Temperature, Heat Waves, Crime, and Injuries in Hanoi, Vietnam

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Dedication

This is dedicated to my family who have believed and supported me through this challenge. To my father Lê Trọng Rung, mother Vũ Thị Thuý, my brother Lê Quyết Thắng, my sister-in-law Vũ Thuỳ Vân, and my nephew Lê Vũ Huy Tùng who always believed in and encouraged me during my very hard times. To my son Lê Nam Quang, who has been the most wonderful blessing during the PhD program and continues to brighten my days with his energy and smiles. To my very special friend, who stayed on my side to listen and support me.

Abstract

Manuscript 1: The effects of temperature on behavior change and mental health have previously been explored, but the association between temperature and crime is less well understood, especially in developing countries. Single-city-level data were used to evaluate the association between the short-term effects of temperature on crime events in urban Hanoi, Vietnam. We used quasi-Poisson regression models to investigate the linear effects and distributed lag non-linear models to investigate the non-linear association between daily temperature and daily crime events from 2013 to 2019. There were 3884 crime events, including 1083 violent crimes and 2801 non-violent crimes during the 7-year study period. For both linear and non-linear effects, there were positive associations between an increase in daily temperature and crime, and the greatest effects were observed on the first day of exposure (lag 0). For linear effects, we estimated that each 5 °C increase in daily mean temperature was associated with a 9.9% (95%CI: 0.2; 20.5), 6.8% (95%CI: 0.6; 13.5), and 7.5% (95%CI: 2.3; 13.2) increase in the risk of violent, non-violent, and total crime, respectively. For non-linear effects, however, the crime risk plateaued at 30 °C and decreased at higher exposures, which presented an inverted U-shape response with a large statistical uncertainty.

Manuscript 2: Heatwaves are a pervasive natural hazard that can have significant public health impacts on society. The effects of heatwaves on health, including mental health disorders, are well documented, but the effects on criminal behavior are unclear, particularly in understudied tropical regions. This study evaluates the heatwave-crime

associations in urban Hanoi, Vietnam, for seven years (2013- 2019). The time-stratified case-crossover study design with a quasi-Poisson regression model was applied for three heatwave definitions of increasing severity. We found that heatwaves were weakly protective factors against crime risk in urban Hanoi under all three heatwave definitions. For non-violent crime, 4-day heatwaves of 34.5 °C showed the most protective effect (RR=0.28, 95%CI = 0.08, 0.94), and for violent crime, 2-days heatwave of 32 °C showed the most protective effect (RR= 0.65; 95%CI = 0.45; 0.93). In addition, longer heatwave durations under all heatwave scenarios decreased violent and non-violent crime risks. However, we used data in only urban Hanoi, so further research is warranted, including the addition of future years and more cities in Vietnam to investigate the comprehensive effects of heat on crime in this southeast Asian study area.

Manuscript 3: Injuries take the lives of 4.4 million people worldwide each year and constitute nearly 8% of all deaths. Vietnam, considered a (low-and-middle-income country) LMIC, has suffered a heavy toll of the burden of injury. This is the first study to investigate temperature-injury associations in Vietnam. This study used emergency visit data from 733 hospitals and clinics in Hanoi to examine the linear and non-linear effects of temperature on injury for three years (2017-2019). We found that the proportion of males visiting emergency department (ED) due to injury is higher than females, and similar trends are observed across different age groups, except for people aged 60 and older. The temperature-injury associations differ between gender and age. For linear effects, the lowest risk was in people aged 60 and older, followed by people aged under 15, people aged 15 to 44 and people aged 45- 59. People exposed to a higher temperature, especially in Q5, show higher injury risk than those exposed to below 21.30 °C (in Q1). For non-linear effects, we observed an increase in the risk of injury at high temperatures but a decrease in the risk of injury at low temperatures, compared to the threshold temperature of 15 °C. Males have a higher injury risk than females when temperature increases. On average, males, and people under 60 were identified to be at higher risk of temperature-related injury than other females and people 60 and older. Future research is warranted to investigate temperature-injury among different groups of people and the causes of injury.

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Organization

This dissertation is organized in five chapters. The first chapter provides background information followed by three chapters containing independent manuscripts and a last chapter with concluding remarks. Because the three manuscripts in chapters 2-4 are in preparation for peer-review, there may be some redundancy in the content.

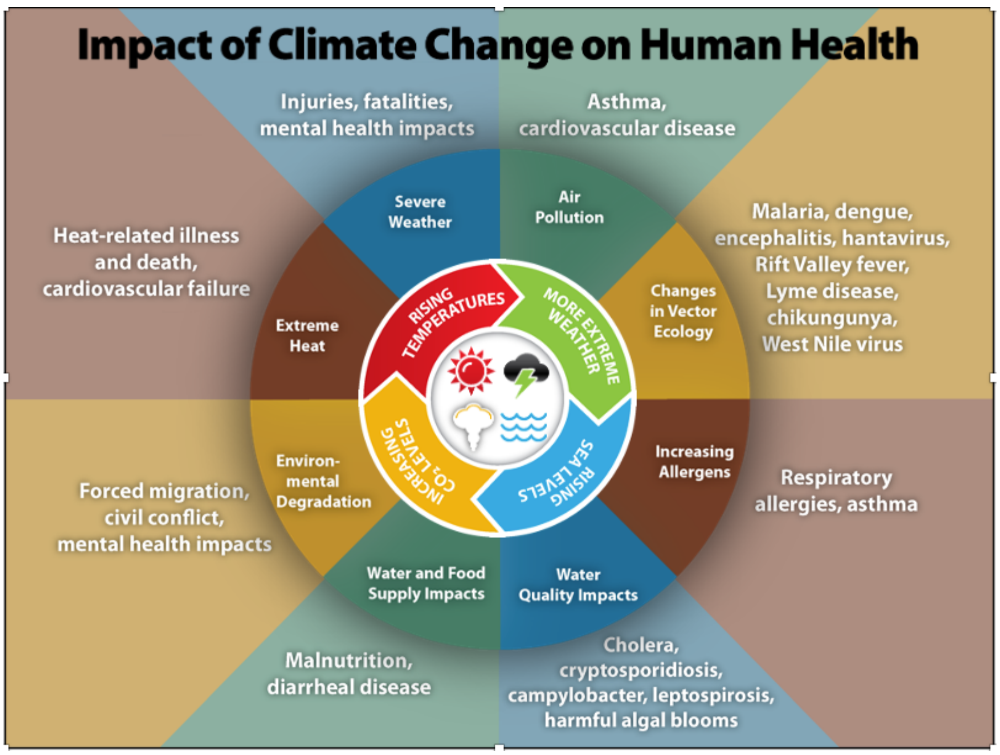
Chapter 1: Introduction

Climate change and the effects on human health

Climate change is a significant public health concern, threatening humanity by leading to adverse environmental consequences, such as rising temperatures and more extreme weather events(1)(2). Changes observed in the Earth's climate since the early 20th century are primarily driven by human activities, particularly fossil fuel burning, which increases heat-trapping greenhouse gas levels in the Earth's atmosphere. The Earth's surface temperature has increased at an average rate of 0.08 degree Celsius (°C) per decade since 1880, but the average rate of increase since 1981 (0.18 °C) has been more than twice that rate(3).

Climate change is affecting human health worldwide, especially among people living in low-and lower-middle-income countries(4). For example, rising mean temperatures can create conditions conducive to the geographic spread of vector-borne diseases, such as dengue. In addition, climate change will have an effect on atmospheric conditions, the frequency, intensity, and duration of some extreme weather and climate events; and sea level(2). Rising temperatures lead to an increase in intensity and duration of extreme heat, which causes heat-related illness and death. The World Health Organization (WHO) estimated that climate change may cause approximately 250 000 additional deaths per year worldwide due to heat stress, diarrhea, malaria, and undernutrition in 2030, put 4.26 billion people at risk of dengue in 2030, then increase the number of people at risk of dengue to 4.64 billion in 2050 (5).

The health effects of climate change differ between urban and rural populations. People living in urban areas may have higher rates of exposure to heat-related illness and air-quality-related respiratory diseases than in rural areas because urban temperatures are further enhanced by anthropogenic heat from vehicular transport and heat waste from buildings(1)(6)(7). However, people living in rural areas may have greater exposure to climate impacts on food production or natural hazard events, which have subsequent effects on household nutrition and food security(1).



Picture 1: Impact of Climate change on human health

Source:https://www.cdc.gov/climateandhealth/effects/default.htm#:~:text=The%20health%20effects%20of%20these,and%20threats%20to%20mental%20health.

Vietnam is one of the most vulnerable countries to climate change impacts, it was ranked as the sixth country in the world most affected by climate variability and extreme weather events from 1999-2018(8). In Vietnam, climate change has affected ecological and agricultural health, national income, and human health. First, the estimated increase in the average temperature is 3.4 °C by 2080-2100, and the annual precipitation change of 10% to 20% by 2045 – 2065(9). The World Bank predicts that rising global temperature will exacerbate natural hazards in Vietnam, such as heatwaves, drought, and floods (9). The percentage of the population vulnerable to flooding will rise from the current rate of 33% of population to 38-46% of population(10). Increasing the intensity and duration of heat waves may also increase the probability of drought occurring in all the country's regions. Vietnam experienced the most severe drought in 90 years, affecting more than two million people, about 275,263 ha of rice paddies, and 189,878 ha of perennial crops(9)(10). It has been estimated that climate change may result in decreasing Vietnamese national income by up to 3.5% by 2050(11).

The climate in Vietnam differs between the North, sub-tropical, and the South, tropical, so the effects of climate change on temperature may vary within the country. Several studies have evaluated the effects of rising temperature or extreme weather events on human health in Vietnam, including physical and psychological health problems. Recent studies have shown the association between increases in temperature and various types of physical problems, such as respiratory, cardiovascular, hand-foot-mouth, dengue, and kidney diseases(12)(13)(14)(15)(16). A multi-province study showed that the risk of hospitalization for all causes, infectious, respiratory, and cardiovascular diseases due to heatwaves, was higher in the North than in South Vietnam(17). Among vulnerable groups, for example, a single-province study in Hanoi (located in the North) estimated increased risk of respiratory disease in cold weather (18), by contrast, another study in Ho Chi Minh City (located in the South) indicated that high temperature is a risk factor for respiratory diseases (19).

In Vietnam, few studies investigated the effects of temperature and extreme weather events on mental health and behavioral problems. Positive associations between heatwaves and hospital admissions due to mental health disorders were reported in the North of Vietnam, especially more persistent heatwaves of at least three days(20). Another study also estimated heatwaves increased all-cause mental health and behavioral disorders hospitalization by 62% in Ho Chi Minh City(21). However, to the best of our knowledge, no studies have evaluated the association between temperature or extreme weather events and violent behaviors (criminal behavior) and injury in Vietnam.

Injury and violence

Injury and violence are significant causes of death and burden of disease in all countries. According to WHO, three of the top five causes of death among people aged 5-29 are injury-related, including road traffic injuries, homicide, and suicide(22). Tens of millions more people suffer non-fatal injuries each year, which lead to emergency department and acute care visits, hospitalizations, or treatment by general practitioners and often result in temporary or permanent disability and the need for long-term physical and mental health care and rehabilitation(22).

Injury and violence are linked together, but their effects differ by age, gender, and sociodemographic factors. They cost society hundreds of billions of dollars in medical care and lost productivity each year in the U.S.A(23). Short-term exposure to violence, such as domestic and community violence, can cause injury, and long-term exposure to violence can increase the risk of mental illness, behavior change, suicide, social problems and chronic diseases(22). In general, being young, male and of low socioeconomic status increases the risk of injury and of being a victim of serious physical violence(22). Across all ages, the three leading causes of death from injuries for males are road traffic injuries, homicide and suicide, while for females they are road traffic injuries, falls and suicide(24).

Violence and crime are considered as a major threat to public health with an influence on the individual and society. Exposure to violence can be experienced in several ways, including victimization, observing violent behavior, or hearing about crime events from other people. Urban residents are at high risk for witnessing violence, resulting in an increasing risk of depression, distress, and aggression, especially among men (25). Violence is associated with an increase in risk of depression and suicidal ideations among Vietnamese secondary-and-high-school students (26). Furthermore, increases in criminal behavior can burden first responders, such as policing agencies and medical facilities. The main role of police is to control and minimize crime, thus increasing crime rate puts a greater burden on police officers. In addition to violence and crime, violence and injury are associated with increased emergency room visits and hospital admissions. Many studies have examined the violence-injury-hospitalizations associations(27)(28)(29), and increased hospital visits affects both healthcare systems and healthcare facilities.

The effects of temperature on violent behavior and crime

In studying the causes of crime, individual and sociodemographic factors are documented as risk factors for criminal behavior(30), yet little work has been done on the associations between physical environment and crime. Current studies indicate that adverse childhood experiences have been associated with adult criminality(31)(32) and recommend early interventions for children who suffered adverse events. Those studies generally focus on long-term effects in which exposures to risk factors in childhood lead to criminal behavior in adults. However, these long-term effects do not explain short-term fluctuations in crime, such as the effects of daily and hourly changes in environmental conditions on crime(33). Environmental factors, including air pollution, humidity and temperatures, affect various types of criminal behavior, and different climate regions suffer different from the influence of weather on crime(34)(35). Take temperature as an example. A current study shows that hot days with maximum temperatures above 29.4 °C lead to an increase of general crime of 2.2% and violent crime of 5.7% crime risk related to heat is higher in low-income neighborhoods than in high-income neighborhoods(34).

The association between ambient temperature and crime has been explored in psychological and epidemiological literature. Anderson described five temperature-aggression models to explain the temperature-crime relationships(36). The Negative Affect Escape model points out that at extremely hot temperature (and at extremely low temperature), if avoiding heat is possible, the prediction of aggression decreases, and the effect of temperature has inverse-U shape at both hot and cold effects. The Simple Negative Affect and Cognitive Neoassociation models predict a U-shaped function across the normal range of temperatures. The latter concludes that uncomfortable temperatures should prime aggressive thoughts regardless of the presence of aggressive cues in the situation. The Excitation Transfer theory assumes hot temperature may not be the main factor to cause aggression; the aggression most likely occurs in conditions in which temperature is a background factor. The fifth model is the Physiological-thermoregulatory model that explains the relation between temperature and aggression by neural and hormonal systems. The link between temperatures and violence may be explained by increasing adrenaline because adrenaline is associated with extreme heat. The effects of adrenaline include vasodilatation, increasing the rate of heartbeat, raising blood pressure, and stimulating respiration(37). The same effects are also occur when the human body and brain need to mobilize for action and possible aggression, during stressful or dangerous situation(37). The Routine Activities theory postulates that warmer weather motivates people go to public areas, increasing social interaction(38)(39). The amount of social interactions is highest in petty crimes, moderate in more serious crimes, and almost negligible in murder and rape(38). In contrast, Social Escape and Avoidance theory indicates that violence is not a linear function of temperature in which on hot days, people will interact less, decreasing violent crime(40). Each of these hypotheses suggests that short-term exposure to temperature may influence criminal behavior.

The positive temperature-crime associations have been documented in epidemiological research. A study in Finland showed that a 2 °C increase in average temperature would increase violent crime rates by more than 3%(41). Research across 436 US. Counties estimated that each 10°C increase in daily temperature was associated with an 11.92% increase in the risk of violent crime. Property crime risk was similar but lower in magnitude (42). Similarly, a study in China (Tangshan) found strong, positive correlations between temperature and both violent and property crimes(43). This study also estimated an increase in crime rate under the highest emission scenario using an ensemble of Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate change simulations. There are two studies in South Africa that reported the effects of temperature on crime; one focused on homicide and indicated that a one-degree Celsius increase in same-day temperature was associated with 1.5% (1.3-1.8%) increase in homicides(44). The other found that a 50% increase in violent crime on hot days compared to very cold days(45). By contrast, Cohn EG, who conducted a study in Philadelphia, Pennsylvania in the US,, found that the highest crime rates were observed when temperatures were a mean daily heat index of 22.6- 28°C(46), but then reduced at higher temperatures. These studies indicate the ambient temperature is linked with crime rates, but different regions may show different relationships.

No previous studies have assessed the impact of heatwaves on criminal behavior. Other studies support an inverted-U shaped association between temperature and crime, especially focusing on high temperature. The Social Escape or Avoidance Theory suggests that people will try to avoid extreme conditions in which, on very hot days, people will interact less, decreasing violent crime(47). Moreover, the Negative Affect Escape Theory proposes that at above a certain temperature, the associations between temperature and aggressive behavior are negative because the motivation to escape outweighs the motivation to be aggressive(48). Two current studies reported an increase in crime risk until around 25 - 26 °C; then, risk begins to decrease in an inverted U-shape response at high temperatures (49)(50). While the current literature supports an association between an increase in temperature and crime, the heat-crime association needs further investigation.

The effects of temperature on injury

Injuries are the leading causes of the global burden of disease and national burden on economies because they increase morbidity, mortality, and reductions in worker productivity. First, injuries take the lives of 4.4 million people around the world each year and constitute nearly 8% of all deaths(22). Among people aged 10-24 and aged 24-49, road injuries ranked first over five causes of disability-adjusted life-years (DALYs) and were in the top ten in the 50-74-year age group (24). In 2019, non-communicable disease and injury years lived with disability (YLDs) take into account more than half of all of the disease burden in 11 countries which in LMICs(24). Moreover, injuries also put national economies at risk by increasing the cost for medical care, life-and-work loss and interventions. In the U.S.A, the Centers for Disease Control and Prevention (CDC) reported that the economic cost of injury in the US was $4.2 trillion, including US $327 billion for medical care, US $69 billion in work loss, and US $3.8 trillion in the value of statistical life and quality of life losses in 2019(51). The study also reported that the highest economic cost was among working-aged adults aged 24-44 and 45-64 years. The average total medical care costs paid out-of-pocket by patients during hospitalization due to injuries were US $270, which is higher than average one-month salary for Vietnamese people (US $180);the total costs were higher for more severe injuries and complex surgeries(52).

In addition to individual risk factors of injury, weather conditions play an important role in contributing to the burden of injury. Long-term exposure to particulate matter ($PM_{2.5}$) is associated with fall-related injury in six LMICs with each 10 $\mu g/m^3$ increase corresponded to 18% increase in fall-related injury(53). Others studies have evaluated an increase in the risk of road traffic fatalities during rainy days, which make driving conditions more dangerous(54)(55)(56). The risk of fall-related injuries for days up to a week is higher after a snowfall than days with no snowfall(57).

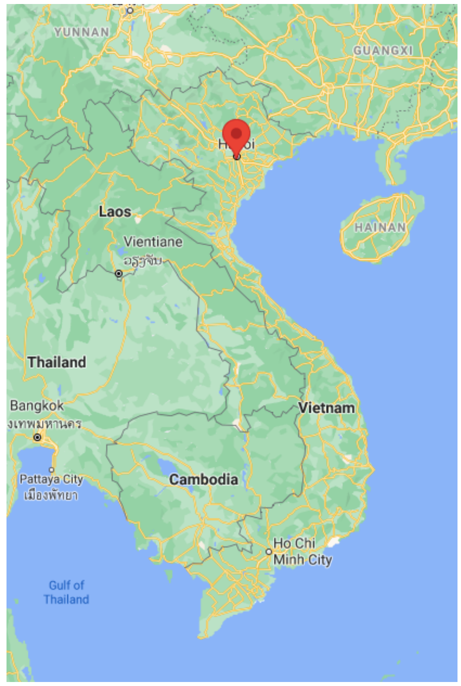
Epidemiological studies have shown evidence supporting positive temperature-injury associations. The existing systematic reviews strongly support that increased temperature is positively correlated with trauma admissions(58). Exposure to heat can increase the risk of accidents, such as drowning and work-related accidents, which are cause of injury(59) . A study in Seoul, South Korea indicated that unintentional injuries increase at both high and low temperatures, and intentional injuries significantly increased only at high temperature. Hot days are also associated with all-cause injury-, vehicle accident-, accidental fall-, and heat-related hospital visits in New Hampshire, U.S(60). High temperatures also increased 11% risk of fall-related injuries in a single-study in China(61). A narrative systematic review showed that hot weather can increase the risk of injuries with each 1°C increase in ambient temperature related to 0.4% to 5.3% increase in injury risk among 11 out of 13 studies. Two of three studies on occupational accidents found an increase in work-related accidents during high temperatures(62).

The biological mechanism of temperature on injury is not entirely understood, but it has been hypothesized that exposure to high temperature may lead to dysfunctional human thermoregulatory mechanisms which is responsible for maintaining a steady internal body temperature of about 37 °C (98.6 °F)(63). The direct effect of temperature on human health is by compromising the body's ability to regulate its internal temperature. Loss of internal temperature control can result in various temperature-related death and illness, including injury, heatstroke, heat exhaustion, and hyperthermia(64). The most vulnerable groups for hot temperature are elderly, children, pregnant women, and outdoor workers(59). While during exposure to high temperature, most people can adapt biologically and physically to incremental increases in average normal temperature, vulnerable groups (children, pregnant women, and elderly) are more susceptible to adverse effects because they are less able to regulate their body temperature. For outdoor workers, high metabolic heat production associated with occupational tasks combined with high ambient and radiant heat, low air flow, and sometimes high humidity, add to human heat strain(7).

Vietnam, classified as a LMIC country, has suffered an increase in the burden of injury. The incidence of injury increased significantly with an increase in the aged-standardized rate of all injuries by 14.6% (11.5%-18.2%) from 2007 to 2017(65). The five leading causes of injury in both 2007 and 2017 were road injuries, falls, exposure to mechanical forces, interpersonal violence, and other unintentional injuries(65). Road injury took an account of 7th over 10 causes of death for both sexes and ages in 2010, then increased to 5th in 2019; it was ranked the 3rd cause of death for males and the 8th cause of death for children aged under 5, respectively(66).

To the best of our knowledge, no studies have evaluated the effects of temperature on criminal behavior and injury in Vietnam, especially in Hanoi- the capital of Vietnam. Hanoi is undergoing rapid changes, manifested by urbanization, social norms, and social economy. With the effect of urbanization, Hanoi inhabitants have suffered higher effects of climate change than people living in rural areas, and the difference has increased substantially. There are supportive evidence to show the effects of temperature on dengue fever, mental health, respiratory and cardiovascular diseases among different age groups(18)(17)(14)(20). Therefore, our project explores other effects of temperature on criminal behavior and injury in which have never been conducted in Vietnam before. We hope to further the understanding of the effects of temperature change on human health. This study may be applied to other populous cities in Vietnam, such as Ho Chi Minh city, Hai Phong and Da Nang which have similar development trends as Hanoi.

Study area overview



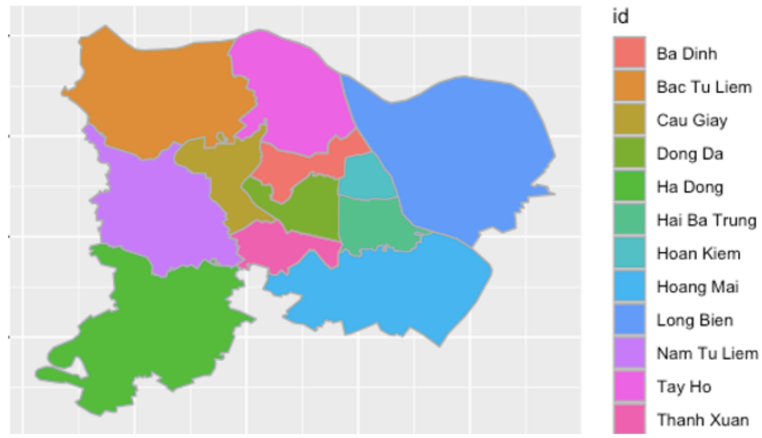
Picture 2: The map of Vietnam

This research will be conducted in urban Hanoi which is the capital of Vietnam. Picture 1 shows a map of Vietnam and where Hanoi is located. Hanoi is situated in the center of the Red River Delta in northern Vietnam and is the second most populous city in the country with a population of 8.05 million people based on 2019 census. Hanoi is divided into 30 districts, including 12 urban districts, 1 districts-leveled town and 17 rural districts. Picture 2 shows the map of urban Hanoi. Within the 12 urban districts, there are a total of 145 wards with nearly half of the total population (3.96 million people). Based on the Annual National Population and Household Report 2019, the population density is estimated as 2,398 people for every square kilometer within the city, compared to the 930 people in the Red River Delta area and 290 in for all of Vietnam. Over 10 years, this growth has continued each year, with an approximate4.4% increase every year in urban areas, compared to that of 0.72% in rural areas. Table 1 shows name and areas of 12 urban districts in Hanoi

Table 1: 12 urban districts in Hanoi

#	District name	Area (km^2)	#	Districtname	Area (km^2)
1	Ba Dinh	9.21	7	Hoang Mai	40.32
2	Hoan Kiem	5.29	8	Thanh Xuan	9.09
3	Tay Ho	24.39	9	Ha Dong	49.64
4	Long Bien	59.82	10	Cau Giay	12.32
5	Dong Da	9.95	11	South Tu Liem	32.19
6	Hai Ba Trung	10.26	12	North Tu Liem	46.32

Hanoi has a sub-tropical climate with four distinct seasons: spring, summer, autumn and winter. Within 10 years, the average annual temperature has increased from 24.9 °C in 2009 to 25.1°C in 2018. Summer is described as the hottest season from May to July, with the mean temperature being around 30 °C. Annual rainfall has risen from 1612mm in 2009 to 1934 mm in 2013 then decreased to 1694 mm in 2018. The heaviest rainfall is from April to September.



Picture 3: Map of urban Hanoi with 12 districts

There are 12 air quality monitors with 11 managed by the Vietnamese government and one managed by the US Embassy in Hanoi. In terms of Vietnamese monitors, three permanent monitors and eight mobile monitors collect daily averages of air pollution in urban Hanoi. The difference between them is that the permanent monitors measure eight air pollutants, including particulate matter (PM_{10} and $PM_{2.5}$), carbon monoxide, sulfur dioxide, nitrogen oxides, nitrogen dioxide, nitrogen monoxide and ozone, and three meteorological variables, including temperature, relative humidity and precipitation. The ambient monitors provide information on four air pollutants (particulate matter, carbon monoxide and nitrogen dioxide) and two meteorological variables (temperature and relative humidity). The US Embassy monitor only measures the daily $PM_{2.5}$. All information of 12 stations is showed in Table 2.

Table 2: Characteristics of 12 air monitors in urban Hanoi

#	Station	PM_1	$PM_{2.5}$	PM_{10}	O_3	NO/ NO_2	SO_2	CO	RH	WS	Tem
1	Nguyen Van Cu (Long Bien)	x	x	x	x	x	x	x	x	x	x
2	US Embassy (Hai Ba Trung)		x								x
3	Hoan Kiem (Hoan Kiem)		x	x		x		x			x
4	Hang Dau (Hoan Kiem)		x	x		x		x	x		x
5	EPD (Dong Da)	x	x	x	x	x	x	x	x	x	x
6	Kim Lien (Dong Da)		x	x		x		x	x		x
7	Minh Khai (Bac Tu Liem)		x	x		x		x	x		x
8	My Dinh (Nam Tu Liem)		x	x		x		x	x		x
9	Pham Van Dong (Cau Giay)		x	x		x		x	x		x
10	Tan Mai (Hoang Mai)		x	x		x		x	x		x
11	Tay Mo (Bac Tu Liem)		x	x		x		x	x		x
12	Thanh Cong (Ba Dinh)		x	x		x		x	x		x

Temp: Temperature; RH: Relative Humidity; WS: Wind Speed; EPD: Environmental Protection Department

Hoan Kiem, South Tu Liem and Dong Da Districts, each have two air quality monitors. Long Bien, Dong Da, North Tu Liem, Cau Giay, Hoang Mai and Ba Dinh Districts, each district has only one monitor. As a result, some districts do not have no monitor (i.e.,Tay Ho, Thanh Xuan, Hai Ba Trung and Ha Dong District).

Chapter 2

Manuscript 1. The effects of daily temperature on crime events in urban Hanoi, Vietnam using seven years of data (2013-2019)

Introduction

Climate change is a significant public health concern, threatening humanity through the perpetuation of adverse environmental consequences, such as increased temperature, extreme weather events, and wildfires(1). Changes observed in Earth's climate since the early 20th century are primarily driven by human activities, particularly fossil fuel burning, which increases heat-trapping greenhouse gas levels in Earth's atmosphere, raising Earth's average surface temperature. Rising global temperature is linked to harmful effects on human health, including communicable diseases, non-communicable diseases, and violence, including criminal behavior.

Whereas a large body of epidemiologic literature describes the relationship of temperature with mortality, mobility, and hospitalization(17)(67), fewer studies have been conducted to assess the relationship between temperature and criminal behavior. Recent evaluations have shown the association between daily temperature and crime events. For example, a study in Finland showed that a 2 °C increase in average temperature would increase violent crime rates by more than 3%(41). Research across 436 U.S. counties estimated that each 10 °C increase in daily temperature was associated with an 11.92% increase in the risk of violent crime. Associations with property crime risk were similar but lower in magnitude (49). A study in one U.S. city (Philadelphia, Pennsylvania) observed the highest crime rates during a mean daily heat index of 22.6- 28 °C(68). These studies indicate that ambient temperature is associated with crime rates, but different regions may show different relationships.

To the best of our knowledge, limited work has evaluated the association between temperature and crime events in tropical or subtropical regions, including Hanoi, Vietnam. Vietnam is a Southeast Asian nation, a region with a high level of exposure risk to climate change-related hazards(69). Moreover, people living in urban tropical areas have suffered from climate change effects at a greater rate than rural populations, and the difference has increased substantially (1). Our investigation examines the potential temperature-crime associations in this understudied region, using seven-years of data from 2013 to 2019 to support our hypothesis that an increase in daily temperature will be associated with the rising daily crime events in urban Hanoi.

Material and methods

We conducted an ecological study to estimate the short-term association between temperature and the risk of criminal behavior in urban Hanoi, Vietnam. We collected data on daily temperatures and crime events from 2013 to 2019. We considered two types of crime, violent and non-violent crime, and three temperature measures, daily minimum temperature, daily mean temperature, and daily maximum temperature.

Crime Count Data

The study outcome was daily reported crime counts. All criminal activities were coded with the Vietnamese Criminal Code (No 100/2015/QH13). We obtained crime data from 1 January 2013 to 31 December 2019 based on daily reports in the PC02 Department, Police Headquarters Hanoi.

The PC02 Department reported six common types of crime representing violent behavior that might physically harm an individual through injury, force, or threat of injury, and three common types of crime representing non-violent behavior that is directed at an individual's property. The six violent crime types included murder/manslaughter, rape, assault, lewd and lascivious behavior with a child under 16, kidnapping, and robbery. Robbery was in the violent crime group because it is defined as "Any person who uses violence, the threat of immediate violence, or commits other acts that render another person unable to resist to obtain his/her property." Three non-violent crimes were: larceny, burglary, and fraud. Other non-violent crimes that are not directed at individuals, such as drug-related and prostitution, were not included in this study because those types of crime were not reported and managed by the PC02 Department.

Each type of daily criminal activity is reported by the local District Police Office and aggregated by Police Headquarters Hanoi using paper reports. The reports include the name of the criminal, age, type of crime, time, date, and location where the crime was committed. For the purposes of this study, only the date, time, location, and type of crime were ascertained. Information on age, sex, personal characteristics, or identifying information were not allowed to be collected for this study in accordance with Vietnamese national security protocols.

A total of 1826 paper reports were collected from 2013 to 2019. The assistance of police department personnel was obtained to enter data from paper reports using an Epidata Software v4.6.0.2 (http://www.epidata.dk/ accessed on 25/12/2021). A 10 percent random sample of the data was checked to ensure the validity of the data entry process; this determined a 99% accuracy rate.

Temperature and potential variables

The Hanoi Environment and Natural Resource Department and Vietnam Environment Administration maintains 11 weather station monitors, including three stationary monitors and eight mobile monitors, that report hourly atmospheric data, including temperature, fine particulate matter ($PM_{2.5}$), and relative humidity (RH).

Estimates of daily environmental measures based on hourly data were calculated in several steps. First, we identified daily minimum, maximum, and mean temperature based on the hourly temperature data of each air monitor. Illogical measurements and outliners were removed. In each air monitor, we removed all days with daily maximum temperatures below daily minimum temperature, while removing all values under 5 °C for daily minimum temperature, over 44 °C for daily maximum temperature, and under 7 °C or over 40 °C for daily mean temperature. These cut points were based on the lowest and highest value of temperature measurements in Hanoi reported in the General Statistics Office of Vietnam (https://www.gso.gov.vn/en/homepage/ accessed on 15/01/2022) and a previous study [13]. Finally, we calculated an average of each daily temperature measurement from the valid daily air monitors. Supplementary Table S1 displays characteristics of daily temperature measurements in each air monitor. A pairwise correlation across the 11 monitors showed strong and positive correlations, ranging from 0.87 to 0.99 (Supplementary Table S2).

This study considered day of the week, holidays, season, year, and additional atmospheric conditions (PM2.5 and R.H.) as time-variant confounders of crime. Holiday was a binary indicator for whether a day was classified as holiday or non-holiday. Holiday included all Vietnamese public holidays, including New Year's Eve, Lunar New Year's Event, Labor Day, Independence Day, and the preceding Friday or following Monday if a holiday fell on a Saturday or Sunday, respectively. (https://www.officeholidays.com/countries/vietnam/2020 accessed on 06/04/2021). Daily PM2.5 (μg/m³) and R.H. (%) represents the average of daily mean measurement of the 11 station monitors.

Statistical analysis for linear effects

We estimated the risks of daily variation in crime counts associated with daily variation in temperature with a quasi-Poisson family for overdispersed data, adjusting for long-term effects of year and seasonal trends (Winter, Spring, Summer, and Autumn). The results were reported as the percent increase in the relative risk (RRI) of a crime occurrence for each 5 °C increase in daily minimum temperature, mean temperature and maximum temperature, separately. The interpretation of the RRI can be considered the percent relative effect and is directly derived from the relative risk. Reporting an RRI allows for a change in risk that may be lower in magnitude, but still statistically significant, to be more easily interpreted. This is calculated as the (Relative Risk −1) × 100.

The primary model (Model 1) was adjusted for day of week and holiday status. Model 2 was adjusted for day of week, holiday status and daily relative humidity. Model 3 was adjusted for day of week, holiday status and daily PM2.5. Model 4 was adjusted for day of week, holiday status, daily relative humidity and daily PM2.5. We estimated the RRI at seven individual lag day models, from 0 to 7 days, to identify the delayed effects of temperature and crime counts. All models were also fit separately for each temperature measurement and crime outcome: violent crime, non-violent crime, and the combination of violent and non-violent crime.

Statistical analysis for non-linear effects

Distributed lag non-linear models (DLNM) were fit to estimate the relative risk of each 1 °C increase in daily temperature and each type of crime. A natural cubic spline with 4 degrees of freedom and 7 lag days for temperature was applied in the DLNM. The modelling framework can describe non-linear relationships both in the day of exposure and lags(70). The models were adjusted for potential time varying confounders of crime, including the day of week and holiday status. Season and year were used to control for seasonal and long-term trends. The results were interpreted as the effect of the exposure versus a reference and reported as both distributed lag effect and individual lag days (71). The choice of the centering value depends on the interpretational issues and does not affect the fit of the model (72). The curve was centered at 12 °C, which represent the 1st percentile of daily mean temperature for the entire 7 years.

Analyses were performed using R Software analysis, version 4.0.5, R Foundation for Statistical Computing (Vienna, Austria).

Sensitivity analysis

We evaluated the sensitivity of the models to different elements: 1) estimating the linear effects of temperature and crime using separated models stratified by holiday status (holiday and non-holiday) and weekend status (weekend and weekday), 2) applying times series analysis adjusted for a time component to control for seasonal and long-terms trends using natural cubic spline with 3, 5, 7 and 9 degrees of freedom per year for linear effects.

Results

We identified 3884 total crimes, including 1083 violent crimes and 2801 non-violent crimes across 2556 data days from 1 January 2013 through 31 December 2019. Crime incidence changed seasonally with more crime occurring in Spring (January through April; Supplement Figure S1). Supplement Figure S2 shows the violent and non-violent crime counts per year with the highest observed crime counts in 2014 and a decreasing trend in subsequent years.

Mean daily minimum, mean, and maximum temperatures were 22.8 °C, 25.8 °C and 30.1 °C respectively (Table 3). On average, there were 1.52 crime occurrences per day with 0.43 daily violent crimes and 1.10 daily non-violent crimes. The average monthly crime counts fluctuated, with the highest counts observed in April, May, and September (Supplement Figure S1). Those months also had highest number of public holidays in Vietnam. Supplement Table S2 shows a strong observed correlation between three types of daily temperature measures. Negative correlations were observed between temperature measures and relative humidity and $PM_{2.5}$ (Table S3). The highest daily mean temperature was observed in June and July, and the lowest daily mean temperature was in January (Figure S3). The standard deviations of daily mean temperature in winter (November to January) were greater than in summer (May to July). Supplement Figure S4 shows the distribution of daily crime counts by type and the presence of several days without any crime events.

Table 3: Daily weather conditions and crime occurrence by type in urban Hanoi, Vietnam, 2013-2019

25th and 75th refer to the 25th and 75th percentile values daily weather conditions and crime occurrence by types.

	Minimum	25th	Median	75th	Maximum	Mean	SD
Minimum temperature (°C)	5.8	19.5	24.1	26.5	33.3	22.8	4.9
Mean temperature (°C)	6.9	21.7	26.9	30.2	38.5	25.8	5.6
Maximum temperature (°C)	8.2	25.3	31.3	35.5	42.6	30.1	6.7
Relative humidity (%)	30.2	66.5	74.3	82.5	99.9	73.9	12.5
$PM_{2.5}$ (μg/m³)	0.33	28.3	37.6	52.8	197.1	44.7	26.8
Violent crime	0	0	0	1	5	0.43	0.68
Non-violent crime	0	0	1	2	8	1.10	1.22
All types of crime	0	0	1.5	2	11	1.52	1.42

The estimated RRI showed revealed that each 5 °C increase in daily minimum, mean and maximum temperature and violent crime, non-violent crime, and all types of crime counts were positively associated in the city of Hanoi (Table 4). The association between all temperature measures and non-violent crime and all crime types were similar across adjusted and unadjusted models, with the strongest association for violent crime. The crime risks were consistently higher for mean temperature compared to risks from minimum and maximum temperature. Additionally, models employing daily mean temperature gave the lowest AIC values among those predicted models, so mean temperature will only be reported (Supplement Table S4).

Table 4: Crude and adjusted models of estimated relative risk increase for violent and non-violent crime for each 5 °C increase in daily mean, maximum and minimum temperature on the day of exposure in urban Hanoi, Vietnam, 2013-2019. An asterix denotes statistically significant estimates ($p<0.05$).

	Model 0** RRI (95%CI)	Model 1⁺ RRI (95%CI)	Model 2± RRI (95%CI)	Model 3¶ RRI (95%CI)	Model 4§ RRI (95%CI)
Missing data (%)	32 (1.2%)	32 (1.2%)	281 (10.1%)	309 (12.1%)	544 (21.3%)
Violent Crime					
Minimum	7.8 (-2.5; 19.1)	7.1 (-3.9; 18.3)	4.0 (-7.7; 15.5)	9.9 (-1.3; 22.5)	7.7 (-4.0; 20.9)
Mean	10.4 * (0.7; 21.1)	9.9 * (0.2; 20.5)	7.9 (-2; 18.9)	11.7 * (1.2; 23.2)	10.2 (-0.8; 22.5)
Maximum	8.1 * (0.6; 16.2)	7.9 * (0.4; 15.9)	6.2 (-2.2; 14.8)	8.9 * (0.9; 17.5)	7.2 (-1.4; 16.6)
Non-violent Crime					
Minimum	5.9 (-0.1; 13.1)	5.6 (-1.0; 12.7)	6.3 (-0.1; 14.1)	7.0 (-0.4; 14.9)	8.4 * (0.3; 17.2)
Mean	7.08 * (0.7; 13.7)	6.8 * (0.6; 13.5)	7.7 * (1.0; 15.0)	8.1 * (1.3; 15.4)	10.0 * (2.5; 18.2)
Maximum	5.05* (0.2; 10.1)	5.0* (0.2; 10.1)	5.9* (0.6; 11.6)	5.6* (0.4; 11.1)	7.4* (1.5; 13.6)
All Crime types					
Minimum	6.3 * (0.6; 12.2)	5.9 * (0.3; 11.8)	5.6 (-0.1; 12.0)	7.6 * (1.4; 14.2)	8.2 * (1.4; 15.4)
Mean	7.8 * (2.5; 13.3)	7.5 * (2.3; 13.2)	7.8 * (2.1; 13.7)	8.9 * (3.2; 15.0)	10.1 * (3.7; 16.8)
Maximum	5.8 * (1.7; 10.1)	5.7 * (1.7; 10.0)	6.0 * (1.5; 10.7)	6.5 * (2.0; 11.0)	7.3 * (2.4; 12.5)

** Crude Model: temperature + season+ year;
+Model 1: Base + public holiday + day of week;
±Model 2: Model 1 + Relative humidity
¶Model 3: Model 1+ $PM_{2.5}$;
§ Model 4: Model 1 + Relative humidity + $PM_{2.5}$.

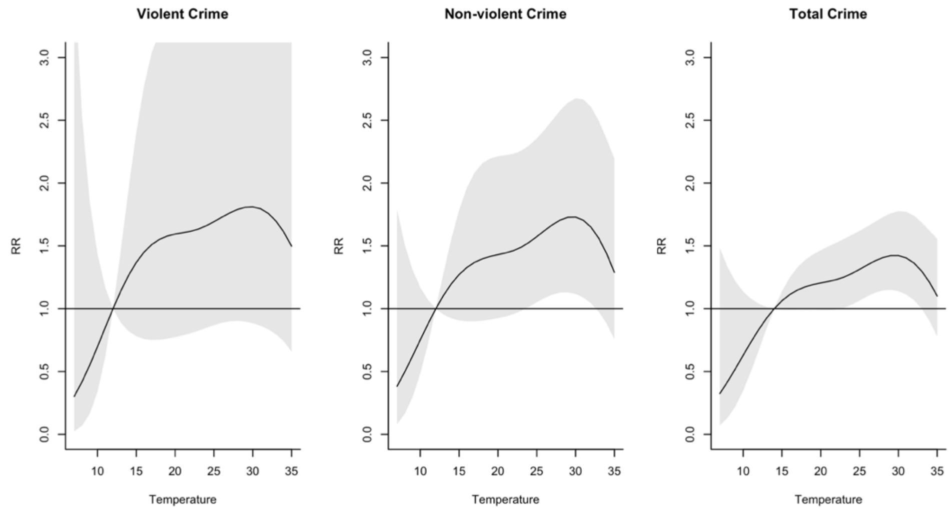
The observed association between daily mean temperature and crime was greatest on the day the crime was committed, with highest risk in violent crime (RRI= 9.9, 95%CI = 0.2; 20.5), followed by all crime types (RRI= 7.5, 95%PI = 2.3; 13.2) and non-violent crime (RRI = 6.8, 95%CI =0.6; 13.5) (Table 5). The crime-temperature associations decreased with each daily lag, and null effects were observed after lag 0 for non-violent and violent crime, but lag 3 for total crimes (Table 5).

Table 5: Estimated percent change in the risk of committing crime for each 5 °C increase in daily mean temperature by lag and crime type with 95%CI in urban Hanoi, Vietnam, 2013-2019. Bold denotes statistically significant estimates.

Lag day	***Violent crime***		***Non-violent crime***		***Total***	
	RRI **	95%CI	RRI*	95%CI	RRI*	95%CI
Lag 0	9.9 *	0.2; 20.5	6.8*	0.6; 13.5	7.5 *	2.3; 13.2
Lag 1	5.6	-3.6; 15.6	5.8	-0.4; 12.3	5.7 *	0.5; 11.1
Lag 2	4.7	-4.4; 14.6	5.6	-0.5; 12.1	5.3 *	0.2; 10.7
Lag 3	4.4	-4.4; 14.3	4.4	-1.7; 10.8	4.3	-0.8; 9.6
Lag 4	2.1	-6.6; 11.7	3.3	-2.7; 9.6	2.9	-2.1; 8.1
Lag 5	1.4	-7.2; 10.9	4.2	-1.8; 10.5	3.3	-1.6; 8.6
Lag 6	0.5	-9.1; 9.8	2.1	-3.8; 8.3	1.6	-3.2; 6.7
Lag 7	0.1	-8.4; 9.3	2.9	-3.0; 9.1	2.0	-2.8; 7.2

*$p < 0.05$
**Model: temperature + season+ + public holiday + year

In our non-linear distributed lag model, we observed an increase in the risk of violent crime, non-violent crime, and total crime with increased daily mean temperature until around 30 °C, at which point the risk begins to decline in an inverted U-shape response (Figure 1). At a daily mean temperature of 30 °C, the risk of violent crime (RR= 1.8, 95%CI= 0.9, 3.6) was similar to that for non-violent crime (RR= 1.7, 95%CI = 1.1, 3.6). Confidence intervals reveal a wide range of uncertainty in the non-linear estimates.



Model: temperature + season+ public holiday + year
Referent temperature = 12 °C

Figure 1: Overall exposure-response associations between daily mean temperature and violent crime (left), non-violent crime (middle), and total crime (right) in urban Hanoi, Vietnam, 2013-2019. The models represent distributed lag curves and shaded areas denote 95% confidence intervals.

Figure 2 demonstrates that the individual lag curves for 20 °C, 30 °C, and 35 °C presented the greatest crime risks on the first day of exposure, then the risks decreased on the following days (lag 1 to lag 7), with the reference was at 12 °C. The increased risk of violent crime was greater in magnitude compared to non-violent crime. The relative risk for violent crime was lowest at 20 °C and highest at 30 °C but decreased at 35 °C. The relative risk for non-violent crime was similar in magnitude at the three different temperatures.

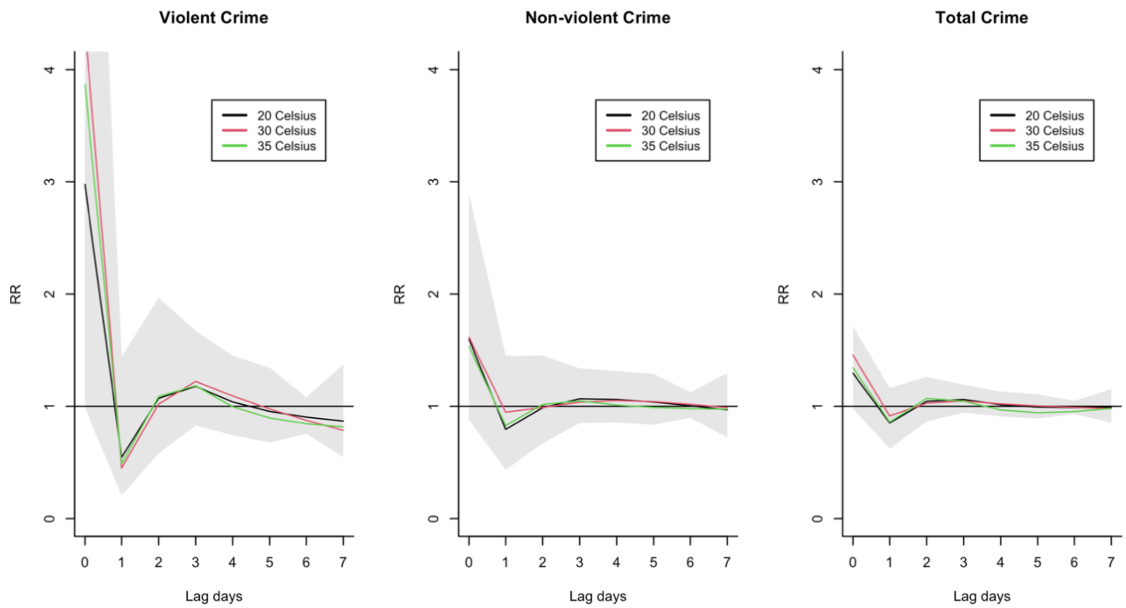


Figure 2: Individual lag-response curves for different temperatures (at 20 °C, 30 °C and 35 °C), reference 12 °C in urban Hanoi, Vietnam, 2013-2019. The models represent individual lag curves (from 0 to 7 days) and shaded areas denote 95% confidence intervals

Supplement Figures S5, S6, and S7 show the individual lag-response curves for violent crime, non-violent crime, and total crime, respectively. The figures confirm the change in mean daily temperature increased the risk of crime on the first day of exposure, and particularly for violent crime.

Crime counts in Hanoi were characterized by relatively few events per day without a sharp seasonal pattern observed. We tested the sensitivity of our model to two temporal smoothers: the year and season variable and a natural cubic spline model for time (Table S5, S6, and S7). It was observed that the spline model resulted in poor models fit with high sensitivity towards degrees of freedom and attenuated effect estimates. Therefore, the season-year metric was identified as a preferred temporal smoother.

Discussion

In this study we observed an association between a short-term increase in daily temperature and an increased risk of violent and non-violent crime in Hanoi, Vietnam. The greatest effect was observed on the day of exposure and the association between crime and mean temperature was non-linear, with increased risk up to 30 °C and then decreasing at higher temperatures, which supports previous research in other populations(49). Our results were robust to metrics of maximum, mean, and minimum daily temperatures with similar associations. To our knowledge, this is the first study to investigate an association between daily temperature and crime risk in Vietnam.

Urban Hanoi offers a unique population to explore temperature-crime associations. Hanoi is in northern Vietnam which has a sub-tropical climate with four seasons per year. This differs from cities in the southern regions of Vietnam, such as Ho Chi Minh city, where two seasons are characterized as dry or rainy. Therefore, the temperature-crime associations in Hanoi may differ from Ho Chi Minh city, as well as cities in the Americas, Africa, and Europe. Hanoi is the second-largest city in Vietnam and has experienced rapid growth through urbanization in the last two decades. Hanoi's urban structure and boundary were expanded in 2008 and policies have strongly promoted population density and social development(73). Hanoi has also been affected by climate change with increasing temperatures that are amplified by the urban heat island effect(74). Moreover, in contrast to other urban areas where studies of temperature and crime have been conducted, our data indicate that Hanoi has much lower crime rates than urban areas in other parts of the world with an average of crime counts per day of 1.52 compared to 39.7 in South Africa or 135 in Baltimore, Maryland(44)(75), although this may be partially attributable to differences in policing and crime reporting.

In the context of climate change, there is an increased interest in whether the rising temperatures could affect criminal behavior (49)(44)(75)(76). One study reported a significant and inverted U-shaped association between daily temperature and crime risk across 436 U.S. counties for the multiple cities level. Each 10 °C increase in daily temperature was associated with increasing the risk of violent crime and non-violent crime(49). Another study, focused on intentional crime, showed linear effects with each 5 °C in daily mean temperature was 9.5% increase in crime risk(76). A study conducted in South Africa indicated a one-degree Celsius increase in daily maximum temperature was associated with a 1.5% increase in crime risk(44). Our finding shows a similar trend and magnitude, but with a reduced precision that is a likely product of reduced crime events from our single low-crime city study. Other single city studies have also identified positive relationships between temperature and criminal behavior(68)(77)(78). For example, a study in Baltimore, Maryland, reported an association between daily maximum temperature and increased total and violent crime (77), but did not examine daily mean or minimum temperature.

A limitation of single city analyses is that they cannot be generalized to larger geographic regions due to different social, demographic and climate factors. Our study was conducted in Hanoi, located in the north of Vietnam, so it may not be generalizable to elsewhere in the country. However, the results from a single-city study can raise the public's awareness of climate change at local level.

This study contributed evidence of a potential linear and non-linear temperature-crime association. For linear effects, we observed an increase in crime risk for each 5 °C increase in temperature which are in line with other single city studies in South Africa and Maryland. The non-linear effect of daily mean temperature showed an inverted U-shaped response with a downward deflection at a very high temperature, which has been described in psychological theories on temperature and aggression(79), and supported in previous observational studies (49)(76). This finding may have implication of potential effects of future heatwave events on criminal behavior which requires further investigation.

We used three temperature measures to estimate temperature-crime associations. Daily minimum, mean and maximum temperature show similar associations and trends, but the precision varied across five models when adjusted for various confounding factors. Several studies have used one or two temperature measurements to examine the effects of temperature on crime, such as minimum and maximum daily temperature or only mean daily temperature(77)(80)(34). Different temperature exposures can highlight the exposure at different times of day (e.g., maximum temperature is indicative of daytime temperatures, while minimum temperature is indicative of early morning temperatures), which may be important for our behavior related outcome. Our study found that minimum, maximum, and mean temperatures had similar predictive ability because of their strong correlation.

We primarily used the mean temperature as a metric as it was the more statistically efficient model based on the AIC, but critically demonstrates that all temperature conditions can be useful for evaluating criminal behavior.

Several limitations need to be acknowledged in this study. First, individual-level information about people who commit crimes was not obtainable due to policy use restrictions on the available data. Thus, we are not able to examine differences in risk by age, gender, or other factors. However, our study investigated the risks in a single population where the underlying distribution of demographic factors is unlikely to change across short time durations, so these factors would be unlikely to confound the population-level results. Second, the original data reported to the Hanoi Police Department are recorded on a paper report, which was then abstracted to an electronic record. This process poses the risk of errors during data entry process, but we believe these were minimized by the data entry verification processes established in the abstraction process. Third, many crimes are underreported for various reasons, so the absolute burden of crime is not known. The extent to which this underreporting is related to temperature is unknown and there may be some selection bias that could not be accounted for in our analyses. Fourth, this study was limited to seven years, which, in concert with the relatively low rate of crime in Hanoi, resulted in a small number of crime events compared to other studies, thus limiting the precision of our estimates. The small number of event limited our ability to adjust for time variable because under or over smoothed estimations may occur based on choosing number of degrees of freedom per year(81)(82). Additionally, there are a number of climate factors that have been found to correlate with crime, such as ozone, wind speed, and precipitation[23], which were not available for this study. Finally, it should be emphasized that our study explored only a single-city and our findings may not be generalizable to other cities in Vietnam or south-east Asia.

Conclusions

The observed association between temperature and crime may be of particular concern in the context of climate change, especially in low-and-middle-income countries. To the best of our knowledge, this study is the first study in Vietnam to examine the relationship between short-term temperatures and criminal behavior. Our findings from both linear and non-linear models support the hypothesis that temperature influences criminal behavior. We expect that our results may be valuable for local police planning and social services in urban Hanoi, Vietnam. Our results indicate that additional investigation that would include other regions of Vietnam is warranted.

Supplementary tables and figures

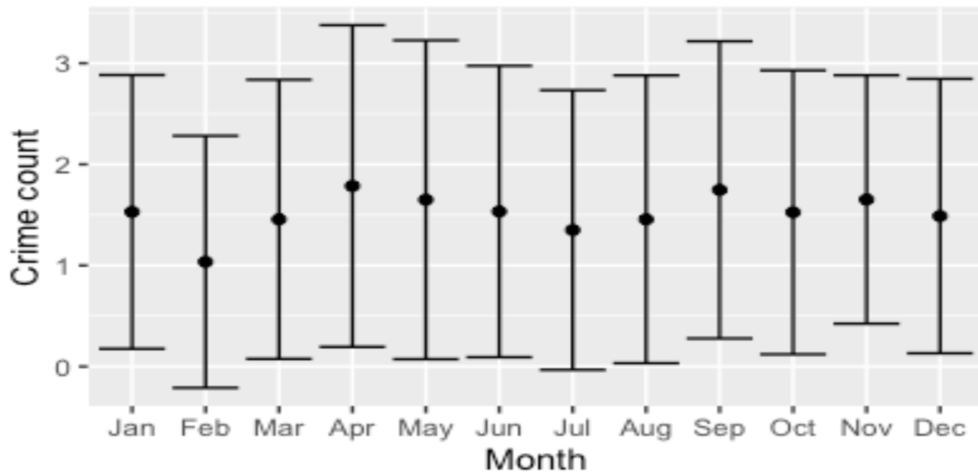


Figure 3 (Supplement Figure S1): Monthly mean and standard deviations of crime count in urban Hanoi, 2013 – 2019

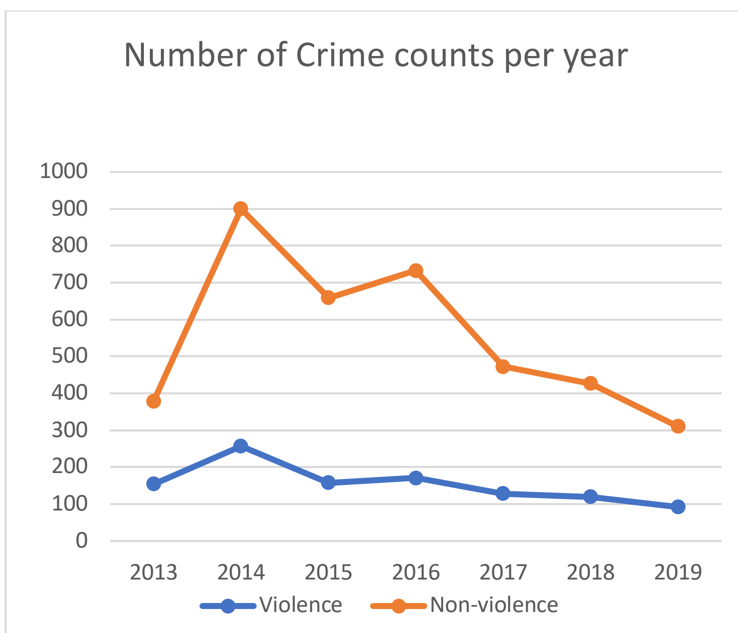


Figure 4 (Supplement Figure S2*):* Yearly crime counts in urban Hanoi, Vietnam, from 2013-2019

Table 6 (Supplement Table S1): Daily temperature (degree celcius) in 11 air monitors in urban Hanoi, Vietnam

Districts	**Mean**	**SD**	**Min**	**Median**	**Max**
Long Bien	25.05	5.44	6.97	26.13	37.31
Minh Khai	25.00	5.18	6.7	26.04	36.51
Trung Yen	25.18	5.19	7.99	26.22	35.67
Hoan Kiem	27.54	5.61	10.27	28.59	39.84
Kim Lien	27.70	5.69	10.35	28.77	40
My Dinh	28.06	5.76	10.59	29.25	39.85
Pham V Dong	27.85	5.56	10.64	28.92	39.52
Tan Mai	27.77	5.74	8.65	28.91	39.90
Tay Mo	27.56	5.66	7.86	28.62	38.99
Thanh Cong	27.47	5.60	9.08	28.46	39.88
Hang Dau	28.13	5.74	6.93	29.30	39.86

Table 7 (Supplement Table S2): The pair-wise correlation of daily mean temperature between each air monitor in 11 air monitors in urban Hanoi, Vietnam

Long Bien	1										
Minh Khai	0.88	1									
Trung Yen	0.90	0.87	1								
Hang Dau	0.90	0.85	0.89	1							
Hoan Kiem	0.95	0.89	0.90	0.95	1						
Kim Lien	0.88	0.88	0.91	0.96	0.99	1					
My Dinh	0.92	0.83	0.85	0.90	0.93	0.94	1				
Thanh Cong	0.93	0.87	0.89	0.95	0.97	0.98	0.92	1			
Tay Mo	0.93	0.88	0.89	0.95	0.98	0.99	0.93	0.97	1		
Tan Mai	0.93	0.88	0.90	0.95	0.98	0.99	0.93	0.98	0.99	1	
Pham V Dong	0.93	0.88	0.89	0.94	0.97	0.97	0.93	0.96	0.97	0.96	1

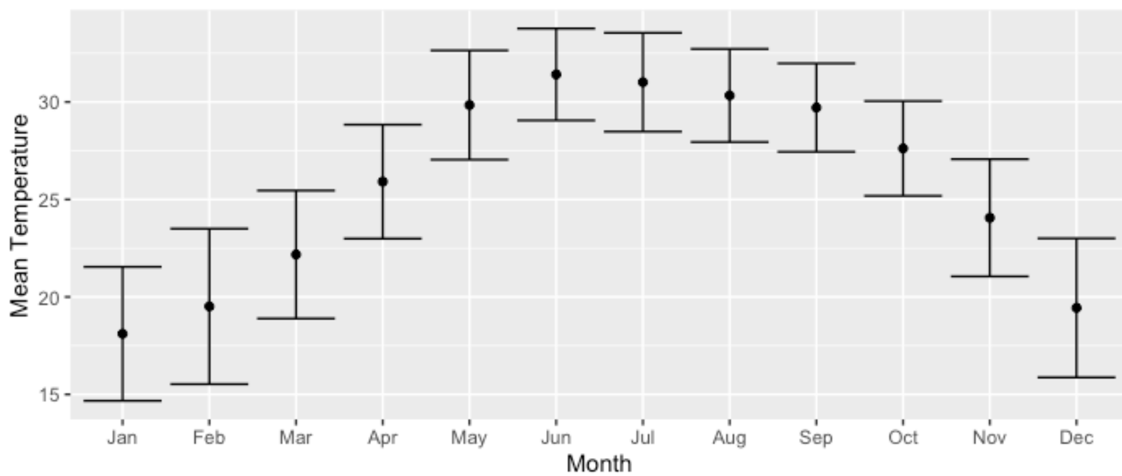


Figure 5 (Supplement Figure S3): Monthly mean and standard deviations of daily mean temperature in Hanoi 2013-2019

Table 8 (Supplement Table S3): Pair-wise daily correlation coefficients between daily minimum, mean and maximum temperatures, daily relative humidity, and daily $PM_{2.5}$ in urban Hanoi, Vietnam, 2013-2019

Minimum temperature	1				
Mean temperature	0.96	1			
Maximum temperature	0.89	0.96	1		
Relative humidity	-0.08	-0.18	-0.27	1	
$PM_{2.5}$	-0.40	-0.36	-0.30	-0.04	1

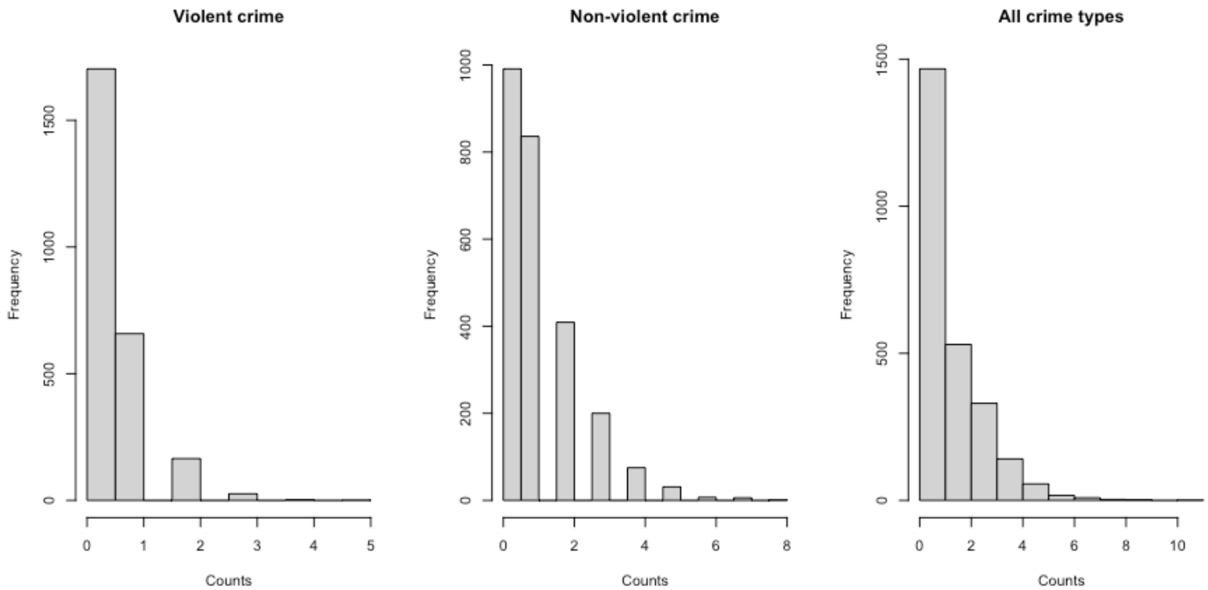


Figure 6 (Supplement Figure S4): Distribution of daily crime counts in violent crime, non-violent crime, and total crime in Hanoi, Vietnam 2013-2019

Table 9 (Supplement Table S4): Akaike information criteria (AIC) values for linear effects models and non-linear effects models between temperature measures and crime

	AIC		
	Violent crime	**Non-violent crime**	**Total**
Linear regression models			
Minimum	4238	6869	7835
Mean	4236	6866	7830
Maximum	4235	6867	7831
Non-linear regression models			
Minimum	4125	6615	7561
Mean	4122	6613	7561
Maximum	4124	6630	7568

Model: Crude + public holiday + year

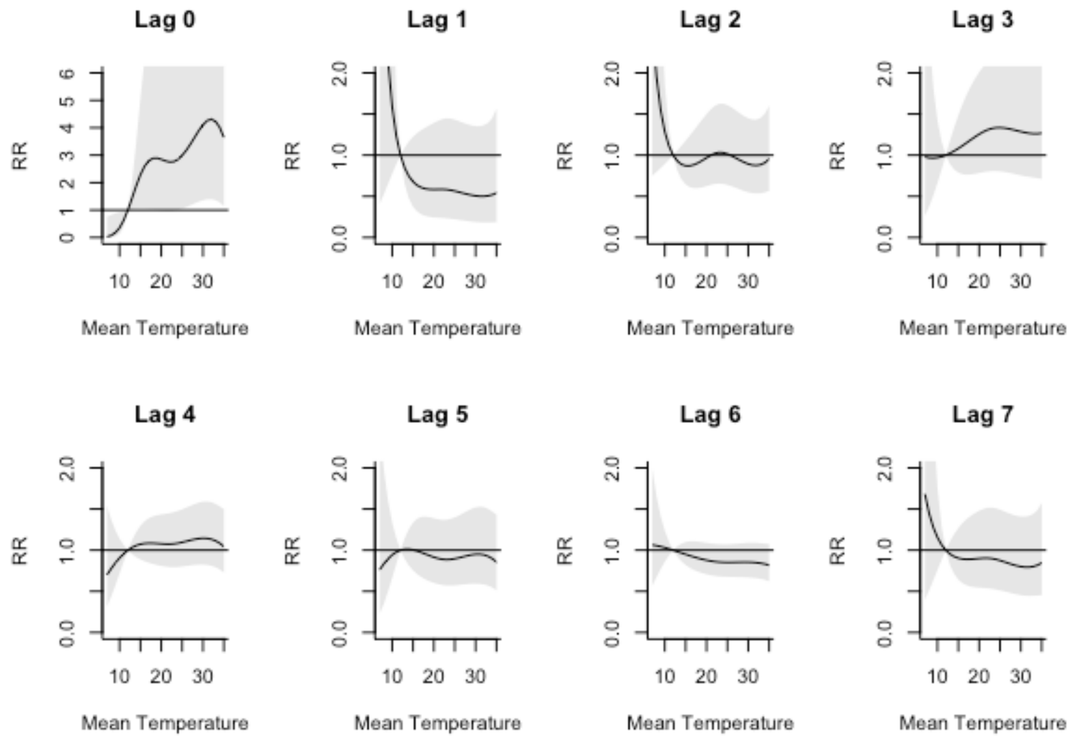


Figure 7 (Supplement Figure S4): Lag-response curve at different lags day for violent crime in urban Hanoi, Vietnam, 2013-2019. Shaded areas denote 95% confidence intervals

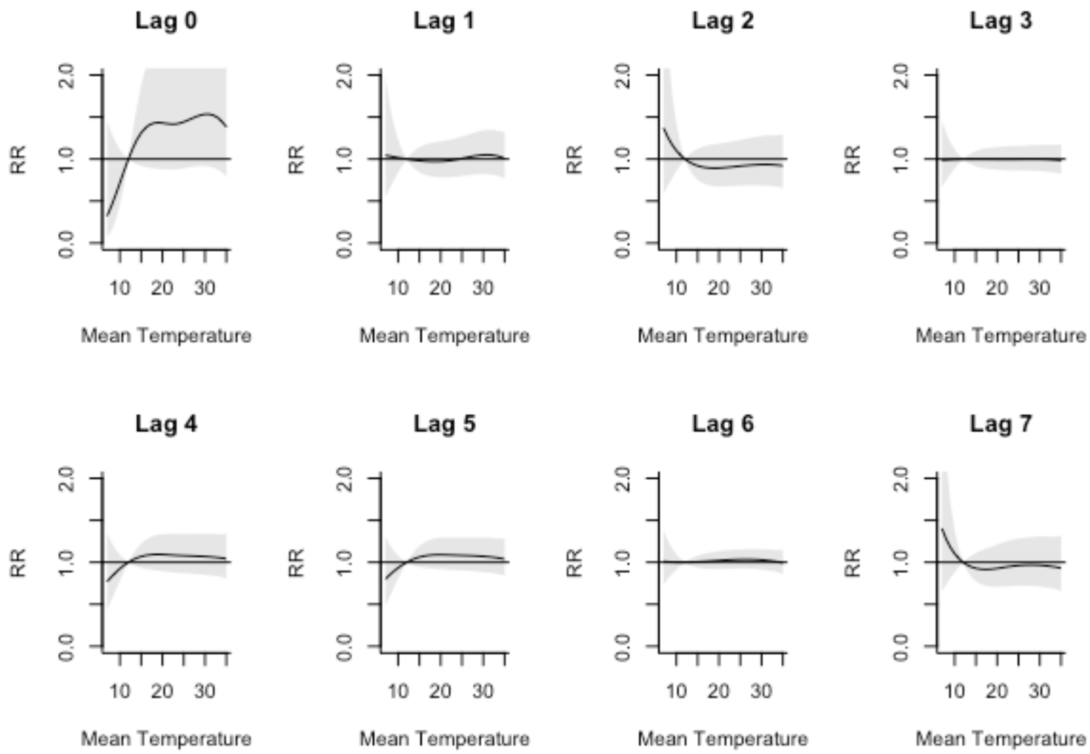


Figure 8 (Supplement Figure S5): Lag-response curve at different lags day for non-violent crime in urban Hanoi, Vietnam, 2013-2019. Shaded areas denote 95% confidence intervals

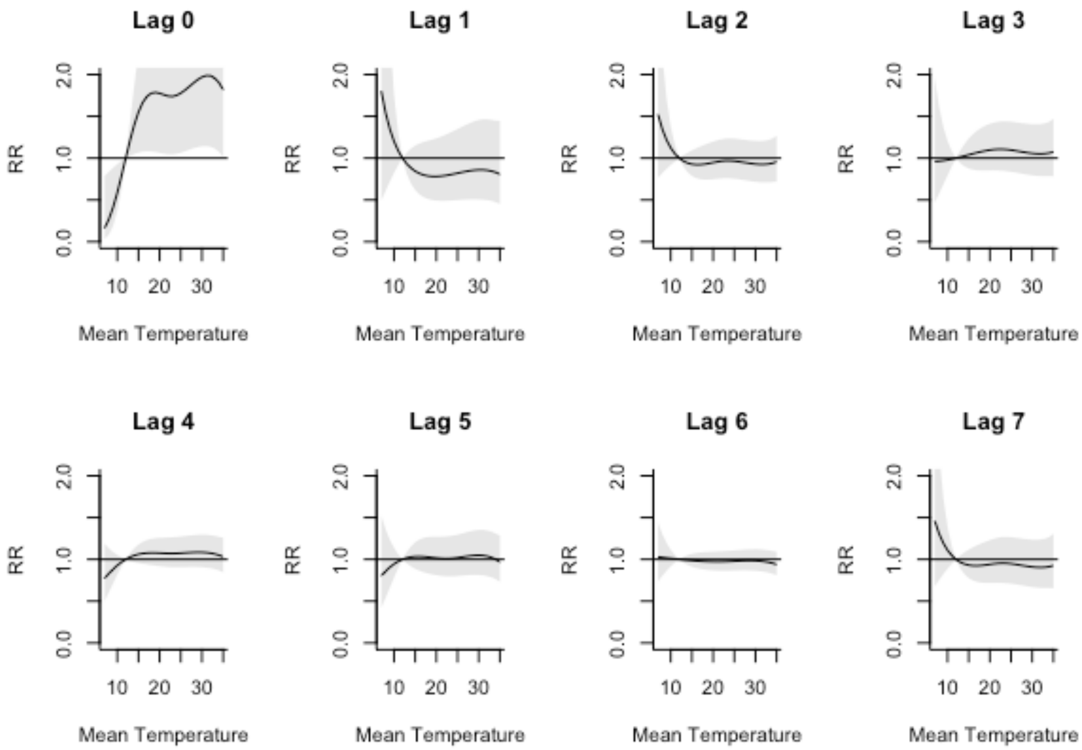


Figure 9 (Supplement Figure S6) : Lag-response curve at different lags day for all types of crime in urban Hanoi Vietnam, 2013-2019. Shaded areas denote 95% confidence intervals

Table 10 (Supplement Table S5): Sensitivity analysis of effect estimates for violent crime, non-violent crime and total crime using time series analysis by different degrees of freedoms for time

Degrees of freedom	**Violent crime**		**Non-violent crime**		**Total**	
	RRI1	95%CI	RRI1	95%CI	RRI1	95%CI
3	7.8	-4.5; 21.7	4.6	-0.2; 18.1	9.1*	2.8; 15.8
5	3.0	-9.7; 17.4	4.3	-1.4; 19.0	7.4*	0.7; 14.5
7	2.5	-10.2; 17.1	4.2	-2.4; 19.2	6.8*	0.1; 14.0
9	4.8	-8.2; 20	4.4	-1.5; 19.5	7.2*	0.5; 14.5

* $p<0.05$

Table 11 (Supplement Table S6): Mean and standard deviation of violent crime, non-violent crime and total crime by holidays and weekends

	Number of days	**Violent crime**		**Non-violent crime**		**Total crime**		**Mean temperature**	
	Total	Mean	SD	Mean	SD	Mean	SD	Mean	SD
All days	2556	0.42	0.68	1.1	1.22	1.52	1.42	25.84	5.56
Non-holidays	2417	0.43	0.68	1.11	NA	1.54	1.42	25.9	5.59
Holidays	137	0.33	0.60	0.85	NA	1.18	1.40	24.0	4.66
Weekdays	1826	0.43	0.68	1.12	NA	1.55	1.44	25.8	5.5
Weekends	730	0.41	0.67	1.04	NA	1.45	1.37	25.9	5.72

Table 12 (Supplement Table S7): Estimated relative risk of violent, non-violent, and total crime for each 5°C increase in daily mean temperature with no lag (lag 0). Estimation from holidays and normal days, and weekends and weekdays

	Violent crime		**Non- Violent crime**		**Total crime**	
	RRI	95%PI	RRI	95%PI	RRI	95%PI
Non-holidays and Holidays						
Non-holiday	8.8	-0.9; 19.5	5.3	-0.9; 11.8	6.1*	0.9; 11.6
Holiday	123.5*	8.2; 361.5	95.9	29.3; 196.7	98.9*	38.2; 186.2
Weekdays and weekends						
Weekdays	10.2	- 1.1; 22.7	7.5*	0.3; 15.3	8.1*	1.9; 14.7
Weekends	7.5	-10.1 – 28.5	5.8	-5.6; 18.7	6.1	-3.4; 16.8

** p<0.05*

Chapter 3

Manuscript 2. Effects of Heatwave events on daily crime in urban Hanoi, Vietnam 2013-2019: A case-crossover study

Introduction

Heatwaves are a natural hazard that are increasing in frequency and intensity and have been shown to have significant public health impacts(85). Exposure to heatwaves compromises the body's ability to regulate temperature. They can result in acute illnesses, such as respiratory diseases, cardiovascular diseases and mental health disorders, which can lead to deaths and hospitalizations(86)(87)(88). In addition, heatwaves can impact disease transmissions, health service delivery, air quality, and critical social infrastructure(85). Heatwave-health associations may differ by country and in different climates. There is no global standard definition for a period of extremely hot weather that represents a heatwave(89). Local and regional heatwaves can be defined, however, based on the intensity and duration of local temperatures(88)(89).

Heatwaves can alter human behavior that has been associated with mental health outcomes and crime (85)(90). Studies from developed and developing countries have reported positive associations between heatwaves and mental health, such as depression, anxiety, substance abuse, and psychotic exacerbation in patients(20)(91)(92). A systematic review found that fifteen of seventeen studies indicate an increased suicide risk with heat and a greater risk of emergency visits for mental health disorders at higher temperatures(93).

The associations between heatwaves and mental health outcomes are documented, but the heatwave-crime associations are unclear. Physiological theories support the hypothesis that exposure to heat can diminish a persons' self-control, which then translates into criminal behavior (94)(95). Studies supporting this association reported that a 10^{o}C increase in mean daily temperature was associated with a 17 percent increase in homicides (44), and a 12 percent increase in violent crimes(49). A multi-cities study found a positive association across nine large U.S. cities but only observed two cities with significantly different associations(96).

By contrast, other studies support an inverted-U shaped association between temperature and crime, especially focusing on high temperatures. First, the Social Escape or Avoidance Theory suggests that people will try to avoid extreme conditions in which, on very hot days, people will interact less, decreasing violent crime(47). Moreover, the Negative Affect Escape Theory proposes that above a certain temperature, the associations between temperature and aggressive behavior are negative because the motivation to escape outweighs the motivation to be aggressive(48). Two current studies reported an increase in crime risk until around 25 - 26 °C; then, risk begins to decrease at high temperatures, resulting in an inverted U-shape response(49)(50). While the current literature supports an association between an increase in temperature and crime, the heat-crime association needs further investigation.

To the best of our knowledge, no research has evaluated heatwaves and crime events in Vietnam or other countries in Southeast Asia. The potential associations in Hanoi, Vietnam may differ from regions with different climates (temperate climate versus tropical climate) and social contexts (developed countries versus developing countries). Additionally, with the effect of climate change, Hanoi inhabitants are experiencing more heat events than before(1), which heightens the importance of understanding potential relationships between heat waves and adverse health and social outcomes such as violent and non-violent crime. We report the short-term association between heat waves and both violent and non-violent crime events in urban Hanoi from 2013 to 2019.

Methods

Atmospheric conditions data and heatwave definition

There are 12 monitors that measures 24-hour atmospheric conditions from 2013 to 2019, managed by the Hanoi Environment and Natural Resource Department. In each monitor, mean value for daily temperature, relative humidity (RH) and particulate matter ($PM_{2.5}$) were estimated as the average of 24-hours values. We removed all the illogical measurements and outliers based on previous reports and research. After that, we assigned values for each day by averaging values of 12 monitors to miniminze potential bias.

There were two steps to create heatwave data. First, we identified heatwave days based on the heatwave definitions. Second, we selected months with heatwave days to the data frame.

There is no global standard definition for heatwaves because heat impacts depend on multiple local social and geographic factors (97). In general, an extremely hot weather event is defined as a multi-day period of higher than average heat with a temperature above 32°C, based on the U.S. Department of Homeland Security. However, in Vietnam, especially in June, the average temperature is around 31.4°C. For this study we used a heatwave definition that combines intensity based on local historical conditions and duration (88). Three heatwave definitions were used for this study: a minimum of two or more days above the daily mean temperature thresholds of the 1) 90^{th}, 2) 95^{th}, and 3) 97.5^{th} percentiles of all days from 2013-2019. This definition has been applied in other heat wave research, including in Vietnam (17)(98). Supplemental Material provides the names and locations of each air monitor in the study area.

We evaluated only the months with a defined heatwave day for final analysis. Heatwave days were observed for five months, from May to September (Supplement Table S2). There was one heat wave day in each month of April and October, but we excluded these anomalous occurrences to reduce potential bias.

Daily crime counts data

Daily crime counts data, including violent and non-violent crime counts, were obtained from daily criminal reports at the PC02 Department, Police Headquarters Hanoi, from May 1 to September 30 within seven years (2013- 2019). Crime data is publicly available upon request. Daily criminal activity in urban districts is first reported by the district level Police Office and then aggregated by Police Headquarters Hanoi. Following a submitted data request, The PC02 Department provided the daily number of offenses by type of offense in the 12 urban districts of Hanoi. Due to privacy and legal restrictions, individual identifying information on the offenders, such as sex, age, and addresses/ locations, was not available. Two police officers entered daily crime count data using Epidata Software v4.6.0.2 ("The Epidata Association" Odense n Denmark), and one police officer checked all data before providing the final version. A 10 percent sample of the data was checked randomly, which confirmed greater than a 98% accuracy rate for the data entry.

The PC02 Department reported nine types of crime, including murder/manslaughter, rape, assault, lewd and lascivious with a child under 16, kidnapping, robbery, larceny, burglary, and fraud, based on the Vietnamese Criminal Code(99). We grouped crime data into two main groups, which were violent behavior and non-violent crimes. The violent crimes because involved force, injury, or the threat of injury. Non-violent crimes, known as property crime, consists of criminal activities without personal interaction or force, including larceny, burglary, and fraud.

Statistical analysis

We examined the heatwave-crime association using a time stratified case-crossover approach with conditional quasi-Poisson models. In the case-crossover design, originally proposed by McClure to estimate risks of non-systematically varying exposures or transient exposures, cases serve as their own controls to eliminate confounding by stable individual characteristics(100). The case-crossover approach has been extended to model case counts in relatively stable populations as an alternative to conventional time series analysis (101) to evaluate the acute association between short-term environmental exposure and the risk of health outcome events from daily time-series data(102). For total crime and each crime group, we estimated relative risk (RR) to evaluate the association between heatwaves and crime risk.

A case-crossover study design takes advantage of dates in the same stratum as a study subject, comparing crime counts within a stratum. For time-stratified case-crossover study, the long-term and seasonal trends were controlled by design using self-matching with the same day of week, month, and year. Matching by the same month and year controlled for potential confounding by seasonal trends in which temperature differs from season to season. Matching by year controlled for potential confounding by long-term trends in which temperatures differ year to year. Matching by day of week controlled for potential confounding that varies within a week, including weekday/weekend differences in rates of crime.

An important part of this study design is a selection of referent time periods, and the time stratified approach is most commonly used to select a reference day because it ensures unbiased regression estimates and avoids bias resulting from time trends (103). We compared crime counts on heatwave days (case days) with crime counts on days within the same day of week, month, and year (reference days). Therefore, each day had 3 to 4 matched reference days.

The data analysis involved two steps. First, we estimated heatwave-crime associations using both crude and adjusted models on total crime and each type of crime. The crude models include only a heatwave variable because day of week, month and year were controlled by design. Adjusted models included heatwaves, $PM_{2.5,}$ and RH variables. Second, we estimated RRs of heatwaves in each threshold with different durations greater and equal to two days, three days, and four days.

To test for the robustness of our association, we explored the following sensitivity tests: 1) an alternate daily maximum temperature measurement to calculate different levels of heat waves, 2) separate individual exclusion of fine particulate matter (PM2.5) and relative humidity under the various heat wave definitions; 3) examining the effects of post-heat on crime using a time stratified case-crossover approach with conditional quasi-Poisson models. We generated post-heat days which are two days after a series of heatwave days; then we run models to estimate ORs of post-heat days to non-heat days and ORs of heat days to non-heat days; 4) examining the combined effects of heat and post-heat on crime in urban Hanoi, Vietnam using the same approach.

Results

There were a total of 1071 data days, from May 1 to September 31, across the seven-year study period. The daily minimum and maximum temperatures of all days were lower than during heatwave days under three heatwave definitions, but the mean daily total crime, violent, and non-violent crime counts of all days were similar across three heatwave definitions.

The number of heatwave days differed based on the exposure definitions, with a total number of heatwave exposure days of 186, 93, and 38 days at the temperature percentile thresholds of 90^{th}, 95^{th}, and 97.5^{th} percentiles, respectively. The mean daily temperature of HW1 (34.0 °C) was lower than that of HW2 (35 °C) and HW3 (36.1 °C). As the HW definitions became more conservative, we observed fewer overall daily crime counts but higher daily mean temperatures (Table 13).

Table 13: Summary characteristics of atmospheric conditions and crime types under heatwave days and all days (from May to September) based on different heatwave definitions in urban Hanoi, Vietnam.

	HW1	**HW2**	**HW3**	**All days**
Number of Heatwave Days	186	93	38	1071
Daily Temperature (°C)				
Mean (SD)	34.0 (1.4)	35.0 (1.3)	36.1(1.1)	30.46 (5.5)
Range	32.0; 38.5	33.0; 38.5	34.5; 38.5	19.07; 38.5
Daily Relative Humidity (%)				
Mean (SD)	60.91 (10.1)	57.1 (10.5)	52.1(11.0)	71.64(12.5)
Range	30.2; 77.1	30.2; 77.1	30.2; 68.5	30.1; 99.9
Daily $PM_{2.5}$ (µg/m³)				
Mean (SD)	31.8 (13.6)	31.6 (10.2)	29.6 (7.1)	33.3(17.1)
Range	12.6; 142.2	15.1; 57.7	17.0; 47.7	0.31; 158.6
Total Crime Events				
Mean (SD)	1.61 (1.5)	1.58 (1.5)	1.57 (1.5)	1.56 (1.5)
Range	0; 11	0; 5	0; 5	0; 11
Violent Crime Events				
Mean (SD)	0.35 (0.6)	0.47 (0.7)	0.47 (0.7)	0.47 (0.7)
Range	0; 5	0; 5	0; 5	0; 5
Non-violent Crime Events				
Mean (SD)	1.12 (1.2)	1.11 (1.2)	1.09 (1.2)	1.10 (1.2)
Range	0; 7	0; 7	0; 7	0; 7

HW1: 90th percentile (32°C), duration >= 2 days
HW2: 95th percentile (33°C), duration >= 2 days
HW3: 97.5th percentile (34.5°C), duration >= 2 days

For our primary model using a heatwave duration of ≥2 days, we observed limited evidence that crime was negatively associated with heatwaves (Table 14). The unadjusted models for HW2 and HW3 showed positive associations between heatwaves and crime, however all adjusted models show the negative heatwave-crime associations. Among adjusted models, for the first heatwave definition (HW1 – 90th percentile daily mean temperature), we observed a statistically significant decreased risk of violent crime associated with heatwave exposure (RR= 0.65, 95%CI= 0.45, 0.93) with decreasing but imprecise associations with non-violent or total crime. For the more restrictive heatwave definitions (HW2 and HW3), there was limited evidence of association observations, although trends did show a decreased crime occurrence during heatwave events. However, the models with more restrictive heatwaves were relatively imprecise as the number of event days became smaller with a more conservative definition. For non-violent crime and total crime types, heatwave-crime trends are overall similar, with a modest decrease in crime risks on heatwave days compared to non-heatwave days in both crude and adjusted models across various heatwave definitions, but these are not beyond the bounds of chance.

For other environmental covariates, we do not find evidence of an association between daily $PM_{2.5}$ and violent, non-violent, and all types of crime. However, each 10% increase in daily relative humidity decreased the risk of crime with a significant difference under HW1 (RR= 0.84, 95%CI= 0.73- 0.97), and other HW definitions show the same trends but non-significant differences.

Table 14: The estimated relative risk of heatwaves and crime using crude and adjusted models in violent crime, non-violent crime, and all crime types. Models were adjusted by daily $PM_{2.5}$, and daily relative humidity, in urban Hanoi, Vietnam.

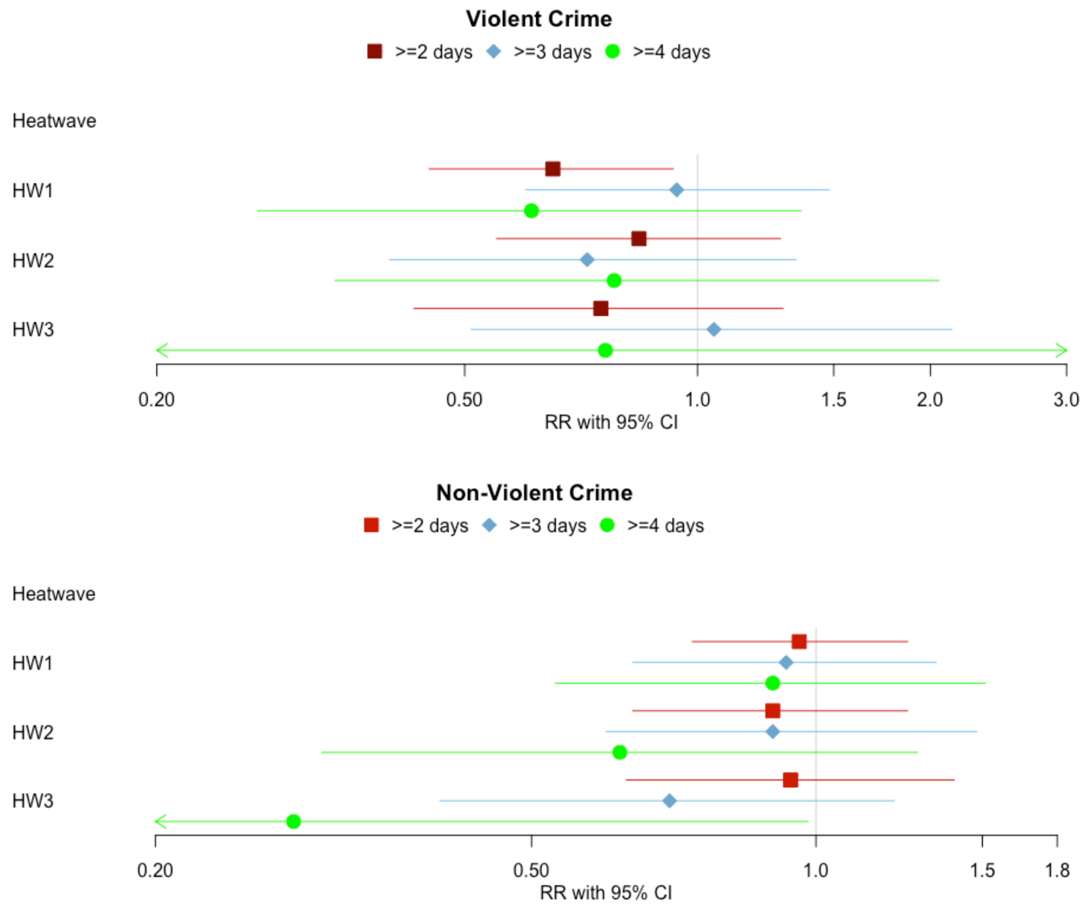
HW definitions	Models	Predictor(s)	Violent crime		Non-violent crime		All crime types	
			RR	95%CI	RR	95%CI	RR	95%CI
HW1	Unadjusted model	HW1	0.77	0.6; 1.1	0.9	0.7; 1.1	0.8	0.7; 1.3
	Adjusted model	HW1	0.65	0.4; 0.9	0.9	0.7; 1.2	0.8	0.7; 1.1
		$PM_{2.5}$	0.98	0.9; 1.1	0.9	0.9; 1.0	0.9	0.9; 1.0
		RH	0.84	0.7; 0.9	0.9	0.8; 1.1	0.9	0.8; 1.0
HW2	Unadjusted model	HW2	1.12	0.8; 1.6	0.7	0.5; 1.0	0.8	0.7; 1.1
	Adjusted model	HW2	0.94	0.6; 1.5	0.9	0.6; 1.3	0.9	0.7; 1.2
		$PM_{2.5}$	1.01	0.9; 1.8	0.9	0.9; 1.0	0.9	0.9; 1.0
		RH	0.89	0.7; 1.1	0.9	0.8; 1.1	1.9	0.9; 1.0
HW3	Unadjusted model	HW3	1.24	0.7; 2.2	0.6	0.4; 1.1	0.8	0.5; 1.1
	Adjusted model	HW3	0.61	0.2; 1.3	0.9	0.5; 1.5	0.8	0.5; 1.2
		$PM_{2.5}$	1.00	0.9; 1.1	0.9	0.9; 1.0	0.9	0.9; 1.3
		RH	0.88	0.7; 1.0	0.9	0.9; 1.1	0.9	0.8; 1.0

HW1: 90th percentile (32^{o}C), duration >= 2 days
HW2: 95th percentile (33^{o}C), duration >= 2 days
HW3: 97.5th percentile (34.5^{o}C), duration >= 2 days

Figure 10 shows the associations between heatwaves and violent and non-violent crime for different temperature thresholds (32 °C, 33 °C, and 34.5 °C) and different heatwave duration (two, three and four days). It was observed that a longer duration of heatwave exposure decreased crime risk in urban Hanoi, Vietnam, notably for non-violent crimes. We further observed that heatwave definitions with higher temperature thresholds showed decreasing risks for non-violent crime, with 4-day heatwaves of 34.5 °C showing the strongest association (RR=0.28, 95%CI = 0.08, 0.94). For violent crime, 2-days heatwave of 32 °C showed the most protective effect (RR= 0.65; 95%CI = 0.45; 0.93). Estimated relative risks of heatwaves and crime by duration can be found in Table S3.

Sensitivity analysis

The results did not meaningfully change our qualitative interpretation when exploring alternate temperature measures for the heatwave definitions. Using daily maximum temperature to define heatwaves events resulted in negative associations across all adjusted models under all three heatwave definitions (Table S4). Table S5 showed that the exclusion of fine particulate matter and relative humidity produced similar results in non-violent crime and total crime across the three heatwave definitions. Finally, we further tested the sensitivity of post-heatwave and the combination of a heatwave and post-heatwave effects on crime presented in Table S6. The RRs of each post-heatwave definitions were similar to the RRs of the main adjusted models for total and violent crime, but for non-violent crime, we observed positive post-heatwave-crime associations. The RRs of combined effects were similar to RRs of the main adjusted models for three crime types.



Adjusted models: heatwaves+ PM_{25}+ RH

Figure 10: The associations of heatwaves and crime (violent crime and non-violent crime) under three heatwave definitions with different durations: equal and greater than two days, equal and greater than three days, and equal and greater than four days in urban Hanoi, Vietnam.

Discussion

Our investigation of the relationship between heatwaves and crime events in urban Hanoi, Vietnam reveal negative heatwave-crime associations with the most compelling evidence in the least strict heatwave definition for violent crime. Additionally, the length of the heatwave duration appears to link to a decreasing crime risk in urban Hanoi, Vietnam.

Urban Hanoi offers a unique opportunity to explore the effects of heatwaves on crime rate, as recent increases in extreme temperature in Hanoi are attributed to climate change and urbanization(104). Hanoi is suffering from higher levels of heatwaves than other cities in the south of Vietnam, and heatwaves affect humans living in urban areas more than in rural areas(1)(105). Therefore, the effects of heatwaves on urban Hanoi citizens may differ from other urban areas and make it a highly vulnerable region for this environmental hazard.

Daily crime counts in urban Hanoi was lower than in other cities, only 1.52 for the total crime, compared to 39.7 homicides per day in South Africa(44); 557 total crime per day in Philadelphia, Pennsylvania, USA(68); and 53.3 total crime per day in Cleveland, Ohio, USA(106). A study in Australia showed a higher each daily crime count than the daily total crime in Hanoi, with 186 assault , 607 theft , and 116 fraud per day(107). The differences may be explained by different criminal policies, criminal report systems between countries and criminal definitions.

Our findings indicate the negative heatwave-crime associations in all adjusted models under various heatwave definitions. The findings may be explained by the Social Escape or Avoidance Theory and the Negative Affect Escape Model which conclude that at high temperatures, people will interact less to avoid the heat (79)(47). These findings align with a study across 436 U.S. counties in which an inverted U-shape function was observed, and crime risk was higher in winter and fall, compared to summer(49). A study in Dallas, Texas found an positive increase in associations between daily mean temperature and aggravated crime beyond 80 °F (26.5 °C),which then turns negative beyond 90 °F (32.2 °C)(50). Research in Philadelphia, Pennsylvania reported that violent crime is highest when mean daily temperature of 22.6 °C - 28 °C. The crime risk may be lower if the police reduce their patrolling in hot days, and people avoid going outside to reduce the effects of heat.

During heatwave days, the crime risk was lower than the non-heatwave days, but other general violent behavior, such as domestic violence, may have different trend. Our study focused only on criminal behavior reported by PC02 Department, and we lacked finer categorical data on violence, such as domestic violence, which may be potentially important. During heatwave days, people may stay at home to prevent the heat related illness, so it may increase the risk of domestic violence. Domestic violence goes underreported due to several factors, such as shame, stigma and low levels of awareness among victims and lack of social supports(108)(109). A national study in Vietnam showed that 90.4% of Vietnamese women who experienced physical and/or sexual violence from their husbands did not seek any help from formal service providers(109). To have a better understanding of temperature on human behavior, data from other sources, such as domestic violence data, hospitalization data or national surveillance data, which are not reported by local police officers are needed.

There was an increase in risk in non-violent crime in post-heatwaves days, compared to non-heatwave days but there was similar risk in total crime and violent crime. After heatwave days, people may go outside more, so it may increase the risk of non-violent crime. However, there is no study evaluating the effects of post-heat on crime, especially non-violent crime. Therefore, we need to investigate this topic in future research.

Other studies show that an increase in temperature is associated with an increase in the risk of different types of crime. Research in South Africa reported that a one-degree Celsius increase in daily temperature was associated with 1.2% increase in homicides(44). Ambient temperature was also associated intentional homicide in four U.S. cities, but only two of the cities showed significant associations. Other studies in Baltimore, Maryland and Tangshan, China reported a positive association between temperature and rates of total and violent crime(75)(43). The associations between heatwaves and crime compared to temperature may be explained by the difference of exposure measurements. Our study used binomial variable to measure exposure: heatwaves and non-heatwaves to compare the risk difference between case days and references days. Other studies use a continuous variable (daily temperatures) to measure the risk difference when a unit increase in temperature. Using a continuous variable is a useful approach to examine the linear effects but introduce uncertainty if the potential is non-linear. Moreover, different cites may show different effects due to population, policing, and infrastructure which also effects heat-crime associations. For example, given exposure to similar levels of temperature, neighborhoods with high poverty levels have a lower risk than neighborhoods with low poverty levels (34) and the property crime risk in urban areas is in lower than rural areas(49) . Therefore, sociodemographic factors regarding race, poverty and age at city-level may contribute an important role to investigate heat-crime associations. Our study is limited by urban Hanoi and a single-city study, and further studies with more cities are warranted

There are some strengths in our study. First, this is the first study to explore the effects of heatwave events on crime, as existing research on this exact exposure is limited. The effects of heatwaves should be explored separately from the effects of increase in temperature, especially in tropical locations where temperature ranges sharply differ from more moderate climates. Second, the effects of heatwaves on mental health problems and hospitalizations are well document in Hanoi, Vietnam (17)(20), but this study is the first study examine the effects of heatwave on crime. It is not easy to obtain crime data in developing countries compared to developed countries, and the crime data in Vietnam is not publicly available.

The study has several limitations. First, this study did not control for individual risk factors, including age, gender, poverty, and education status, in the analysis. However, individual factors are less of a concern for confounding our model, as they are rarely time-dependent, except for age, and those factors of criminals cannot be collected due to Vietnamese national security.

The crime dataset posed additional challenges with a small sample size and single-city data. In time series data, using a time series analysis for small sample size may lead to overestimate or underestimate due to the selections of degree of freedom per year which is normally used to control for long-term and seasonal trends. To avoid this, we used case-crossover study approach in which long-term and seasonal trends were controlled by study design(110)(101). The latter leads to problems in generalizing the results. Our study investigated in an urban population in Hanoi, the second-most populous city in North Vietnam, so the results cannot be generalized to rural Hanoi and other cities in Vietnam. We encourage future research explore other cities in different geographic regions in Vietnam.

In conclusion, heatwaves appear to be negatively associated with violent crime in urban Hanoi, Vietnam. We also observed that longer durations under different heatwave definitions decreased violent and non-violent crime risks but not significant differences. Therefore, to investigate the comprehensive effects of heat on crime, we need further research that includes more years or more cities in Vietnam.

Supplementary tables and figures

Table 15 (Supplement Table S1): Summary characteristics of daily mean temperature by month from 2013 – 2019 in urban Hanoi, Vietnam

	Mean	SD	Minimum	Maximum
January	18.1	3.44	6.97	24.7
February	19.5	3.99	11.4	28.3
March	22.2	3.28	14.5	28.6
April	25.9	2.92	12.5	33.3
May	29.8	2.80	19.1	37.2
June	31.4	2.36	26.0	38.5
July	31.0	2.53	25.1	38.0
August	30.3	2.39	36.5	24.2
September	29.7	2.27	22.0	34.4
October	27.6	2.43	19.2	32.8
November	24.1	3.01	16.0	29.4
December	19.4	3.57	10.6	29.2

Table 16 (Supplement Table S2)*:* Total number of heat way days by month based on different heat wave definitions from 2013 – 2019 in urban Hanoi, Vietnam

	HW1	HW2	HW3
January	0	0	0
February	0	0	0
March	0	0	0
April	1	0	0
May	24	12	5
June	55	32	12
July	54	28	16
August	34	17	5
September	17	3	0
October	1	0	0
November	0	0	0
December	0	0	0
Total	**186**	**92**	**38**

Table 17 (Supplement Table S3): The estimated relative risk effects of heatwaves on crime for 3 types of heat wave definitions based on different duration (equal and greater than two days, three days, and four days) in urban Hanoi, Vietnam.

Violent crime			
	>=2 days	>=3 days	>=4 days
HW1	0.6 (0.4; 0.9)	0.8 (0.7; 1.1)	0.8 (0.6; 1.2)
HW2	0.9 (0.6; 1.5)	0.8 (0.6; 1.2)	0.7 (0.5; 1.2)
HW3	0.6 (0.2; 1.4)	0.6 (0.4; 1.2)	0.3 (0.1; 0.9)
Non-violent crime			
HW1	0.9 (0.7; 1.2)	0.8 (0.6; 1.3)	0.7 (0.4; 1.3)
HW2	0.9 (0.6; 1.4)	0.7 (0.4; 1.3)	1.1 (0.6; 2.1)
HW3	0.6 (0.3; 1.4)	0.8 (0.3; 2.1)	0.8 (0.2; 3.4)
All crime			
HW1	0.8 (0.7; 1.1)	0.8 (0.6; 1.2)	0.9 (0.6; 1.3)
HW2	0.9 (0.7; 1.2)	0.9 (0.6; 1.4)	0.6 (0.3; 1.1)
HW3	0.8 (0.5; 1.2)	0.6 (0.3; 1.2)	0.2 (0.1; 0.9)

HW1: 90^{th} percentile (32ºC), duration >= 2 days
HW2: 95^{th} percentile (33ºC), duration >= 2 days
HW3: 97.5^{th} percentile (34.5ºC), duration >= 2 days

Table 18 (Supplement Table S4): Alternative estimated effects of heat waves on crime using daily maximum temperature to define different types of heat waves in urban Hanoi, Vietnam

	Duration (s)	Violent crime		Non-violent crime		All crime types	
		Crude	Adjusted	Crude	Adjusted	Crude	Adjusted
90^{th} (38.5)	> =2 days	1.0 (0.8; 1.4)	0.9 (0.6, 1.3)	0.8 (0.6, 1.1)	0.9 (0.7, 1.2)	0.9 (0.7, 1.1)	0.9 (0.7, 1.1)
95^{th} (39.5)	> =2 days	1.1 (0.8, 1.7)	0.9 (0.6, 1.4)	0.7* (0.5, 0.9)	0.7 (0.5, 1.1)	0.8 (0.6, 1.1)	0.8 (0.6, 1.1)
99^{th} (40.5)	> =2 days	1.3 (0.7, 2.6)	0.8 (0.4, 1.8)	0.8 (0.5, 1.4)	0.9 (0.5, 1.6)	0.9 (0.6, 1.5)	0.9 (0.5, 1.4)

Crude models: heatwaves
Adjusted models: heatwaves+ PM_{25}+ RH

Table 19 (Supplement Table S5): Alternative estimated effects of heat waves on crime controlled for $PM_{2.5}$ and RH, separately

HW definitions	Violent crime		Non-violent crime		All crime types	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
HW1	0.7 (0.5; 1.0)	0.6 (0.5; 0.9)	0.9 (0.7; 1.1)	0.9 (0.7; 1.1)	0.8 (0.7; 1.1)	0.8 (0.6; 1.0)
HW2	1.1 (0.7; 1.6)	1.0 (0.7; 1.5)	0.8 (0.5; 1.1)	0.8 (0.5; 1.1)	0.8 (0.6; 1.1)	0.8 (0.6; 1.1)
HW3	0.8 (0.4; 1.7)	1.1 (0.5; 1.9)	0.7 (0.4; 1.2)	0.7 (0.4; 1.2)	0.7 (0.5; 1.1)	0.8 (1.5; 1.2)

Model 1: heatwaves + PM_{25}
Model 2: heatwaves+ RH

Table 20 (Supplement Table S6): Alternative estimated effects of post-heat waves on crime using daily temperature to define different types of heat waves; and the estimated combined effects of heatwaves and post-heatwaves on crime using daily temperature to define different types of heat waves in urban Hanoi, Vietnam

	Violent crime		Non-violent crime		All crime types	
	Model 3	Model 4	Model 3	Model 4	Model 3	Model 4
PH1	0.8 (0.6; 1.2)	0.7 (0.5; 0.9)	1.1 (0.8; 1.4)	1.05 (0.8; 1.2)	1.02 (1.0; 0.8)	0.9 (0.8; 1.1)
PH 2	0.8 (0.7; 1.7)	0.8 (0.6; 1.1)	1.1 (0.5; 1.2)	1.02 (0.7; 1.4)	0.9 (0.6; 1.2)	0.9 (0.7; 1.1)
PH 3	0.8 (0.4; 1.8)	0.7 (0.4; 1.3)	1.1 (0.6; 1.8)	0.96 (0.6; 1.4)	0.9 (0.6; 1.5)	0.8 (0.6; 1.1)

Model 3: post-heatwaves + PM_{25} +RH
Model 4: heatwaves-post-heatwaves + PM_{25} +RH

Chapter 4.

Manuscript 3. Temperature-related emergency department visit due to injury in Hanoi, Vietnam, 2017-2019

Introduction

Injury is a leading factor in the global burden of disease and a burden on economies by increasing morbidity, mortality, and reductions in worker productivity. Injuries takes the lives of 4.4 million people worldwide each year and constitute nearly 8% of all deaths(22). Among people aged 10-24 and 24-49, road injury was the leading cause of disability-adjusted life-years (DALYs) globally in 2019,but was tenth in the 50-74-year age group (24). The economic burden injury is substantial and can impact national economies due to loss of life, costs of medical care, decreased worker productivity, and interventions to prevent injuries. In the U.S.A., the Centers for Disease Control and Prevention (CDC) reported that the economic cost of injury was U.S. $4.2 trillion, including the U.S. $327 billion for medical care, U.S. $69 billion for work loss, and U.S. $3.8 trillion in value of statistical life and quality of life losses in 2019(51).

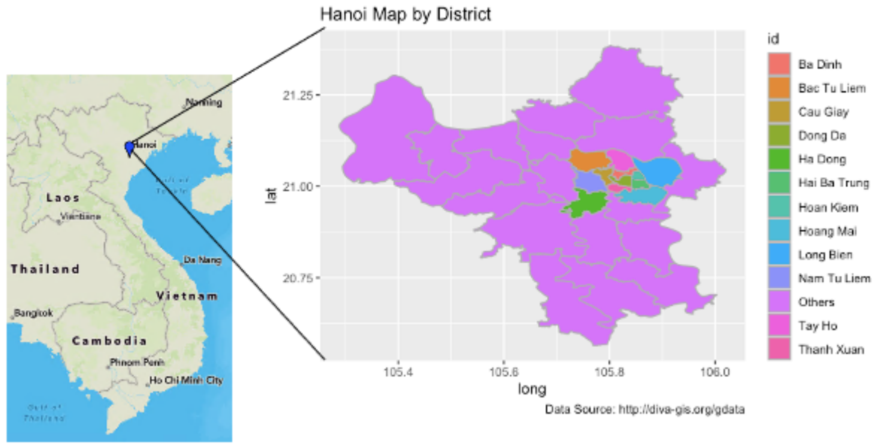
Individual factors and environmental conditions are considered to increase the risk of injury. Occupational injury rates have been rising in low-and middle-income countries (LMICs) but decreasing in high-income countries (HICs). Male and younger workers are at higher risk for workplace injury(2)(111). In addition to individual risk factors, weather conditions also play an important role in injury risk. Long-term exposure to particulate matter ($PM_{2.5}$) is associated with fall-related injury in six LMICs, with each 10 μg/m^3 increase corresponding to an 18% increase in fall-related injury(53). Other studies have been evaluated a rise in the risk of road traffic fatalities on rainy days, which make driving conditions more dangerous(54)(55)(56). After a snowfall, fall-related injuries is higher for days up to a week compared to days with no snowfall(57).

The existing literature has supported positive temperature-injury associations in high-income countries, but few studies have been conducted in low-and-middle-income countries (LMICs) (112)(60). Male and younger workers are identified as at higher risk of temperature-related injury(113)(114). Older people have a higher risk of fall-related injury during winter, however(61)(112). A study in Seoul, South Korea, indicated that unintentional injury increased at both high and low temperatures, but intentional injury significantly increased only at high temperatures (112). Hot days were also associated with all-cause injury-, vehicle accident-, accidental fall-, and heat-related hospital visits in New Hampshire, U.S(60). A narrative systematic review showed that hot weather could increase the risk of injury with each 1°C increase, resulting in a 0.4% to 5.3% increase in injury risk in high-income countries(62). A single-city study reported that high temperatures increased the risk of fall-related injury 11% at lag 0; the effects of ambient temperature varied with age and gender in Ma'anshan, China(61).

Vietnam, considered a LMIC country, has suffered a heavy toll from the burden of injury. The aged-standardized incidence rate of all injuries increases by 14.6% (11.5%-18.2%) from 2007 to 2017(65). The five leading causes of injury in both 2007 and 2017 were road injury, falls, exposure to mechanical forces, interpersonal violence, and other unintentional injuries (65). Moreover, the average total medical care costs paid out-of-pocket by patients during hospitalization due to injury were U.S. $270, which is higher than the one-month average wage for Vietnamese people (US $180) reported by the General Statistics Office of Vietnam(73). The total costs were higher for more severe injuries and complex surgeries(52). To date, no studies have examined the relationship between ambient temperature and injury in Vietnam. In this study, we present an analysis of the associations between ambient temperature and emergency department visits due to injury in Hanoi, Vietnam from 2017 to 2019.

Methods

We conducted a 3-year retrospective time-series analysis to explore the effects of temperature on emergency department (ED) visits due to injury, morbidity, and mortality of external causes within 30 districts of Hanoi. The study was reviewed and approved by the University of Minnesota Human Subjects Research Office. Picture 4 shows the map of Hanoi with 30 districts.



Picture 4: Map of Hanoi with 30 districts highlighting 12 urban districts

Emergency department visits

ED visit data were derived from a dataset of all hospitalizations in Hanoi from 2017 to 2019 provided by Hanoi Social Security, Hanoi's governmental insurance organization. The dataset included 733 hospitals and clinics, located in Hanoi, with all 27 national hospitals, 110 provincial and district hospitals, and 596 public and private clinics.

The ED visits due to injury data included the date of admission and discharge, age, gender, primary diagnosis, and residence status. This limited dataset did not include personal identifying information and, after being reviewed by the Human Subjects Research Committee at the University of Minnesota was classified as not human research. These administrative data are limited by one code per visit; thus injury was designated by either an external cause or an injury diagnosis. For this analysis, we included all diagnoses indicating an unintentional injury, which were classified by the 10^{th} reversion of International Classification of Diseases (ICD10). External causes of injury (S00-T32), accidents (V01 - X59), and other injury-related factors (T66 – T78, Y20 – Y34 and Y90 – Y98) were selected. Visits from patients living outside Hanoi were excluded based on their residence status; residency required living in Hanoi for a minimum of 3 weeks.

The study outcome was the daily count of ED injury visits. Three outcomes were generated from the primary data: total ED visits, ED visits stratified by gender (male/female), and ED visits stratified by age groups (<15, 15- 44, 45- 59, ≥60) (Table 21).

Table 21: Number of emergency visits due to injury based on ICD10 and number of populations in 2019 in Hanoi, Vietnam

	Total (%)	**Gender**		**Age**			
		Male (%)	Female (%)	<15 (%)	15-44 (%)	45-59 (%)	≥60 (%)
Emergency visits due to injury							
Injury (S00-T32)	37 636 (95.73)	22 868 (95.86)	14 768 (95.54)	12 627 (95.99)	12 473 (95.78)	6 076 (94.55)	6 464 (96.33)
Accident V01-X59)	498 (1.27)	357 (1.50)	155 (1.00)	194 (1.47)	175 (1.34)	60 (0.93)	69 (1.03)
Others (T66- T78, Y20- Y34, Y90- Y98)	1 179 (3.00)	644 (2.70)	535 (3.46)	333 (2.53)	375 (2.88)	290 (4.51)	177 (2.64)
Total	39 313 (100)	23 855 (60.67)	15 458 (39.33)	13 154 (33.45)	13 023 (33.12)	6 426 (16.30)	6 710 (17.13)
Estimated populations of Hanoi 2019*							
2019	8 093.90 (100)	4 012.70 (49.57)	4 081.20 (50.43)	2 033.89 (25.12)	3 777.04 (46.67)	1 263.67 (15.62)	1 018.40 (12.59)

*Thousand persons
Source: General Statistics Office of Vietnam

Atmospheric conditions

Atmospheric data includes daily mean and maximum temperature, relative humidity (RH), and daily particulate matter ($PM_{2.5}$). Atmospheric data were obtained from Hanoi Environment and Natural Resource Department, which manages 12 monitors measuring 24-hour weather data in urban Hanoi. We calculated daily values using 24-hour data of each monitor and removed illogical measurements based on previous research and study(18)(12). For example, daily relative humidity over 100% would be removed and coded as missing. The daily values of 12 monitors were averaged to estimate daily mean weather values.

Data analysis

Time-series analysis with quasi-Poisson models were fit using R software, version 4.2.0 (https://www.r-project.org/) to estimate the short-term effects of temperature on ED visits due to injury on both linear and non-linear scale. We also examined delayed effects (lagged effects) of temperature on ED visits based on potential evidence from previous studies(112)(58).

For both linear and non-linear effects models, we adjusted for time, the day of week, holiday, daily relative humidity, and daily particulate matter as potential confounding factors. Smooth function of time (natural cubic splines) with 7 degrees of freedom per year was used to adjust for long-term and seasonal trends. Previous studies showed that 7 degrees of freedom provides adequate control for seasonality and another confounding by trends in time(82)(81). The day week was used to control different baseline ED visits for each day. We controlled for daily mean $PM_{2.5}$ and daily mean RH using natural cubic splines with 3 degrees of freedom on the same day. Holiday was a binary indicator for whether a day is classified as holiday or non-holiday. Holiday will include all Vietnamese public holidays, including New Year's Eve, Lunar New Year's Event, Labor Day, Independence Day, and the preceding Friday or following Monday if a holiday falls on a Saturday or Sunday. (https://www.officeholidays.com/countries/vietnam/2020).

For linear effects, results are reported in two separate ways: 1) percentage increase in the relative risks (RRI) of injury for each 5 °C increase in daily mean temperature and 2) RRI of injury for each quintile increase in daily mean temperature. We examined the sensitivity of our findings with respect to degrees of freedom in the smooth functions of time (5,7 and 9 degrees of freedom per year); degrees of freedom in the smooth functions of daily relative humidity and daily particulate matter (3, 4, and 5 degrees of freedom); and using daily maximum and daily minimum temperature instead of daily mean temperature.

To examine non-linear effects, distributed lag non-linear models (DLNMs) were fit with quasi-poison regressions. The relative risk was interpreted as the effect of the exposure versus a reference and reported as both distributed lag effect and individual lag days (71). All co-variables were similar to linear models, such as day of week, holiday, time, relative humidity, and particulate matter. DLNMs use a “crossbasis” function to describe a two-dimensional temperature-injury associations along the dimensions of temperature and lag(70). We choose 5 degrees of freedom for daily temperature and 4 degrees of freedom for lag. The choice of the centering value depends on the interpretational issues and does not affect the fit of the model (72). In this study, the centering value was 15 °C which equals to the10 percentile of daily temperature to reduce the effects of outliners. We fit separate models to evaluate variation in estimated risks across total ED visits, different age groups, and gender using single-day temperature lag models from 0 to 5 days. Sensitivity tests revealed our results were robust to adjustment of different degrees of freedom for time, temperature, and lag.

Results

There were 39,313 emergency visits for injury across all districts of Hanoi over the whole study period (Table 1). The number of visits for males was higher than for females, who accounted for 60.7% and 39.2% of visit, respectively. Table 2 shows the daily mean total visits were around 36 per day, and there was a difference within gender and age. The mean daily visits of males (21.8 per day) was higher than that of females (14.1 per day). We also observed the difference between daily visits within age groups with the lowest daily mean visits among people 60 and older. The trend of daily emergency visits increased from 2017- 2019 (Supplement Figure 1). The daily mean temperature was 26.5 °C and ranged from 10.6 °C to 38.5 °C (Table 22).

Table 22: Descriptive statistics for daily atmospheric conditions and daily emergency visits in Hanoi, Vietnam

	Mean	Min	25%	Median	75%	Max
Emergency Department Visits						
Total	35.9 ±16.7	4.0	23.0	35.0	47.0	92.0
Gender						
Male	21.8 ± 10.1	1.0	14.0	21.0	29.0	56.0
Female	14.1 ± 7.6	0.0	8.0	14.0	19.0	45.0
Age group						
< 15	12.0 ± 6.1	0.0	7.0	12.0	16.0	34.0
15 – 44	11.9 ± 5.9	0.0	8.0	11.0	16.0	35.0
45 – 60	6.2 ± 3.8	0.0	3.0	6.0	9.0	21.0
≥60	5.7 ± 4.1	0.0	3.0	5.0	8.0	24.0
Atmospheric conditions						
Temperature (°C)	26.5 ± 5.5	10.6	22.5	27.4	30.9	38.5
RH (%)	64.5 ± 13.4	35.6	59.4	67.5	73.7	88.1
$PM_{2.5}$	38.6 ± 18.4	5.3	27.8	35.2	44.9	140.5

For linear effects, a 5 °C increase in same-day mean temperature was associated with a 4.7% increase (95% CI= 2.3; 7.2%) in the risk of ED visits due to injury on average (Table 23). The risk differed by sex with males experiencing nearly double the increased risk per 5 ºC compared to females; with RRI= 5.8% and RRI= 3.0%, respectively. The proportion of male visiting ED due to injury is higher than female (Table 22), and similar trends are observed across different age groups, except for people aged 60 and older (Table 23). The proportion of males under 15 is more than two times higher than that of females, but the trend changes in people 60 and older, with that of females being greater than the proportion of males.

The findings show positive temperature-injury associations among different age groups. The lowest risk was in people aged 60 and older (RRI= 1.3%, 95%CI = -3.2; 6.2), followed by people aged under 15, people aged 15 to 44 and people aged 45- 59.

Table 23: Association between daily mean temperature and emergency visits for injury by total visits and stratified by gender and age for each 5 °C increase in daily mean temperature at lag 0

	ED visits (%)	**RRI**	**95%CI**
Injury	39 313 (100)	4.7	2.3; 7.2
Stratified by Gender			
Male	23 855 (60.76)	5.9	3.0; 8.9
Female	15 458 (39.24)	3.0	-0.4; 6.5
Stratified by Age			
<15	13 154(33.15)	5.1	1.2; 9.0
15 - 44	13 023 (33.14)	5.6	1.7; 9.6
45- 59	6859 (16.52)	5.7	0.5; 11.3
≥60	6277 (17.19)	1.3	-3.2; 6.2
Stratified by Age with different gender			
<15			
Male	9170 (69.70)	4.3	2.2; 10.6
Female	3984 (30.30)	6.9	0.3; 13.9
15 - 44			
Male	7962 (61.13)	5.9	1.1; 10.1
Female	5061 (38.87)	5.2	-0.5; 11.4
45- 59			
Male	3942 (58.32)	10.7	3.6; 18.3
Female	2917 (41.68)	-0.7	-8.1; 7.1
≥60			

Male	2781 (44.31)	4.9	-2.4; 12.8
Female	3496 (55.69)	-1.4	-7.6; 5.3

Adjusted by day of week, holiday, RH, PM, and time

The risks of ED visits due to injury differed between and within age groups. The lowest effect of temperature on injury is among people aged 60 and older. The temperature-injury association for males was lower than females aged under 15, but the opposite was true for all other age groups, particularly for ages 45 and older. The highest effect is among males aged 45 – 59 (RRI= 10.7, 95%CI = 3.6; 18.3), and the lowest effect is among females aged 60 and older (RRI= -1.4, 95%CI = -7.6; 5.3).

The analysis by quintile supported an increased risk of injury with increasing temperature, and the differences by gender and age. People exposed to a higher temperature, especially in Q5, show higher injury risk than those exposed to below 21.30 °C (in Q1); the results are shown in Table 24. The RRIs within gender are similar to the RRIs shown in Table 23 that male had higher injury risk than female when exposure the same temperature. The effects of temperature differ within age groups. We observed an increase in RRIs among people aged 60 and older but did not observe statistically significant differences across all quantiles of daily temperature. For people in two age groups from 15 to 59, the effects of temperature in Q4 and Q5 were higher than that in Q2 and Q3.

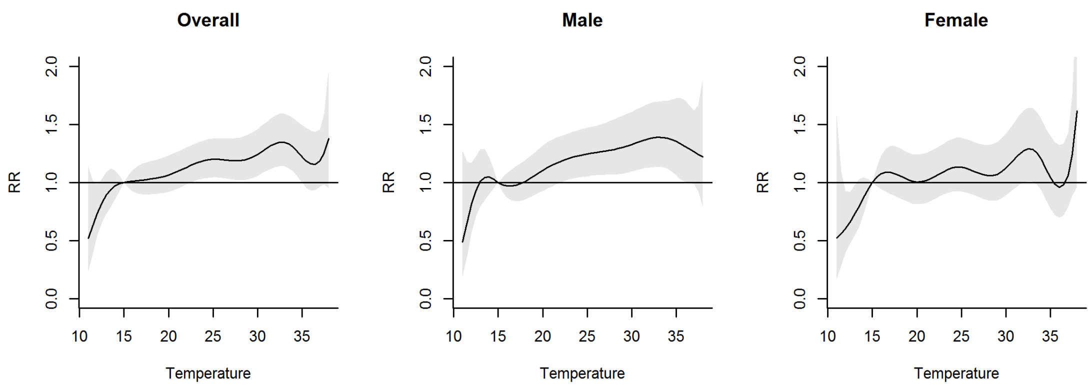
Table 24: Association between daily mean temperature and emergency visits for injury of external causes by total visits and stratified by gender and age for each quantile increase in daily mean temperature at lag 0

Total visits and stratified by gender						
	Overall		*Male*		*Female*	
	RRI	95%CI	RRI	95%CI	RRI	95%CI
Q1	1.0		1.0		1.0	
Q2	8.8	3.8; 13.9	13.4	7.4; 19.8	1.9	-4.6; 8.9
Q3	8.3	2.6; 14.4	10.4	3.5; 17.8	5.3	-2.6; 13.9
Q4	13.5	5.4; 22.3	15.8	6.1; 26.4	10.3	-0.7; 22.8
Q5	15.6	7.1; 24.8	16.8	6.8; 27.9	13.9	2.0; 27.2

Stratified by Age								
	<15		*15-44*		*45-59*		*≥60*	
	RRI	95%CI	RRI	95%CI	RRI	95%CI	RRI	95%CI
Q1	1.0		1.0		1.0		1.0	
Q2	17.6	9.5; 26.2	5.6	-1.9; 13.7	1.4	-8.4; 12.3	4.4	-5.4; 15.3
Q3	8.7	10.0; 18.4	7.6	-1.3; 17.3	11.3	-1.2; 25.4	5.4	-6.1; 18.5
Q4	14.2	1.7; 28.3	12.8	0.3; 26.9	26.2	7.6; 48.2	1.6	-13.4; 19.3
Q5	17.7	4.4; 32.7	13.5	0.5; 28.1	24.2	5.2; 46.4	8.1	-8.1; 27.4

Adjusted by day of week, holiday, RH, PM, and time
Q1: 1st -20th percentile daily temperature (under 21.30 °C)
Q2: 21st – 40th percentile daily temperature (under from 21.30 to under 25.62 °C)
Q3: 41st – 60th percentile daily temperature (from 25.62 to under 28.97 °C)
Q4: 61st – 80th percentile daily temperature (from 28.97 to under 31.43 °C)
Q5: 81st – 100th percentile daily temperature (above 31.43 °C)

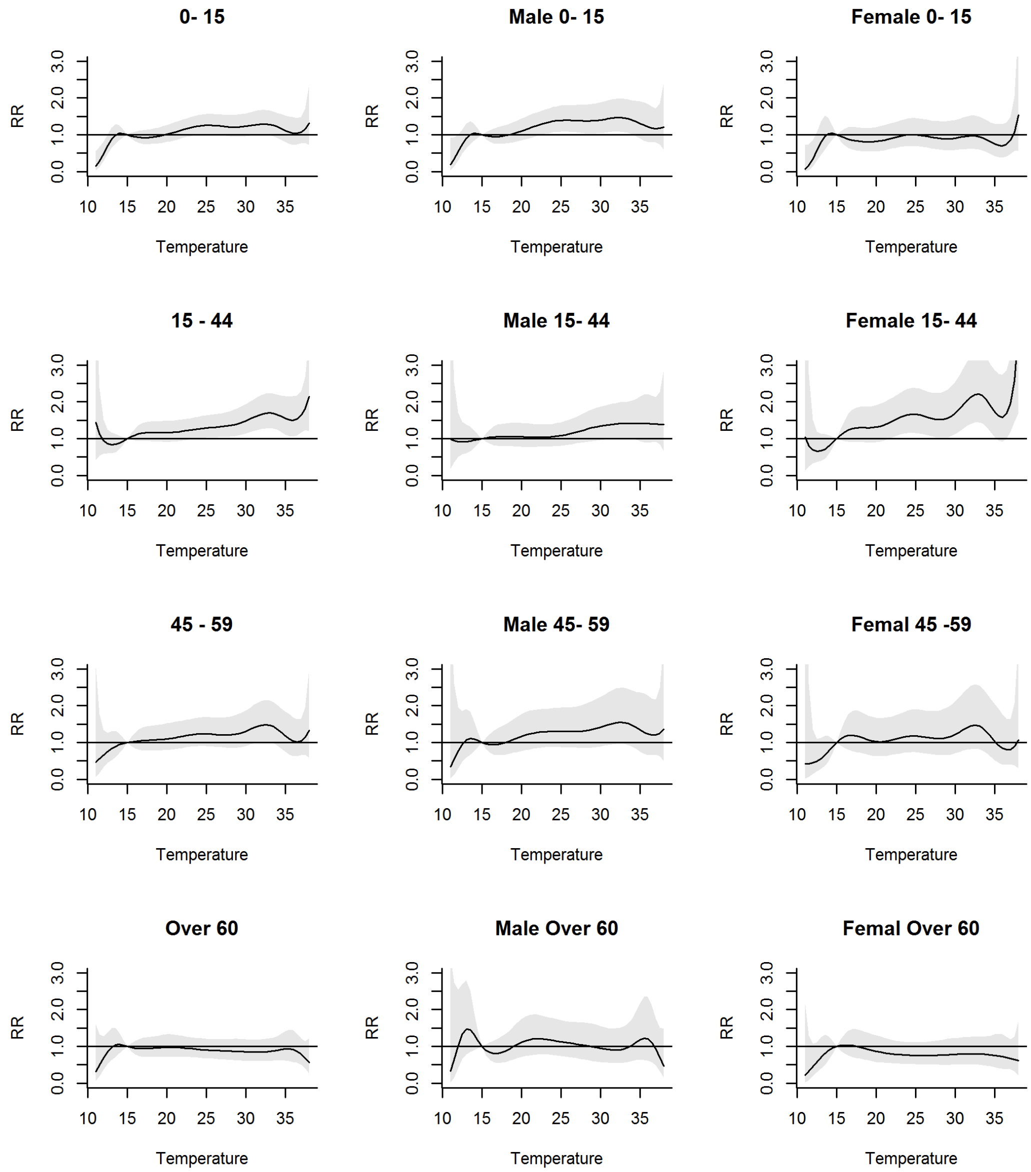
For non-linear effects model, we observed an increase in the risk of injury at high temperatures but a decrease in the risk of injury at low temperatures, compared to the threshold temperature of 15 °C across three models on average (Figure 11). The temperature-injury curves were different between male and female, which reflects the results from the linear and categorical models. For male, the curve increases to 33 °C, at which point the risk decreases in an inverted U-shape response. For women, however, the curve fluctuated and then reached the highest at the highest temperature.



Adjusted by day of week, holiday, RH, PM, and time
Referencing temperature is at 15 °C

Figure 11: Plot of overall exposure-response association curves between daily mean temperature and ED visits due to injury, presented as total visits(left), ED visits for male (middle), and ED visits for female (right) in Hanoi, Vietnam, 2017-2019. The models represent distributed lag curves, and shaded areas denote 95% confidence intervals.

Temperature-injury curves show the different risks between age groups and gender. The temperature-injury curves among people aged 15-44 increase for each unit increase in temperature; however, increasing temperature was inversely related to injury among people aged 60 and older. The temperature-injury curve shows an increase in risk from 15 °C among female aged 15-44, however males aged 15- 44 showed no increased risk below 25 °C (Figure 12). Other models indicated that male have a higher injury risk than female when the temperature increases.



Adjusted by day of week, holiday, RH, PM, and time
Referencing temperature is at 15 °C

Figure 12 : Plot of overall exposure-response association curves between daily mean temperature and ED visits due to injury among different age groups and age groups stratified by gender in Hanoi, Vietnam, 2017-2019. The models represent distributed lag curves and shaded areas denote 95% confidence intervals.

We examined the effects of lags, stratified by gender and age, in both linear and non-linear effects (Supplement Table S1, Figure S1, and Figure S2). For linear effects, total visits showed similar results at lag 0-4, then decreased at lag 5. While female showed higher injury risk at lag 3 and 4, male showed the highest injury risk at lag 0. People aged 60 and older showed the highest effect at lag 0 and negative effects after that, but people aged under 15 and 15-44 showed the highest effect at lag 3 and lag 2, respectively. All age groups presented the lowest effects at lag 5. For non-linear effects, most curves show a positive impact on the first day of exposure, and a negative impact on the fifth day of exposure. However, a lag-response curve for people aged 15 shows the lowest effects on the first day of exposure, then increase in the following days. In conclusion, we observed delayed effects between temperature and ED visits due to injury, and the effects differ between gender and age groups.

We tested the robustness of models by fitting models with varying degrees of freedom for time and temperature (Supplement Table S2- S4). Overall, the main models proved to be robust to these changes and the choice of mean temperature produced the strongest association. Changing the degrees of freedom for time and lag had minimal impacts on the temperature-injury curves (Supplement Figure S3 – S5). The magnitude of the curves for male and female was attenuated when we changed the degree of freedom for temperature in a crossbasis function, but the trends remained increasing.

Discussion

This is the first study that evaluated both linear and non-linear effects of temperature on ED visits due to injury in Hanoi, Vietnam. There were 39,313 ED visits due to injury from January 1, 2017, to December 31, 2019, with the number of visits among males higher than females and the number of visits among people aged under 15 and 15- 44 higher than people aged 46-59 and over and equal 60. On average, we observed an association between a short-term increase in daily temperature and an increased risk of ED visits due to injury; the injury risks differ within gender and age groups. High temperatures showed protective effects among people aged 60 and older. To date, this is the first study that investigated the effects of temperature on injury in Vietnam using claimed data from Hanoi Social Security.

Hanoi, the capital of Vietnam, presents a distinctive city to explore the short-term association between temperature and injury. First, injury accounts for more than 9.3% of deaths in Vietnam which is higher than the global average (around 8%), according to World Bank data(9). Road injury was one of the most common leading causes of death in 2019 in Vietnam(66). Second, Hanoi is a second most populous city in Vietnam with a humid sub-tropical climate that makes the effects of temperature on injury different from other regions in Vietnam and other countries. The daily temperature ranged from 10.6 to 38.5 °C, which differs from daily temperature ranges reported in other studies, e.g. -14.6 to 31.8 °C in South Korea(112), -7.0 to 35.4 °C in China(61), and 9.0 to 23.1°C in Japan(115). Our study did not observe very low daily temperatures (<0°C), thus, the injury patterns related to temperature may differ from other studies. Located in a humid sub-tropical climate, relative humidity in Hanoi is often high (mean of 64.5%), especially in the summer . The combination of high relative humidity and high ambient temperature can exacerbate temperature related effects(116).

Our findings indicated that young people experienced higher risk of injury than people 60 and older when exposed to increased temperature across three temperature measurement models. For linear models, the effects of temperature on injury among the elderly were around four times lower than in other age groups. Similarly, among the elderly, non-linear models identified an inverse association with temperature, and low temperature did not increase injury risk. In contrast, other studies found a positive association between injury risk related to low temperature among the elderly(112)(61). These differences may be attributed to differences in atmospheric conditions, i.e., in Hanoi the winter is not as cold as in South Korea and China. There is no snow and freezing, thus reducing the risk of slips and falls due to very cold weather for the elderly. Furthermore, occupational studies found that young workers (aged under 25) and middle-aged groups have a higher risk of injury-related to temperature than other age groups(113)(117)(114). Young workers are more likely to work in more hazardous jobs, and pay less attention to occupational safety and health(2), thus, they increase the risk of injury, especially during hot working days.

On average, given exposure to the same level of increased temperature, mean daily injury and injury risk among males was higher than females event male population is lower than female population (shown in Table 1). Occupational and epidemiological studies have observed different injury risks between males and females. Several work-related injury studies have indicated that males have a higher risk of temperature-related injury than females globally(2)(113)(117)(118). Similarly, population-level research found that males have a higher injury risk than females with increasing temperature(62)(115)(119)(120). There are some plausible behavioral pathways that have been used to explain the different risks between genders. For example, males are more likely to engage in out-door activities, such as working and exercising, than females during warmer conditions, which leads to an increased injury risk(121).

We found the delayed effects between temperature and injury across all genders and ages, except for the elderly. The greatest effect was at lag 0 for males, lag 3 for females, lag 3 for people aged under 15, and lag 2 for people aged 15- 45. Lags 4 and 5 were associated with the lowest injury risk. The lagged effect may be due to temperature or injured patients not presenting to the hospital for one or more days after the injury. A qualitative study showed tthat the wo main reasons for patients to delay going to a hospital for injury treatment in Vietnam were socio-cultural and financial (122). Patients may go to traditional healers (traditional medicine) for treatment instead of going to the emergency department, which is associated with modern medicine, because they believe that using herbs is better than using antibiotics(122). Moreover, because Hanoi's hospitals are often over-crowded, especially public hospitals, patients fear sharing a room with others, and waiting for a long time for treatment (122)(123). Additionally, patients delayed going to hospitals because average total medical care costs paid out-of-pocket are higher than the monthly average salary(52).

The findings of this study must be interpreted in light of some limitations. First, we did not investigate the causes of injury because of limited information. When patients visited ED, doctors might classify diseases by body region and nature of injury (Chapter XIX) or causes of injury (Chapter XX). In this study, most ED visits due to injury were coded as chapter XIX (95.73%), so causes of injury were not always available to investigate. Second, individual identifying information, such as job, was not explored in this study, so distinguishing work-related and nonwork-related injuries was not possible. Certain occupations are at higher risk of temperature-related injury than others, e.g. outdoor workers (59) who are regularly exposed to higher than recommended temperatures (124)(125). Third, this is a single-city study, which investigated the effects of temperature on injury in Hanoi. Thus, the findings cannot be generalized to other cities in Vietnam.

Additionally, misclassification may occur due to missing weather monitors in rural Hanoi. However, Hanoi is a small area, and we assumed that Hanoi habitants experienced the same levels of daily increased temperature. Last, we lacked data on other atmospheric conditions, such as rainfall, wind speed, and sunshine duration, which may confound our results. Unfortunately, these atmospheric conditions were not comprehensive to adjust for this study.

Conclusions

This is the first study that examined the effects of temperature on ED visits due to injury in Hanoi, Vietnam investigating both linear and non-linear estimations. Our findings support the hypothesis that temperature increases ED visits due to injury in Hanoi, and different gender and age groups showed different injury risks. On average, males, and people under 60 were identified to be at higher risk of temperature-related injury than other females and people 60 and older. Future research is warranted to investigate temperature-injury among different groups of people and the causes of injury.

Supplementary tales and figures

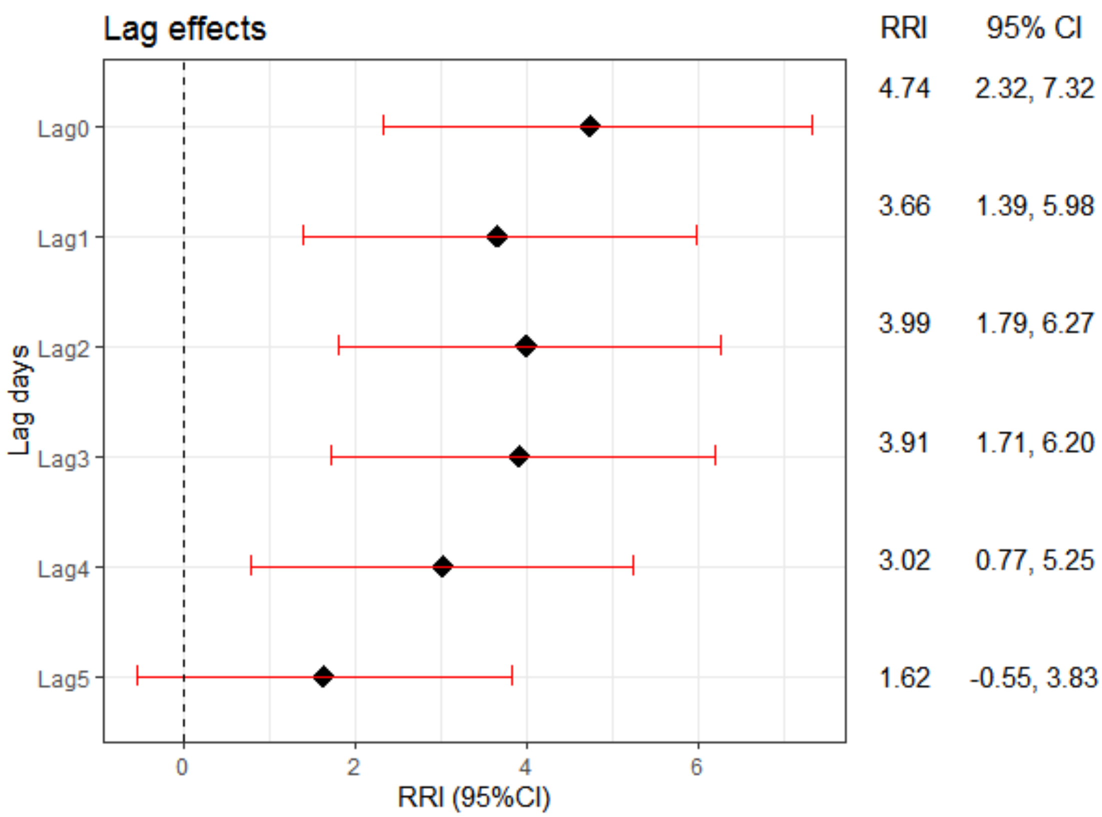


Figure 13 (Supplement Figure S1): Estimated percent change in the risk of emergency visits for injuries of external causes for each 5°C increase in daily mean temperature by lag (0-5 lags) with relative risk increase and 95%CI

Table 25 (Supplement Table S1): Estimated percent change in the risk of emergency visits for injuries of external causes for each 5°C increase in daily mean temperature by lag, gender, and age

	By Gender		By Age			
	Men RRI (95%CI)	**Women** RRI (95%CI)	**<15** RRI (95%CI)	**15-45** RRI (95%CI)	**46-60** RRI (95%CI)	**≥60** RRI (95%CI)
Lag 0	5.8 (2.9; 8.8)	2.9 (-0.4; 6.5)	5.1 (1.2, 9.0)	5.6 (1.7; 9.65)	5.7 (0.1; 11.3)	1.3 (-3.2; 6.2)
Lag 1	4.4 (1.7; 7.2)	2.4 (-0.8; 5.7)	3.1 (-0.4; 6.8)	7.6 (3.8; 11.4)	3.4 (-1.4; 8.5)	-2.8 (-7.3; 1.8)
Lag 2	4.7 (2.0; 7.4)	2.8 (-0.5; 6.1)	4.7 (1.1; 8.4)	7.9 (4.1; 11.6)	1.1 (-3.5; 6.1)	-2.3 (-6.7; 2.3)
Lag 3	4.3 (1.7; 7.1)	3.2 (0.0; 6.5)	6.6 (3.1; 10.4)	6.6 (2.9; 10.3)	1.1 (-4.5; 5.9)	-3.9 (-8.2; 0.5)
Lag 4	2.8 (0.2; 5.5)	3,1 (-0.4; 6.4)	4.5 (1.1; 8.2)	4.0 (0.4; 7.6)	2.2 (-3.2; 7.1)	-1.7 (-6.2; 2.9)
Lag 5	1.4 (-1.1; 4.02	1.9 (-1.1; 5.1)	2.7 (-0.8; 6.3)	2.3 (-1.1; 5.8)	2.4 (-2.2; 7.3)	-3.1 (-7.7; 1.3)

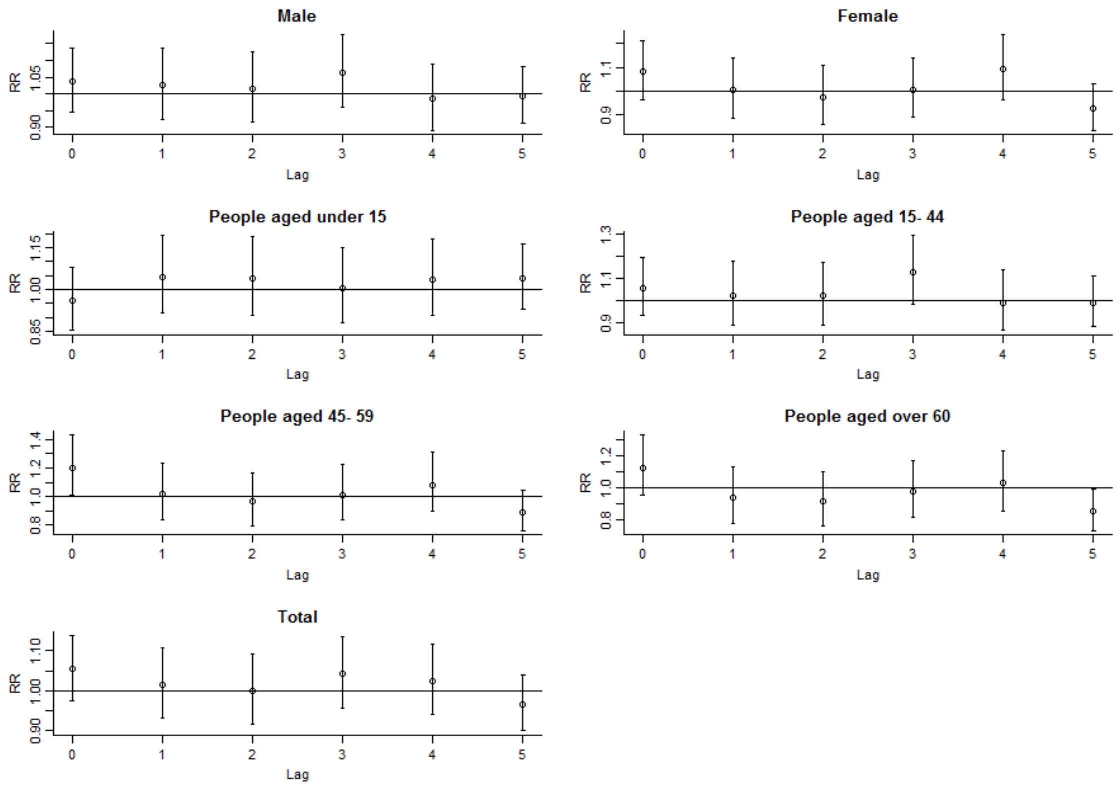


Figure 14 (Supplement Figure S2): Individual lag-response curves for temperatures at 30 °C ref. 21.30 °C in Hanoi, Vietnam, 2013-2019. The models represent individual lag curves (from 0 to 7 days) and shaded areas denote 95% confidence intervals

Table 26 (Supplement Table S2): Sensitivity analysis of linear effect estimates for injury using time series analysis by different degrees of freedoms for time (5,7, and 9 degrees of freedom)

Total visits and stratified by gender						
	Overall		*Men*		*Women*	
	RRI	95%CI	RRI	95%CI	RRI	95%CI
5 df	4.8	2.4; 7.2	5.7	2.8; 8.7	3.4	0.1; 6.9
7df*	4.7	2.3; 7.2	5.9	3.0; 8.	2.9	-0.4; 6.5
9df	4.3	1.9; 6.7	5.5	2.6; 8.	2.3	-1.1; 5.9

Stratified by Age								
	<15		*15-44*		*45-59*		*≥60*	
	RRI	95%CI	RRI	95%CI	RRI	95%CI	RRI	95%CI
5 df	4.8	1.1; 8.8	4.9	1.1; 8.8	6.7	1.4; 12.4	2.8	-2.3; 7.9
7df*	5.1	1.2; 9.0	5.6	1.7; 9.6	5.7	0.5; 11.3	1.3	-3.2; 6.2
9df	4.4	0.5; 8.4	5.4	1.5; 9.4	6.1	0.6; 11.8	0.5	-4.2; 5.6

**Main models*

Table 27 (Supplement Table S3): Sensitivity analysis of linear effect estimates for injury using time series analysis by different degrees of freedoms for relative humidity and particulate matter (3,4, and 5 degrees of freedom)

Total visits and stratified by gender						
	Overall		*Men*		*Women*	
	RRI	95%CI	RRI	95%CI	RRI	95%CI
3 df*	4.7	2.3; 7.2	5.9	3.0; 8.8	2.9	-0.4; 6.5
4 df	4.5	2.1; 7.1	5.9	3.1; 8.9	2.6	-0.7; 6.3
5 df	4.5	2.1; 7.0	5.9	2.9; 8.9	2.4	-1.0; 5.9

Stratified by Age								
	<15		*15-44*		*45-59*		*≥60*	
	RRI	95%CI	RRI	95%CI	RRI	95%CI	RRI	95%CI
3 df*	5.1	1.2; 9.0	5.6	1.7; 9.6	5.7	0.5; 11.3	1.3	-3.2; 6.2
4 df	4.8	0.8; 8.6	5.5	1.7; 9.5	5.9	0.6; 11.6	1.1	-3.8; 6.1
5 df	4.6	0.8; 8.6	5.5	1.6; 9.5	5.9	0.5; 11.6	1.1	-3.9; 6.1

**Main models*

Table 28 (Supplement Table S4): Sensitivity analysis of linear effect estimates for injury using time series analysis by different temperature measurements: daily minimum, mean and maximum temperatures

Total visits and stratified by gender						
	Overall		*Men*		*Women*	
	RRI	95%CI	RRI	95%CI	RRI	95%CI
Min	3.3	0.7; 6.1	4.8	1.6; 8.1	1.1	-2.5; 4.9
Mean*	4.7	2.3; 7.2	5.9	3.0; 8.8	2.9	-0.4; 6.5
Max	3.6	1.8; 5.5	4.8	2.1; 6.6	2.5	-0.1; 5.2

Stratified by Age								
	<15		*15-44*		*45-59*		*≥60*	
	RRI	95%CI	RRI	95%CI	RRI	95%CI	RRI	95%CI
Min	2.7	-1.3; 7.1	5.4	1.3; 9.8	3.8	-1.8; 9.9	-0.1	-5.2; 5.4
Mean*	5.1	1.2; 9.0	5.6	1.7; 9.6	5.7	0.5; 11.3	1.3	-3.2; 6.2
Max	3.3	0.4; 6.3	3.8	0.9; 6.8	5.1	1.01; 9.47	2.6	-2.2; 6.5

**Main models*

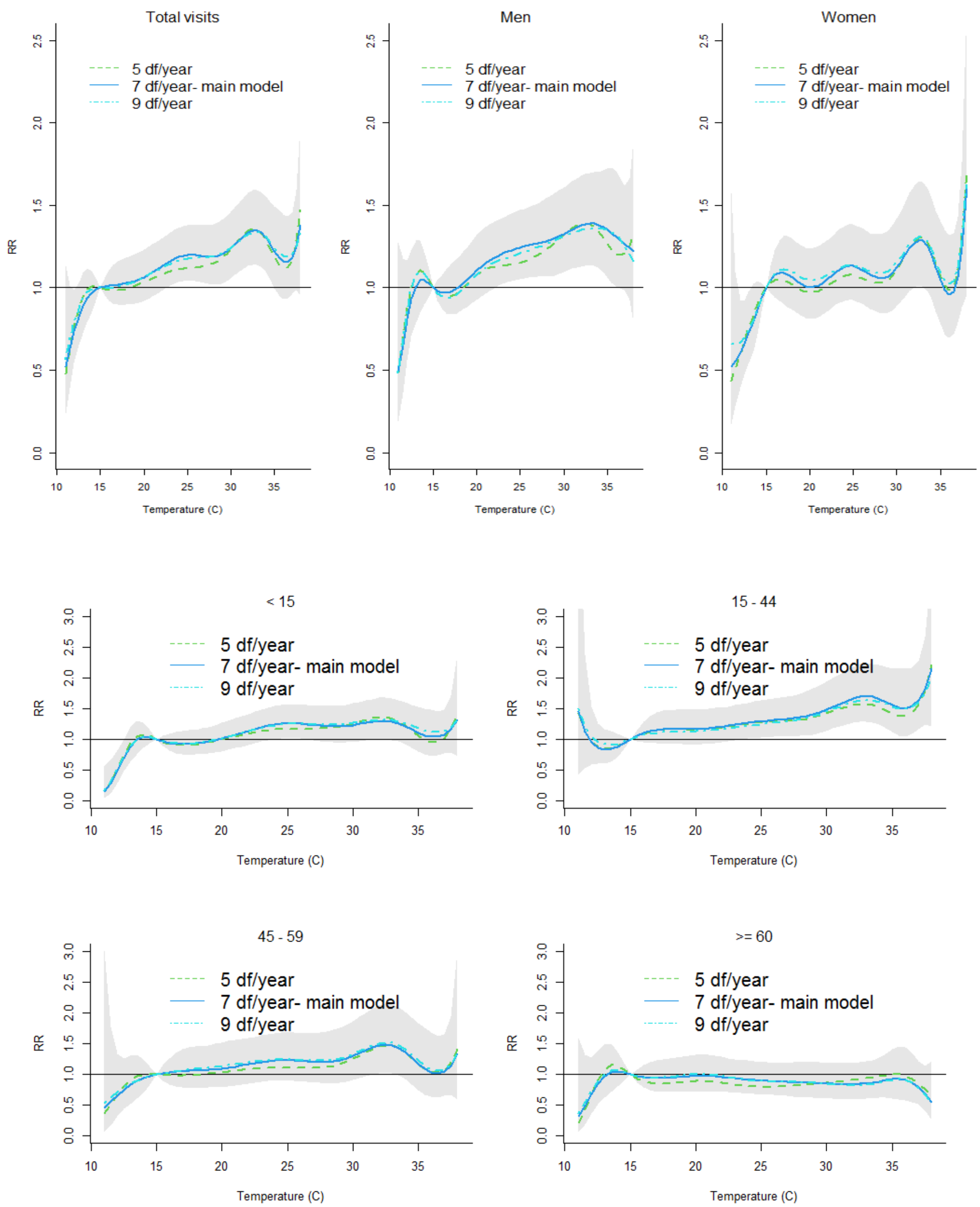


Figure 15 (Supplement Figure S3): Sensitivity analysis of non-linear effect estimates for injury using time series analysis by different degrees of freedoms for time

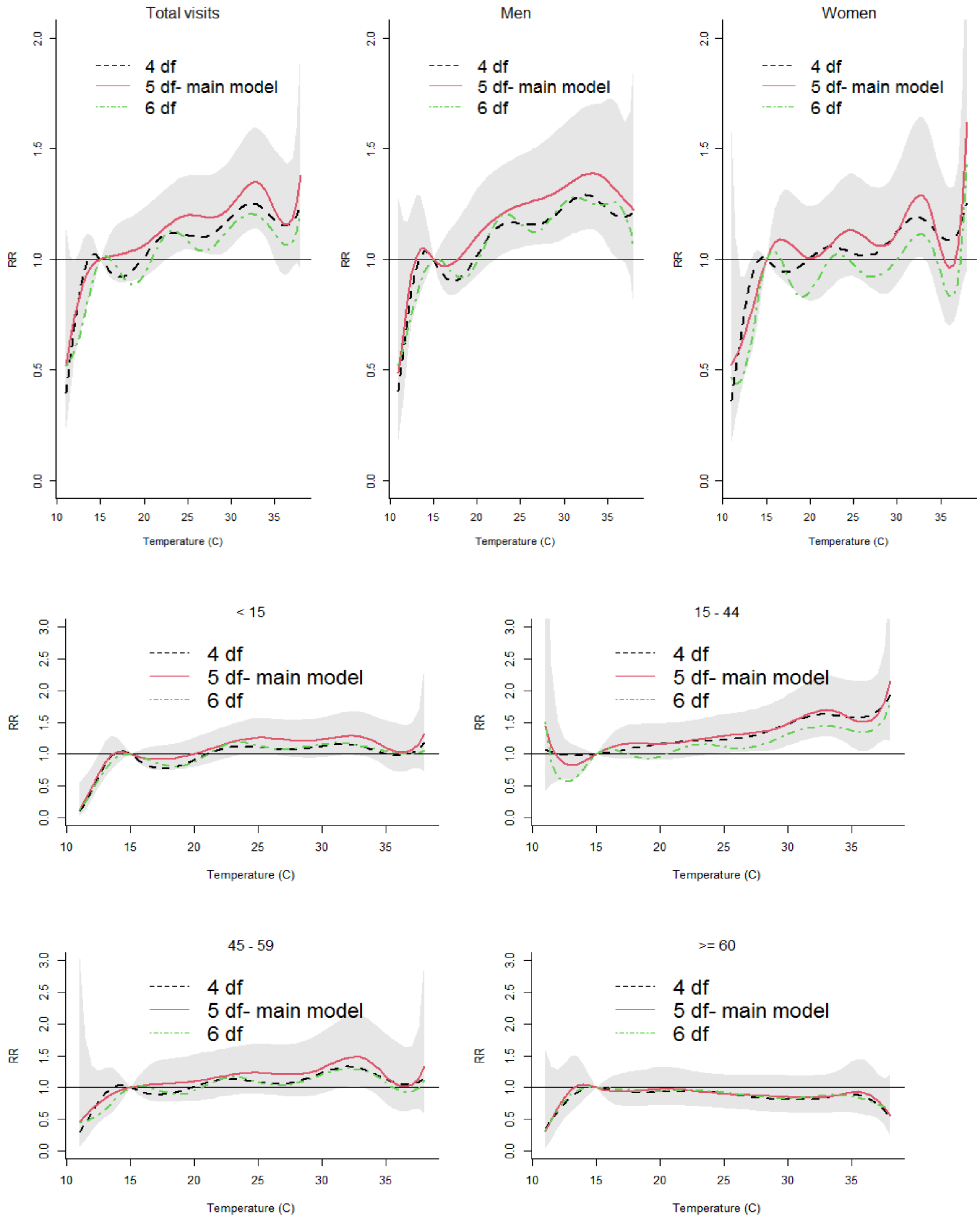


Figure 16 (Supplement Figure S4): Sensitivity analysis of non-linear effect estimates for injury using time series analysis by different knots of temperature (in the crossbasic function)

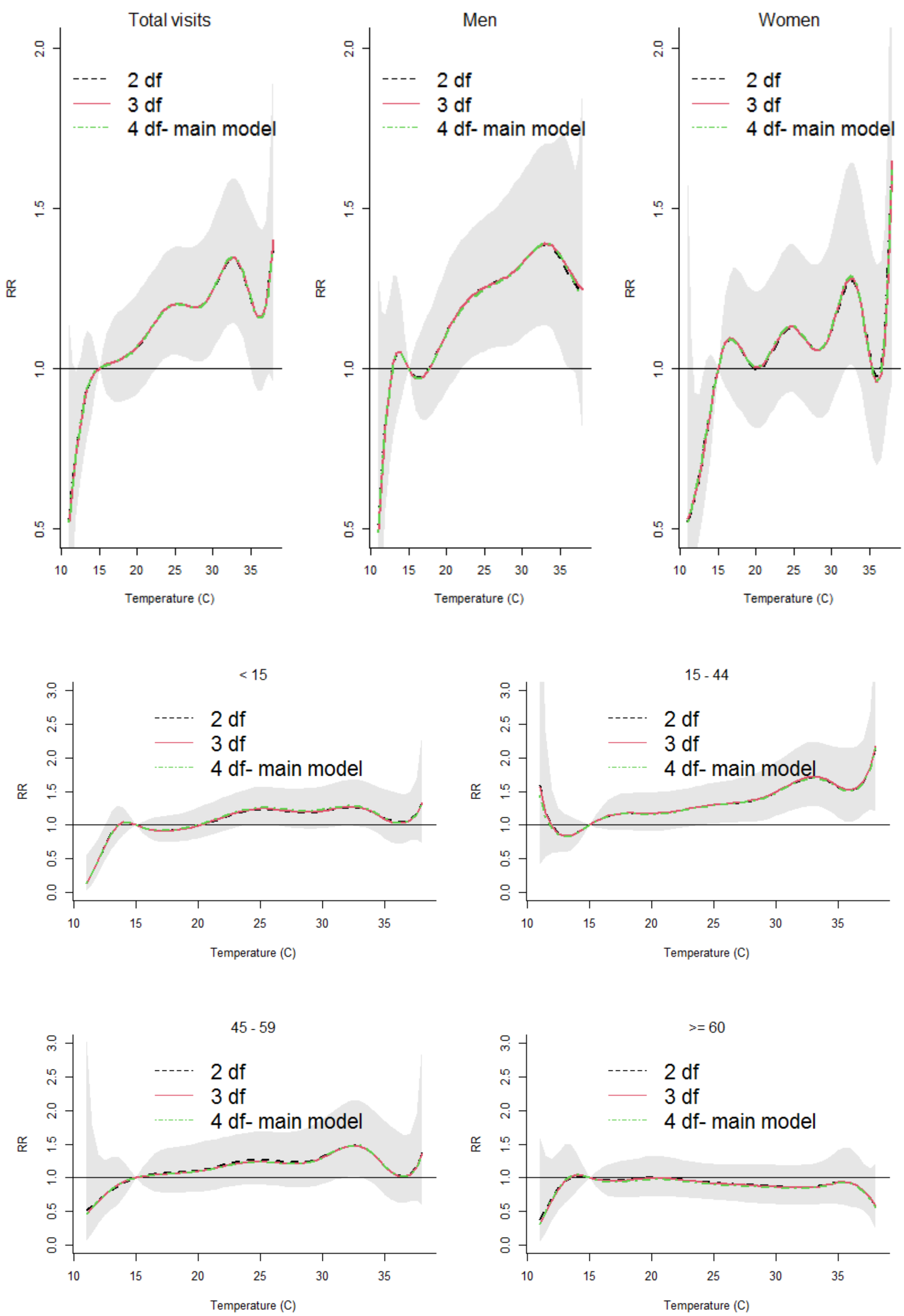


Figure 17 (Figure S5): Sensitivity analysis of non-linear effect estimates for injury using time series analysis by different knots of lag (in the crossbasic function)

Chapter 5

Summary Discussion

In this study, we examined the short-term effects of temperature on human health outcomes, including crime and injury, in Hanoi, Vietnam. We used both linear and non-linear models to estimate the percentage increase in the risk of each health outcome. Our findings indicated that an increase in daily mean temperature was associated with increased crime and ED visits due to injury. Heatwaves were considered weak protective factors against crime risk in urban Hanoi under three heatwave definitions. The findings did not meaningfully change when evaluating the sensitivity of the models to different elements. To date, this is the first study conducted to examine the effects of temperature on crime and injury in Hanoi, Vietnam.

In ***manuscript 1***, single-city-level data was used to evaluate the association between the short-term effects of temperature on crime events in urban Hanoi, Vietnam. We applied quasi-Poisson regression models to investigate the linear effects and distributed lag non-linear models to investigate the non-linear association between daily temperature and daily crime events from 2013 to 2019. For both linear and non-linear effects, there were positive associations between an increase in daily temperature and crime, and the greatest effects were observed on the first day of exposure (lag 0). For linear effects, we estimated that each 5 °C increase in daily mean temperature was associated with 9.9% (95%CI: 0.2; 20.5), 6.8% (95%CI: 0.6; 13.5), and 7.5% (95%CI: 2.3; 13.2) increase in the risk of violent, non-violent, and total crime, respectively. For non-linear effects, however, the crime risk plateaued at 30 °C and decreased at higher exposures, which presented an inverted U-shape response with large statistical uncertainty.

Our results contribute to expanding the literature supporting an elevated risk of crime with each unit increase in temperature. Recent evaluations have shown the association between daily temperature and crime events. For example, a study in Finland showed that a 2 °C increase in average temperature would increase violent crime rates by more than 3%(41). Research across 436 U.S. counties estimated that each 10 °C increase in daily temperature was associated with an 11.92% increase in the risk of violent crime. Associations with property crime risk were similar but lower in magnitude (49). A study in one U.S. city (Philadelphia, Pennsylvania) observed the highest crime rates during a mean daily heat index of 22.6- 28 °C(68). These studies indicate that ambient temperature is associated with crime rates, but different regions may show different relationships.

Manuscript 2 evaluates the heatwave-crime associations in urban Hanoi, Vietnam, from May to September for seven years (2013- 2019). The time-stratified case-crossover study design with a quasi-Poisson regression model was applied for three different heatwave definitions. Heatwaves were considered weak protective factors against crime risk in urban Hanoi under three heatwave definitions. For non-violent crime, 4-day heatwaves of 34.5 °C showed the most protective effect (RR=0.28, 95%CI = 0.08, 0.94). For violent crime, 2-days heatwave of 32 °C showed the most protective effect (RR= 0.65; 95%CI = 0.45; 0.93). In addition, longer durations under different heatwave definitions decreased violent and non-violent crime risks.

To the best of our knowledge, there is no existing literature reporting the effects of heatwaves on crime. However, we found some related evidence showing decreased crime risk at high temperatures. Our findings are explained by the Social Escape or Avoidance Theory and the Negative Affect Escape Model, which conclude that at a high temperature, people will interact less to avoid the heat (79)(47). These findings align with a study across 436 U.S. counties, which reported an inverted U-shape function, and a higher crime risk in winter and fall compared to summer(49). A current study in Dallas, Texas, found a positive increase in associations between daily mean temperature and aggravated crime beyond 80 °F (26.5 °C) , which then turns negative beyond 90 °F (32.2 °C)(50). Research in Philadelphia, Pennsylvania, reported that violent crime is highest when the mean daily temperature of 22.6 - 28 °C. The crime risk may be lower if the police reduce their patrolling on hot days and people are allowed not to go outside to minimize the effects of heat. In conclusion, we need additional research to examine the effects of heatwaves on crime is warranted.

Finally, in ***manuscript 3***, we reported the effects of temperature on ED visits due to injury in Hanoi, Vietnam using three years of data (2017 – 2019). For linear effects, each 5 °C increase in same-day mean temperature was associated with a 4.74% increase in the risk of ED visits due to injury on average (95%CI = 2.32 - 7.23%), and people exposed to higher temperatures at Q2, Q3, Q4 and Q5 show higher injury risk than those exposed to Q1 with 8.80%, 8.36%, 13.55%, and 15.66%, respectively. For non-linear effects, we observed an increase in the risk of injury at high temperatures but a decrease in the risk of injury at low temperatures, compared to the threshold temperature of 15 °C across three models. Men and young people had higher risk of injury than women and the elderly.

Our findings are consistent with previous studies. Occupational and epidemiological studies have observed different injury risks between men and women. Several work-related injury studies have indicated men have a higher risk of temperature-related injury than women globally(2)(113)(117)(118). Similarly, population-level research found that men have a higher injury risk than women with increased temperature(62)(115)(119)(120). There are some plausible behavioral pathways that have been used to explain the different risks between genders. Men are more likely to engage in outdoor activities during warmer conditions, such as working and doing exercises, than women during warmer conditions, which leads to increased injury risk(121). Moreover, relevant studies also found injury risk related to temperature among the elderly was lower than in other age groups, but the elderly seemed more sensitive to low temperature (112)(61).

Conclusions

While a large body of epidemiologic literature describes the effects of temperature on cardiovascular, respiratory, and mental health, fewer studies have been conducted to assess the effects of temperature on crime and injury. Our study is the first study conducted in Vietnam, a LMIC, to evaluate the temperature-crime and temperature-injury associations. The findings, in both linear and non-linear models, support the hypothesis that temperature influences criminal behavior and ED visits due to injury in Hanoi- the capital of Vietnam, which is consistent with previous studies. However, we observed that the crime risk decreased during heatwave days compared to non-heatwave days, and longer durations under different heatwave definitions decreased violent and non-violent crime risks. There is a lack of studies that examine the effects of heatwaves on crime. Further research is needed to investigate the comprehensive effects of heat on crime in different cities, countries, and regions.

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Appendix A.

Table: Form to collect hourly weather data (apply for each air monitor)

Name of the air monitor							
Date	Hours	Temp (°C)	RH (%)	$PM_{2.5}$ (μg/m^3)	NO_2 (μg/m^3)	O_3 (μg/m^3)	CO (μg/m^3)
01/01/2013	0						
	2						
	2						
	3						
	4						
	5						
	6						
	7						
	8						
	9						
	10						
	11						
	12						
	13						
	14						
	15						
	16						
	17						
	18						
	19						
	20						
	21						
	22						
	23						
…	…						
31/12/2019	0						
	1						
	2						
	3						
	4						
	5						
	6						
	…						
	23						

Appendix B.

Table 29: Form to collect daily crime data

Date	Violent crime	Non-violent crime	Total crime
01/01/2013			
01/02/2013			
01/03/2013			
….			
31/12/2019			

Appendix C.

Table 30: Form to collect emergency visit data

#	Age	Gender	District	Day-in	ICD10	ED visit (Yes/No)
1						
2						
3						
4						