofi. The other authors declare no competing interests.

Acknowledgements

We thank Matthew Ashby and his colleagues for collecting and providing the homicide data. Also, many thanks to PRISMA climate group at Oregon State University for providing the meteorological data.

Funding

This work was supported by China Scholarship Council [grant numbers 201806010405 and 201906010310] and Australian National Health and Medical Research Council [grant numbers APP1109193, APP1107107, and APP1163693].

Role of funding source

The funding sources played no role in study design, data collection, data analyses, data interpretation, or writing of the paper.

Ethics approval

Ethical approval was not required for secondary analysis of anonymous data from publicly available sources.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2020.105992.

References

Hipp, J.R., Bauer, D.J., Curran, P.J., Bollen, R.A., 2004. Crimes of opportunity or crimes...


