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REPORT

Relationships between high temperatures and hospitalization risk in different ecological regions in Vietnam

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PROJECT SUMMARY

About the Project

This technical report was the final product of a research project funded by the Global Disaster Preparedness Center of the American Red Cross, the Red Cross Red Crescent Climate Centre, and the Global Heat Health Information Network (GHHIN), under the Project titled "Research on Extreme heat". The research project was carried out from May to October 2022. The research project provides a comprehensive assessment of the hospitalization risk of extreme heat and heatwave events in eight ecological regions in Vietnam using longitudinal hospitalization and meteorological dataset.

Project Objectives

1. To assess the short-term effects of ambient temperature on hospitalization risk in eight ecological regions in Vietnam
2. To assess the main effect and added effect of heatwaves on hospitalization risk in eight ecological regions in Vietnam

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LIST OF ABBREVIATION

DLM	Distributed Linear Model
HW	Heatwave
OP	Optimal Temperature
UNFCCC	United Nations Framework Convention on Climate Change
WHO	World Health Organization

EXECUTIVE SUMMARY

Introduction: The increased ambient temperatures worldwide have an adverse impact on health outcomes, including hospitalization risk. Vietnam is among the most vulnerable countries in the world to the negative impacts of climate change and severe weather events. However, most previous studies on the temperature-hospitalization relationship were implemented in high-income nations with a temperate climate. The research in low- and middle-income countries, including Vietnam, with tropical climates and a low climate change adaptation capacity, has not been focused. There were few studies examining the temperature-hospitalization association, especially multi-provincial studies representing all ecological regions in Vietnam.

Objective: The study aims to examine the impact of high temperature and heatwaves on the risk of all-cause and cause-specific hospitalization in eight ecological regions in Vietnam using a large multi-province data set.

Methods: The study uses data from daily hospital admission and weather data in eight provinces representing eight ecological regions of Vietnam, including Northwest, Northeast, Red River Delta, North Central Coast, South Central Coast, Central Highlands, Southeast, and Mekong River Delta. For a given province, the hospitalization and meteorological data were available for between five and ten years (in the period of 2005-2020), depending on when each provincial hospital implemented a computerized database and how complete the data were.

A time-series approach was applied using distributed lag linear models with the family of Poisson to examine hospitalizations for extreme temperatures and heatwave events. A random-effects meta-analysis was used to estimate the pooled risk of hospitalization for all causes and specific diseases including infectious, respiratory diseases, and mental health disorders.

Results: At the country level, the pooled estimates of effect showed a significant impact of an increase in temperature above the threshold (19ºC) by 1ºC with the marginal effects of 0.8% (RR=1.008 [95%CI:1.004-1.012]) on hospital admissions for all-cause, and 2.4% (RR=1.024 [1.018-1.03] for hospitalization of infectious diseases at lag 0-1 day. However, the heat effect on respiratory and mental health disorders was not significant (RR=1.004 [0.996-1.011], 1.012 [0.995-1.030], respectively). In terms of heatwave impacts, the result showed that the pooled main effects (due to high temperature) were greater than the added effects (due to the duration of hot days). The pool estimated for the whole country effect indicated that heatwave events were significantly associated with all-cause hospitalization (RR=1.07 [1.02-1.11]) and infectious diseases (RR=1.27, [1.13-1.44]) at lag 0–3 days. At the region-level effect, high temperatures affected all-cause admission higher in the Northern than in the Southern. The main effect for all-cause admission was highest in the Northeast (RR=1.23 [1.18-1.28]), followed by the Northwest (RR=1.09, [1.05-1.13]), the Southeast (RR=1.06. [1.02-1.1]), and Mekong River Delta (RR=1.04, [1.02-1.05]). There was no statistically significant effect of heatwaves on other regions including Red River Delta, North Central Coast, South Centre Coast, and Central Highland.

Conclusions: This is the first study in Vietnam to evaluate the effects of heat on residents' health living in eight ecoregions, representing Vietnam's geographical and climatic patterns. The findings enhance the evidence that high temperatures and heatwaves are associated with increased hospitalization risk, especially infectious diseases. The differences in size effects among regions suggest the importance to identify heat-vulnerable regions and local-specific adaptation strategies to protect residents from extreme temperature conditions

Keywords: Climate change, *Temperature, Heatwaves, Hospitalization, Ecological regions, Vietnam,*

INTRODUCTION

Extreme heat and heatwaves are the most common phenomena associated with climate change, with an increase in frequency, intensity, and adverse effects on a global scale (Watts et al., 2018). Nearly one-third of the world's population is estimated to be currently facing extreme heat events for at least 20 days a year and this percentage is expected to increase to 50% by 2100 (Mora et al., 2017). The World Health Organization (WHO) declared extreme heat to be one of the most serious natural hazards, but this has still not received adequate attention (McGregor et al., 2015). Extreme heat and heatwaves are expected to increase in the coming decades and have serious consequences for the environment, society, economy, and human health.

Exposure to heat and heatwaves can compromise human health both directly and indirectly and lead to an increase in the burden of disease (Watts et al., 2018). Health effects of heat exposure are multiple and complex, can ranging from minor symptoms, such as heat oedema, fatigue, and headache to severe fainting, heat exhaustion, and heatstroke, and can even lead to heat-related death (Guo et al., 2017; Watts et al., 2018). In addition, heat exposure exacerbates existing health conditions, increases the risk of hospitalization and mortality, as well as creates threats of communicable diseases (Benevolenza & DeRigne, 2019). These effects seem to be long-lasting, costly, and serious (Steffen et al., 2014).

The research was conducted in Vietnam - one of the countries that are most vulnerable to climate change, natural hazards, and extreme temperature events while having limited resources and a disadvantaged healthcare system. However, Vietnam currently lacks evidence-based guidelines and regulations on heat exposure. In recent years, the studies that assess heat-related health issues have been more studied; however, a lack of studies exists that assess the impacts of heat on hospitalization risk on a national scale. For these reasons, the study was implemented to fill the gaps in the literature, aiming to assess the association between increasing temperature and the risk of hospitalization across eight ecological regions in Vietnam.

LITERATURE REVIEW

1. Climate Change in Viet Nam

Located in the Southeast Asian typhoon belt, Vietnam is among the most vulnerable countries to the impacts of climate-related extreme events. According to The Global Climate Risk Index 2020, Vietnam is the sixth country in the world most affected by climate change. During the period from 1999 to 2018, Vietnam experienced a total of 226 extreme climate events that led to 28580 deaths and 2018.77 million US$ losses (equivalent to 0.47% GDP) (Eckstein et al., 2019). The geographical location, topography, and demographic characteristics of Vietnam are some of the main reasons that make this nation become one of the world's most disaster-prone areas. Vietnamese territory spans 15 degrees of latitude, is S-shaped, and has a total land area of approximately 331,000 km2, with a long coastline of 3260 km. It is a long narrow country, the north-to-south distance of Vietnam is 1,650 km, the wide at the narrowest point is around 50 km, and a coastline of 3260 kilometres (Thao et al., 2014).

The Vietnamese population in 2019 was more than 96.2 million, ranking 15th worldwide, with an average annual population growth rate of 1.14% (General Statistics Office of Vietnam, 2019). The population density of Vietnam was 290 people per square kilometre, which ranked second in Southeast Asia (after Singapore) (The World Bank, 2018). Although the current average greenhouse gas emissions in Vietnam (1.8 metric tons per capita) is still far lower than that on the global average (4.98 Mt/capita), the impacts of climate change on the economy and health of Vietnamese people are significant (The World Bank, 2020). A health vulnerability and adaptation assessment conducted in Vietnam showed that the health sector has been facing a "high" level of natural hazard exposure while a "very low" level of adaptive capacity (Tuyet Hanh et al., 2020). These features contribute to increasing the vulnerability of Vietnam to climate change and extreme weather events currently and in the future.

The increase in frequency, intensity, and duration of heatwaves is the most common phenomenon of climate change. In Vietnam, the average temperature has risen between 0.5 to 0.7°c during the recent 50 years. From 1970 to 2010, the average surface temperature in Vietnam increased by 0.26°C (±0.10°C) per decade, this was double the rate of global temperature during the same period (Nguyen et al., 2014). Vietnam lies in a tropical region; the climate condition is hot and humid throughout the year. The country has diverse climates with humid subtropical conditions prevalent in the northern, tropical monsoon conditions in the central, and tropical savannah conditions in the southern (Global Facility for Disaster Reduction and Recovery (GFDRR), 2011). In the northern part, the temperature ranges from 15-20oC in winter to 22-27.5ºC in summer while in the south, with a narrower range of the temperature, is from 26-27ºC in winter to 28-29ºC in summer (The World Bank, 2020). The combination of high temperature and high humidity reduces sweating, affects the body's cooling system, and increases vulnerability to extreme temperature (Eckstein et al., 2019; Sherbakov et al., 2018).

2. Future Climate Change Scenarios in Vietnam

Temperature and extreme weather events in Vietnam are projected to increase in the next decades. The average ambient temperature is forecasted to rise by 1.8°C in 2050 and by 3.36°C by 2080–2100 under the highest emission pathway (Representative Concentration Pathway 8.5 - RCP8.5) compared to the baseline period of 1986-2005 (AusAID, 2017). The number of heatwaves are expected to increase by 180% by 2050 (USAID, 2017). In parallel with this, the impacts of extreme climate events are projected to increase in the coming decades (AusAID, 2017). Compared to the period 1986-2005, the number of hot days (above 35°C) is projected to significantly increase by 27.2 days in 2050 under RCP 8.5, especially in summer from May to July, and the increase in temperature is expected to be highest in Southern Vietnam (World Bank Group, 2019). Annual rainfall could generally increase in a range of 5% to15% for RCP 4.5 (is the most probable baseline scenario without climate policies) and 20% for RCP8.5. The number of annual storms is forecasted to tend to increase. The summer monsoon will start earlier and end later while monsoon rainfall has an increasing trend. The number of extreme cold nights and days is projected to be declined in the areas of the North, the Red River Delta, and the North Central while hot days (Tmax ≥ 35°C) could increase with high volumes of hot days may occur from September to November, and 'hot' nights from June to August (Thang et al., 2020). As temperature rises and rainfall deficits decrease in the dry season, drought events are projected to become more severe (Thang et al., 2020). By the late 21st century, the sea level could rise about 55 cm (from 33-75 cm) for RCP4.5 and 77cm (from 51-106 cm) for RCP8.5. Under the RCP8.5 emissions pathway, climate change in Vietnam is projected to annually affect additional 433,000 people and damage GDP by $3.6 billion in 2030 (The World Bank, 2020). Increasing ambient temperatures and extreme weather events can cause a variety of health issues and diseases associated with climate change, increase the economic burden, and challenge the capacity of the health system.

3. Research on Human health impacts of extreme heat and heatwaves

Definition of heatwaves

Although heatwaves and their effects have been more reported in recent years, there is no standard definition for a heatwave. Each country and region have its own heatwave definition depending on local weather conditions and geographical characteristics (Xu et al., 2016). Therefore, the weather conditions that are determined as a heatwave in one region may not be considered as a heatwave in other areas. Key criteria which are often used to consider as a heatwave include duration (from 2-6 days and above), maximum temperature (above 35ºC, 37ºC, above 95^{th} or 97.5^{th} percentile), or minimum temperature, and some definitions combine humidity index and season (Azhar et al., 2014; D'Ippoliti et al., 2010; Tong et al., 2010). Basically, a heatwave is an unusually high outdoor temperature that lasts for a couple of days and may have detrimental health impacts (Robinson, 2001). In order to sufficiently assess the effect of heatwaves, it is important to take into account the effect of both the intensity of high temperatures (so-called "main effect") and the prolonged heat for several consecutive days (so-called "added effect")

Human health impacts of extreme heat

Exposure to high ambient temperature and heatwaves can lead to heat-related illnesses, increases the hospitalization risk, exacerbate current chronic conditions, spread outbreak, and even heat-related deaths (Guo et al., 2017; Watts et al., 2018). These health effects seem to be long-lasting, costly, and serious (Steffen et al., 2014). Figure 1 summarises the impacts of heat exposure on human health.

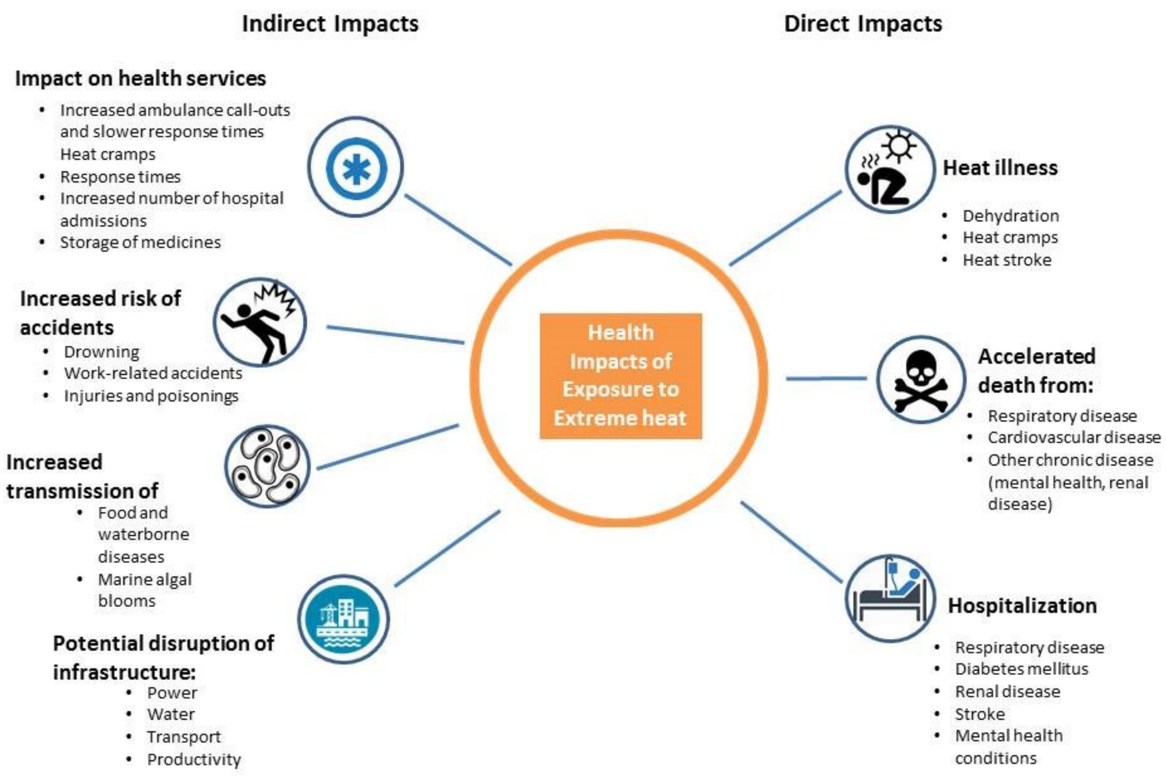


Figure 1. Impacts of extreme heat on human health

Source: https://www.who.int/globalchange/publications/heat-and-health/en/

After exposing heat, the individuals are at a high risk of heat rash due to clogged sweat glands; heat syncope due to strenuous work or a failure to adapt to rapid changes in temperature; and heat cramps caused by an electrolyte imbalance after heavy sweating (Jackson & Rosenberg, 2010). More seriously, heat exhaustion may happen with symptoms of muscle weakness, heavy sweating, rapid pulse, and fatigue due to dehydration. Heatstroke is the most serious HRI with a high risk of permanent organ damage and a fatality rate may up to 50% (Nutong et al., 2018). A study by Xiang et al. (2015) reported that 1°C increase in maximum temperature (above 35.5°C), the risk of occupational heat illnesses raised 12.7%.

Extreme heat also can increase the risk of all-cause and cause-specific hospitalizations (Cheng et al., 2019). For example, a meta-analysis of 64 heat-health studies showed that heatwave exposure and the increase in the difference between the daily maximum and minimum temperature significantly increased the risk of cardiovascular hospitalization by 2.2% and 0.7%, respectively (Phung, Guo, Thai, et al., 2016). Similarly, hospitalizations risk for other chronic diseases such as respiratory, diabetes mellitus, and kidney diseases were also associated with the increase in temperature (Anderson et al., 2013; Huang et al., 2011).

In addition, the increase in ambient temperatures can raise the risk of emerging and re-emerging communicable diseases. Changes in temperature and other climate conditions can lead to changes in the distribution and transmission capacity of vector-borne and water-borne diseases. For example, when temperature increase, the viral replication rate goes faster in the mosquito, and transmission dynamics increase. According to the Lancet Countdown report, changing climatic conditions have been contributing to an increase in vectorial capacity for dengue fever transmission, reflecting an estimated 9.4% increase since pre-industrial times (1950) (Watts et al., 2018).

More seriously, extended periods of extreme heat can create cumulative physiological stress and exacerbate the leading causes of death globally, especially cardiovascular, and respiratory diseases, kidney diseases, and diabetes mellitus (Cheng et al., 2019; Deng et al., 2019). A systematic review of heat-health association among people as age 65 and over showed that there was a 2–5% increase in all-cause mortality among elders for each 1ºC increase during hot temperature intervals (Yu et al., 2012).

4. Vulnerable groups in extreme heat

While all populations can be affected by extreme heat exposure, some groups are at a higher risk of illness and death than others. Literature has identified high-risk groups of heat exposure, including children, elders, and people with pre-existing health problems (Watts et al., 2018; Zeng et al., 2014), manual labourers and outdoor workers (Hanna et al., 2011), those who have low incomes, low educational level, being homeless, social isolation, living in poor housing conditions, and some urban dwellers (Jabeen & Johnson, 2013). Infants have immature thermoregulation, and a higher body surface area-to-mass ratio than adults (Hanna et al., 2011). In contrast, the elderly and those with existing chronic diseases have reduced physical capacity, weaker immune systems, comorbidities, decreased thermostatic function, and reduced ability to care for themselves (Bai et al., 2014; Kenny et al., 2010; Yin & Wang, 2017). Therefore, these groups are at a high morbidity and mortality risk during extreme heat events. A meta-analysis and systematic review by Yu et al. (2012) showed an association of a 2-5% increase in all-cause mortality among the elderly group per 1ºC increase in temperature during hot weather. Also, WHO (2018) estimated that between 2030 and 2050, there might be approximately 38,000 additional deaths per year related to heat exposure among elderly people worldwide. In addition, outdoor labourers including construction workers, farmers, fisheries, forestry, freelance, and street vendors are at a particularly high level of heat exposure because working outside for long hours is their job characteristics (Hanna et al., 2011; Xiang et al., 2015).

5. Current legislation and public health programs related to climate change and extreme heat adaptation in Vietnam

Vietnam is one of the first countries in Southeast Asia to participate in international climate change negotiations in the 1990s. Vietnam has been a member of the United Nations Framework Convention on Climate Change (UNFCCC) since 1994, ratified the Kyoto Protocol in 2002, and The Hyogo Framework for Action in 2005 (Nachmany et al., 2015). The Vietnamese government had issued Laws, Decrees, and Decisions related to Climate change adaptation and mitigation, and integrated disaster mitigation strategies into National policy and legislation for social and economic development (see Figure 2 for some important milestones). The National Target Programme to Respond to Climate Change was first issued in 2008, which required the mainstreaming of all climate change adaptation activities in all sectors such as agriculture, industry, education, and health. The Ministry of Natural Resources and Environment has the principal responsibility for implementing climate change adaptation activities combined with the legal advice of the Department of Legal Affairs and the collaboration of other ministries and organizations (Nachmany et al., 2015).

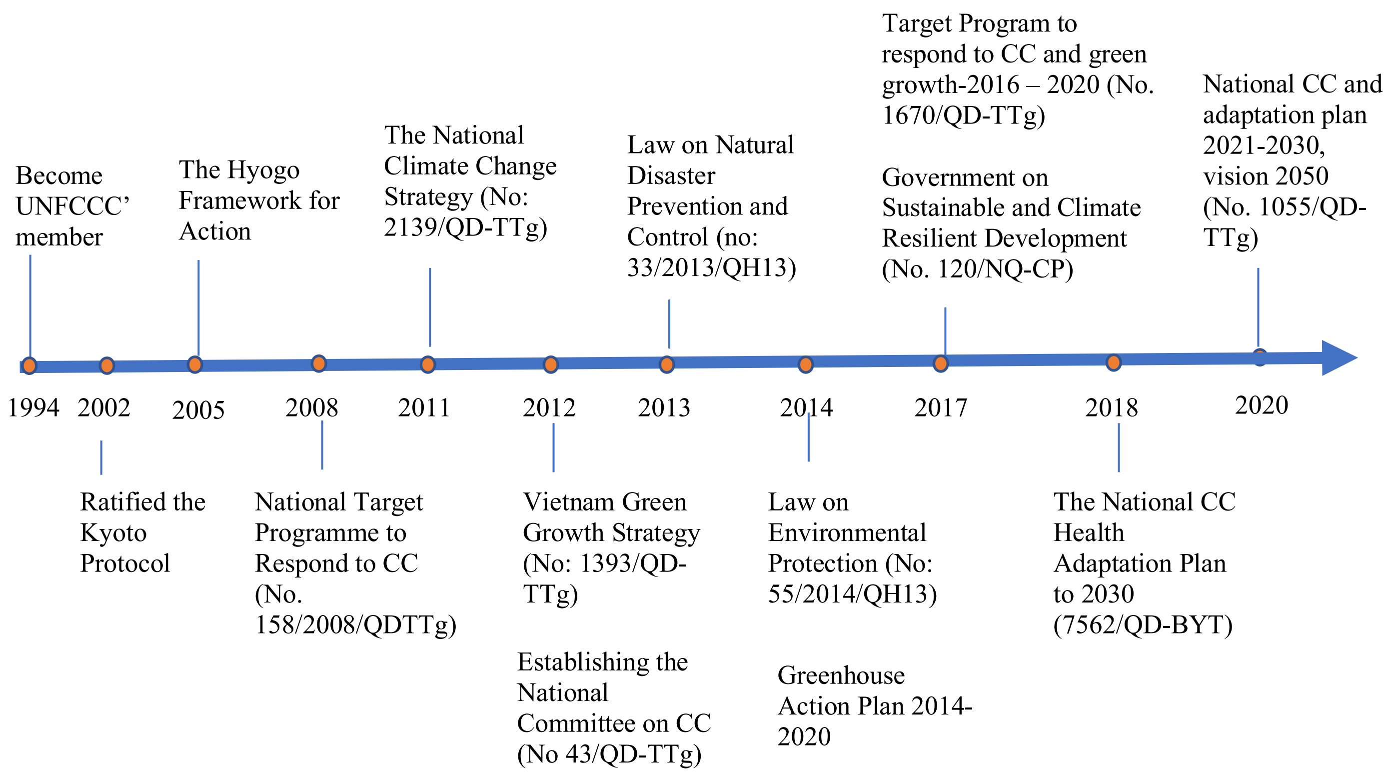


Figure 2. Climate change policies in Vietnam since 1994

In general, strategies to respond to climate change are gaining increasing attention in Vietnam. However, there is a lack of specific regulation for some extreme weather events such as damaging cold, freezing, and heatwaves. According to Law on Natural Disaster Prevention and Control in 2013 (Decision 33/2013/QH13) and new amendments to natural disaster, dike, and construction laws in 2020 (Decision 60/2020/QH14), extreme heat is mentioned as a natural hazard. However, unlike floods and storms, there are currently no specific regulations and guidelines to prevent heat exposure and minimize the health effects of extreme heat. The Ministry of Health (MOH) and The Standard and Quality Institute have issued some heat-humidity threshold guidelines for workplaces. For example, Decision number 26/2016/TT-NYT stipulates that if the humidity is from 40-80%, the temperature threshold at workplaces should be around 20-34°C for light work, 18-32°C for medium work and 16-30°C for heavy tasks, respectively. If humidity is above 80%, these thresholds need to be lowered (Ministry of Health, 2016). Meanwhile, many regions in Vietnam have an average of more than 200 days per year with a heat index equal to or above 34°C (Opitz-Stapleton, 2014). A large population, therefore, are at a very high risk of heat exposure if lacking proper cooling equipment.

6. Challenges in assessing the heat-health relationship

It is noted that examining the heat-health association is quite difficult because heat impacts are often indirect and tend to accumulate over time while it is complex to determine the beginning and end time (Stanke et al., 2013). Heat-related morbidity and mortality are essentially unknown and underestimated because a high proportion of people suffering from heat-related illnesses such as headaches, dizziness, and fainting often treat themselves and do not appear in medical reports (Jackson & Rosenberg, 2010). Also, these symptoms can be confused with symptoms of other illnesses such as pesticide poisoning, gastrointestinal diseases, or some other common viral diseases. As a result, these patients may not be considered to have heat-related illnesses (Methner & Eisenberg, 2018). In addition, a high number of morbidity and mortality occurring in extreme heat events were not clinically associated with the heat, however, high temperatures contributed to the failure of an already weakened body system (Green et al., 2019). Therefore, heat may not be recorded as direct causing nor contributing to death in death certificates (Benmarhnia et al., 2015). A systematic review of heatwaves and health impacts by Campbell et al. (2018) showed that most of the reviewed studies were conducted in the mid-latitude regions and developed countries with low- to medium-population density. It means that regions most vulnerable to heatwaves exposure, such as Africa and Asia were not represented. Underreporting of heat-related illnesses and limited data from low- and middle-income countries could challenge the quality and reliability of the studies' results. Furthermore, not only ambient temperature but also many other factors such as humidity, wind, radiant temperature, physical activities, clothing, and existing health conditions combine and influence a person's thermal comfort (Müller et al., 2014). Therefore, assessing the impacts of extreme and heatwaves on human health is very complex.

METHODOLOGY

Study period

The research project was carried out from May to October 2022. The study used a longitudinal dataset from multi-provinces across Vietnam. For a given province, the hospitalization and meteorological data were available for between five and ten years (in the period 2005 to 2020), depending on the availability and quality of the data.

Study sites

This is a national-scale study. Eight selected provinces are representative of eight ecological regions of Vietnam classified by topography, soils, and climate. Figure 3 shows the geographic locations of the eight selected provinces and Table 1 describes some baseline information on these provinces based on the report of the Vietnam General Statistics Office 2019

Table 1. General information on selected provinces

Province	Area (Km2)	Average population	Population density (Person/km^2)	Regions
Bac Giang	3895.6	1841.6	473	North East
Dien Bien	9541.3	601,700	63	North Weast
Ha Nội	3358.6	8246.6	2455	Red River Delta
Ha Tinh	5990.7	1,290,300	215	North Central
Binh Dinh	6066.2	1,487,800	245	South Central
Dak Lak	6509.3	637.9	98	Central Highland
Bình Phước	6876.8	1011.1	147	South East
Đồng Tháp	3383.8	1600.0	473	Mekong Delta

Source: General Statistics Office of Vietnam (2019) - https://www.gso.gov.vn/wp-content/uploads/2021/07/Nien-giam-Tom-Tat-2020Ban-quyen.pdf

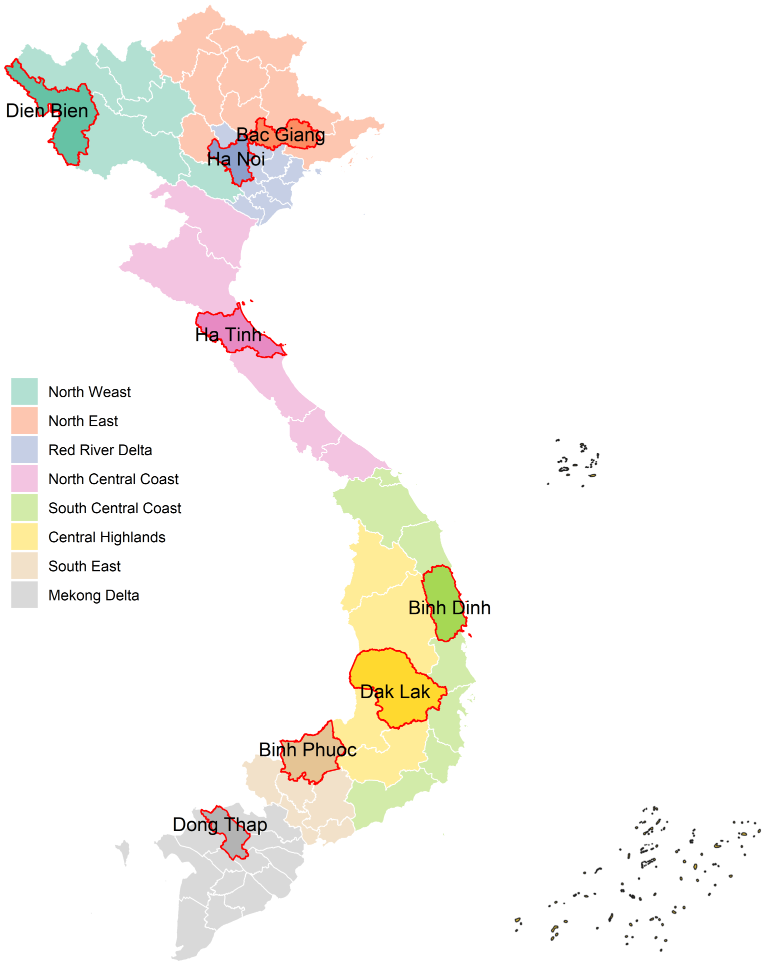


Figure 3. The map of eight provinces represents eight ecological regions in Vietnam.

(Note: This map is created from the shapefile (an empty map) that is publicly available from http://gadm.org)

Data availability

The study used secondary data from admission records of provincial hospitals and hydro-meteorological stations. The hospital admission record is deidentified data that cannot be linked to individual information. The hospitalization dataset is managed and provided by Vietnam Health Environment Management Agency, Ministry of Health – the organization has responsibility for climate change and health adaptation in Vietnam. In addition, provincial hydro-meteorological stations provide weather data. A part of the dataset was also used for the previous studies that examined the association between extreme heat and hospitalization risk in specific age groups and specific health outcomes in Vietnam (Phung et al., 2017; Phung, Guo, Thai, et al., 2016; Talukder et al., 2022).

Information for each admission comprised of date of birth, sex, date of admission, date of discharge, residential locations, and the International Classification of Diseases – 10th Revision (ICD 10) code (codes for all-cause – excluding external causes, and the codes for some group of diseases). Table 2 presents some groups of diseases (with the corresponding ICD 10 code) that may be associated with temperature changes.

Data on meteorology was obtained from the provincial hydro-meteorological stations. Weather data included daily minimum, maximum and average temperature (°C), relative humidity (%), and daily cumulative rainfall (mm).

Table 2. ICD-10 Codes for heat-sensitive diseases.

	Disease/Group of diseases	ICD-10	Notes
0	All hospital admission	A00-Z99	Exclude: delivery (O80-84); health services (Z00-99); External causes (V01-Y98)
1	Certain infectious and Parasitic diseases	A00-99	Exclude: Infections with a predominant sexual mode of transmission (A50-64)
		B00-99	Exclude: HIV (B20-24); Helminthiases (B65-83); Sequelae of infectious and parasitic diseases (B90-94)
2	Mental and Behavioural Disorders	F01-99	Exclude: mental retardation (F70-79); disorders of psychological development (F80-89)
3	Diseases of the respiratory system	J00-99	Exclude: Lung diseases due to external agents (J60-70)

Definition of heatwaves

Although minimum, mean, maximum temperatures, and the range difference between the maximum and minimum temperatures were common indicators used in some studies. Previous national-scale and multicountry studies suggest that the heat-health association may be better estimated by daily mean temperature than by other indicators (Guo et al., 2017; Zhao et al., 2019). In this study, we applied different definitions of heatwaves based on the percentile of daily mean temperature and duration of hot days. Table 3 presents heatwave definitions used in this research.

Table 3. Definition of Heatwaves

Heatwave Type	Heatwave name	Heatwave definition
HW1	**hw.2.97**	**97th percentile with ≥2 days duration**
HW2	hw.2.98	98th percentile with ≥2 days duration
HW3	hw.2.99	99th percentile with ≥2 days duration
HW4	hw.4.97	97th percentile with ≥4 days duration
HW5	hw.4.98	98th percentile with ≥4 days duration
HW6	hw.4.99	99th percentile with ≥4 days duration

Statistical analysis

A time-series analysis was applied using time-varying distributed lag linear models (DLM) to analyze the data. Time-series analysis allows us to assess the short-term relationship between exposure (daily temperature and heatwaves) and health outcomes (hospitalization and mortality) while controlling for other potential confounding factors. This analysis method has been described in previous studies (Bhaskaran et al., 2013; Gasparrini, 2011). The analysis process included two main stages: a common model applied to each province and then a meta-analytic procedure to derive the pooled estimates for the country-level.

In the first stage, the author examined the association between daily average temperature, heatwaves, and hospitalization admission risk for each province by using the GLM with a quasi-Poisson family. The long-term trends and seasonality were controlled by using a national cubic B-spline of time with equally spaced knots and 4 degrees of freedom. In addition, the analysis adjusted for humidity (by using a national cubic B-spline of time with equally spaced knots and 3 degrees of freedom) and days of the week. The risk of heat-related health issues usually depends not only on the temperature of hospital admission day but also on the exposure to the high temperatures of some previous days. For this reason, the DLM for lags up to 7 days was applied to calculate the delayed effect of temperature for a week.

The complete model to examine the temperature – hospitalization relationship is described in the following equation

$$Y_t \sim Poisson\ (\mu_t)$$

$$Ln(\mu_t) = \alpha + \sum_{t=i}^{l} \beta_i T_{t-i} + \beta_j H + \beta_k R + s(time, 4df * year) + \gamma DOW$$

- where, Y_t is the daily count of all-cause hospitalization on day t.
- α is the intercept
- *Ti* is the average daily temperature on day i and l is the max lag
- *H* is the daily average humidity,
- *R* is the daily cumulative rainfall,
- *s(time)* is the flexible spline function of time (4 knots per year),
- *DOW* is the day of the week.

To examine the main and added effects of heat waves on hospitalization risk, the continuous average temperature variable and the heatwave event variable ('1' if a heatwave occurred vs '0' if otherwise) were put into the model at the same time.

In the second stage, the country-level pooled effects of temperature and heatwaves on hospitalization were calculated through a random effect meta-analysis. The pooled estimates were calculated for hospital admission (all-cause and cause-specific). The effect sizes were assessed for the lags 0-7 days. Statistical analysis was performed using R software (version 4.0.2).

RESULTS

1. General description of data set

Table 4. Descriptive statistics of hospitalizations and temperature in eight regions.

Province	Region	Study period	Hospitalization (daily mean)	Temperature (average °C)*	Number of heatwaves (# days)
Dien Bien	Northwest	1/1/2005 - 31/12/2015	51.4	22.1	153
Bac Giang	Southwest	1/1/2008 - 31/12/2015	97.2	24.4	924
Ha Noi	Red River Delta	1/1/2008 - 31/12/2013	47.4	24.2	656
Ha Tinh	North Central Coast	1/1/2017 - 31/12/2020	76.1	25.3	30
Binh Dinh	South Central Coast	1/1/2008 - 31/12/2012	140.0	26.3	45
Dak Lak	Central Highland	1/1/2017 - 31/12/2020	133.1	24.0	36
Binh Phuoc	Southeast	1/1/2008 - 31/12/2014	74	28.3	57
Dong Thap	Mekong River Delta	1/1/2002 - 31/12/2013	62.1	27.3	71

Table 4 presents the descriptive statistics of the data, including daily admission, average temperature, and the number of heatwave events in eight provinces representing eight ecological regions in Vietnam. The mean temperature ranged from 22.1 to 28.3 °C. The total number of hospital admissions by all causes from the study period at eight provincial hospitals was 1,614,286. The daily number of hospital admissions fluctuated with mean values ranging between 47 to 140 cases across the provinces. Regarding infectious diseases, the percentage of hospital admissions in the Mekong River Delta was the largest, accounting for 23.8%. Daily hospitalizations by mental health disorders accounted for the lowest proportion of all- cause admissions.

During the study period, the daily maximum temperature ranged from 26.7°C in the Northwest to 33.6 °C in the Southeast. The lowest average daily temperature was 24°C in Central Highland. Meanwhile, the daily minimum temperature was highest in the Southeast at 25.1°C and lowest in the Northwest, at merely 17.5% in eight regions of Vietnam. The daily mean relative humidity ranged from 73.9 to 83.3 for the Northwest and the Mekong River Delta, respectively.

Figure 4 shows the time series plot of the daily basis of all-cause hospitalization, temperature, and humidity of each province. The time study is between four to ten years, depending on the availability of the dataset. The red lines indicate the summer period of each year from May to July which had high temperatures (average above 28°C, and sometimes reached 35 °C). Heatwave events often occurred during these periods. The observed daily hospital admissions also seemed to be high during the summer months.

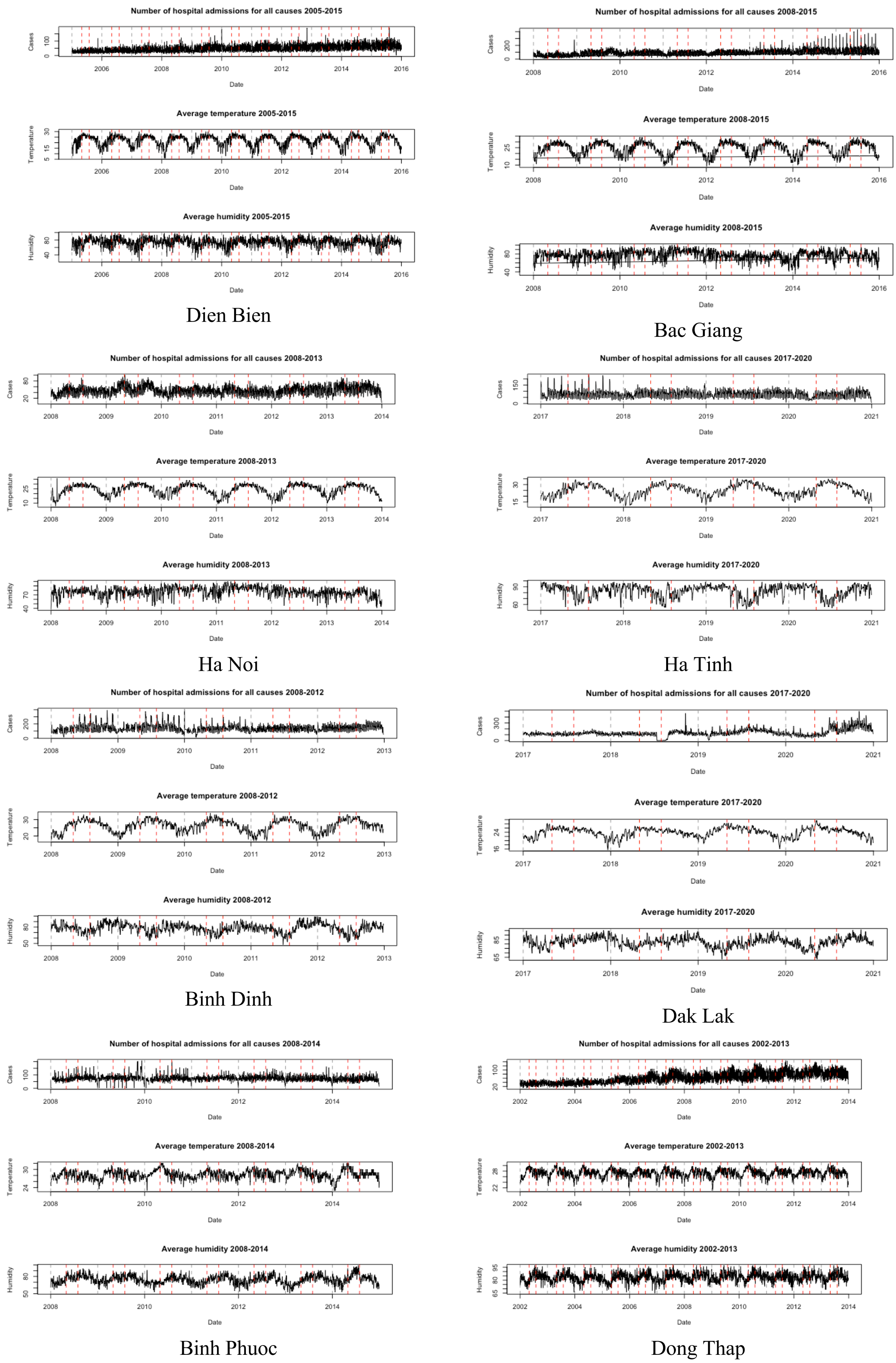


Figure 4. Time series plot of the daily all-cause hospitalization, temperature and relative humidity in eight provinces (The red lines indicate the summer period from May to July).

2. The province-level effect of temperature and heatwaves on hospitalization in different ecological regions

2.1. The province-level effect of temperature

The short-term effects of temperature on hospitalization for cumulative lag days, and disease groups varied across eight provinces. Overall, the association between temperature and the risk of hospital admission for all-cause and cause-specific was mostly observed for cumulative lag for 1 day (lag 0-1 day) (Table 5). The effects seemed to be higher in Northern Vietnam including Southwest, Southeast, and Northwest) than in other regions.

Regarding all-cause hospital admissions, positive associations between the high temperatures and the hospitalization risk were observed in six regions excluding the South Central Coast and Central Highland. The effect was highest in Southeast, followed by Mekong River Delta, Northwest, Southwest, North Central Coast, and Red River Delta. For example, in Southeast, significant associations were found up at lag 0-1 with 1.016 [95%CI: 1.003-1.03] equivalent to an increase of 1.6% risk of hospitalization for 1°C increase in average ambient temperatures above the threshold. Similarly, the risk (RR, [95%CI]) of all-cause hospitalization increased by 1.015 [1.009-1.021] in Mekong River Delta and 1.004 [1.000 - 1.067] in Red River Delta at cumulative lag 0-1.

In terms of infectious diseases, the significant association between temperature and hospitalisation were observed in most regions except for South Central Coast and Central Highland regions. Also, the effects were found from cumulative lag 0-1 to lag 0-7. The risk was highest in the North Central Coast region while lowest in the Mekong River Delta region (1.037 [1.022-1.052]) vs 1.018 [1.006-1.029], respectively). Regarding respiratory disease admissions, significant relationships were observed in North Central Coast and Northwest which increased hospital admission risk by 1.013 [1.004-1.022] and 1.014 [0.003-0.025], respectively at a cumulative lag of 0-1 day. For mental health disorders, the effects of high temperatures seemed to be not significant in all regions except for North Central Coast. For instance, for each degree increased after the threshold, the risk of mental health admissions increased by 1.047 [1.011-1.085] in North Central Coast. The impacts of temperatures in other cumulative lag days (from lag 0-1 to lag 0-7days) were presented in Appendix 1.

Table 5. Cause-specific hospital admissions increase in per cent per 1oC increase by mean, at lag 0-1.

Regions	% Change (95% CI) associated with 1°C increase in daily average temperature above threshold (lag 0-1)			
	All-cause	Infectious diseases	Respiratory diseases	Mental health disorder
Northwest (OT=19°C)	1.2 (0.5-2.0)*	2.5 (0.6-4.6)*	1.4 (0.3-2.5)*	0.7 (-2.3-3.9)
Southwest (OT=19°C)	1.0 (0.5-1.6)*	2.8 (1.3-4.4)*	-0.8 (-2.0-0.5)	-2.1 (-6.9-2.9)
Red River Delta (OT=19°C)	0.4 (0.02-0.9)*	2.3 (1.3-3.3)*	0.3 (-0.9-0.4)	0.0 (-2.6-2.7)
North Central Coast (OT=19°C)	0.8 (0.1-1.6)*	3.7 (2.2-5.2)*	1.3 (0.4-2.2)*	4.7 (1.1-8.5)*
South Central Coast (OT=20°C)	0.1 (-0.9-1.0)	2.2 (0.9-3.5)*	0.2 (-1.2-1.7)	0.6 (-5.7-7.4)
Central Highland (OT=20°C)	0.2 (-1.2-1.7)	1.4 (-0.5-3.3)	0.5 (-1.3-2.3)	0.7 (-7.1-9.2)
Southeast (OT=26°C)	1.6 (0.3-3.0)*	1.3 (-1.1-3.7)	2.0 (-0.3-4.4)	1.2 (-5.6-8.4)
Mekong River Delta (OT=25°C)	1.5 (0.9-2.1)*	1.8 (0.6-2.9)*	1.0 (0.2-2.3)	3.5 (-0.3-7.5)
* Statistically significant at a p-value of 0.05 or lower. OT: Optimum temperature				

2.2. The province-level effect of heat waves

The associations between heatwaves (the main and added effects) and hospitalization by causes of admissions in eight provinces presenting eight ecological regions are presented in Table 6. The heatwave defined as from the 97th percentile with two or more days duration shows the highest effect on the hospitalization risk. Other the pooled main and added effects with tests for heterogeneity across eight regions under different heatwave definitions (Appendix 2). Overall, the association between heatwaves and hospitalization risk was observed for a cumulative lag 0-3. The main effect of heatwaves on all-cause admission varied across regions, it was highest in the Northeast (1.23 [1.18-1.28]), followed by the Northwest (1.09, [1.05-1.13]), the Southeast (1.06. [1.02-1.1]), and Mekong River Delta (RR=1.04, [1.02-1.05]). In other regions, the main effect of heatwaves was not significant. The main effect of heatwaves (due to high temperature) seems to be stronger than added effect (due to the duration of the hot days) in most of analyse.

In Northwest (Dien Bien), it was observed that the main effect of heat waves significantly increased the risk of hospitalization, in which the RRs were 1.09 [95%CI: (1.048-1.133)] for all-causes, 1.319 [95%CI: (1.19-1.462)] for infectious diseases and 1.139 [95%CI: (1.077-1.205)] for respiratory diseases.

Table 6. Province-level estimates of the effect of heatwaves on hospitalizations by causes (lag 0-3).*

	All causes		Infectious		Respiratory		Mental health	
	Main effect	**Added effect**	**Main effect**	**Added effect**	**Main effect**	**Added effect**	**Main effect**	**Added effect**
Northwest (Dien Bien)	**1.09 (1.05-1.13)**	0.98 (0.96-1.01)	**1.32 (1.19-1.46)**	0.95 (0.88-1.03)	**1.14 (1.08-1.20)**	0.97 (0.93-1.02)	0.94 (0.79-1.10)	1.02 (0.89-1.16)
Southwest (Bac Giang)	**1.23 (1.18-1.28)**	0.97 (0.93-1.01)	**1.55 (1.37-1.74)**	0.88 (0.69-1.07)	0.92 (0.83-1.02)	0.87 (0.72-1.02)	0.62 (0.23-1.01)	0.70 (0.43-1.12)
Red River Delta (Ha Noi)	1.03 (0.99-1.064	0.97 (0.937-1.003)	**1.35 (1.25-1.46)**	0.95 (0.90-1.01)	0.88 (0.75-1.01)	0.98 (0.95-1.01)	1.11 (0.91-1.36)	0.98 (0.84-1.13)
North Central Coast (Ha Tinh)	1.06 (1.00-1.13)	0.96 (0.91-1.02)	**1.74 (1.55-1.95)**	**1.18 (1.07-1.30)**	**1.13 (1.05-1.22)**	0.99 (0.91-1.07)	**1.93 (1.44-2.58)**	0.93 (0.7-1.23)
South Central Coast (Binh Dinh)	1.04 (0.98-1.11)	1.02 (0.97-1.07)	**1.35 (1.24-1.47)**	1.03 (0.96-1.10)	1.08 (0.98-1.19)	0.96 (0.88-1.05)	1.53 (0.98-2.39)	0.83 (0.58-1.2)
Central Highland (Dak Lak)	1.02 (0.96-1.09)	**0.93 (0.88-0.99)**	**1.12 (1.03-1.22)**	0.86 (0.70-1.02)	1.03 (0.95-1.11)	0.94 (0.87-1.02)	1.13 (0.80-1.63)	0.99 (0.72-1.36)
Southeast (Binh Phuoc)	**1.06 (1.02-1.10)**	1.04 (0.99-1.08)	1.05 (0.98-1.13)	1.07 (0.99-1.16)	**1.07 (1.001-1.14)**	**1.08 (1.00-1.16)**	1.04 (0.85-1.27)	0.93 (0.74-1.17)
Mekong River Delta (Dong Thap)	**1.04 (1.02-1.05)**	**1.08 (1.06-1.10)**	**1.06 (1.03-1.09)**	**1.11 (1.07-1.15)**	1.002 (0.97-1.04)	**1.11 (1.06-1.16)**	1.10 (0.99-1.22)	1.12 (0.99-1.28)

(OT=19ºC), *97th percentile with ≥2 days duration
Bold for statistical significance

In Southwest (Bac Giang)**,** the main effect for all-cause admission was highest at 1.547 (1.374-1.743) for infectious diseases, followed at 1.227 (1.176-1.281) for all causes. Meanwhile, the main effect of heat waves on the hospitalization risk for mental health disorder admissions and respiratory diseases were not significant. In Red River Delta (Ha Noi), the main effect of heat waves was associated with the increase in hospitalizations (1.349; [1.249-1.457]) but not for all-causes and other diseases. In North Central Coast (Ha Tinh), the main effect of heat waves on mental health admission was highest compared to other cause admissions [RR=1.929 (1.441-2.581)]. The RR of the main effect was substantially higher than those of the added effect in infectious admissions with RR=1.737 (95%CI: 1.545-1.952) and RR= 1.179 (95%CI: 1.072-1.298), respectively. In South Central Coast (Binh Dinh), only hospital admissions for infectious diseases were affected by the main effect with RR= 1.346 (1.236-1.465). In Central Highland (Dak Lal), the main effect of heat waves was associated with the increase in hospitalizations for infectious admissions (RR=1.122, 95%Cl 1.031-1.22). In Southeast (Binh Phuoc), the main effect of heat waves was highest in hospitalizations for respiratory diseases [RR=1.07 (1.001-1.143)], followed by all causes admissions [RR=1.056 (1.017-1.096)]. In Mekong River Delta (Dong Thap), we found a significant association between the main effect of heatwaves and the number of hospitalizations due to all causes with RR = 1.036 (95% CI 1.02-1.053) and infectious diseases with RR = 1.058 (95% CI 1.027-1.09). The summary main effect of heatwaves on hospitalization for all-cause and cause-specific admissions in each province is presented in Figure 5.

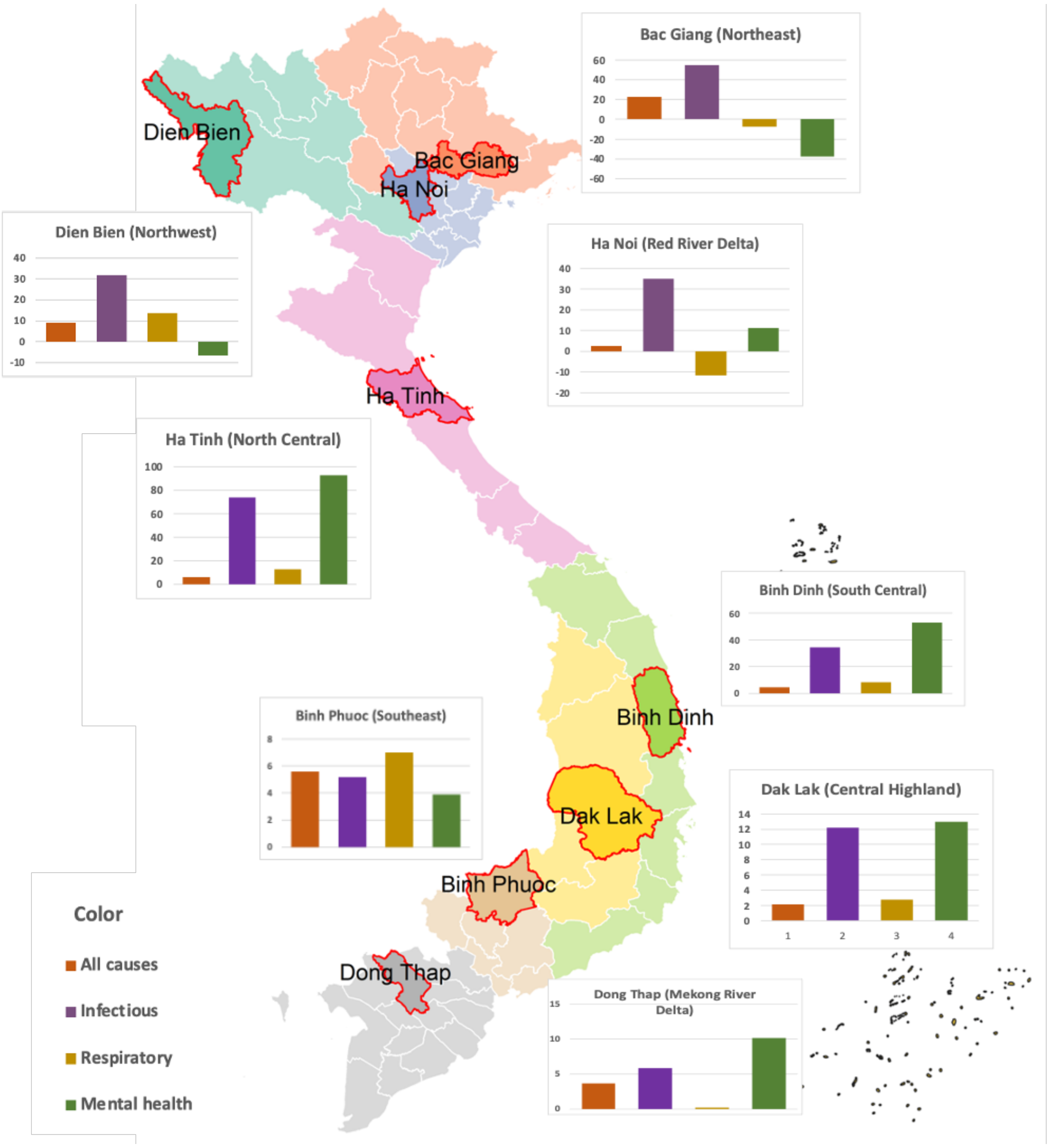


Figure 5. Province-level effect of a heatwave for all causes and specific diseases

(% changes in admissions associated with the main effect of heatwave]

3. Country-level pooled effects

3.1. Pooled effects of high temperature

Figure 6 shows the result of the pooled effect of short-term ambient temperature on hospitalization. In general, the pooled estimate of temperature has been significantly associated with a 0.8% (RR=1.008 [1.004-1.012]) increase in all-cause admissions

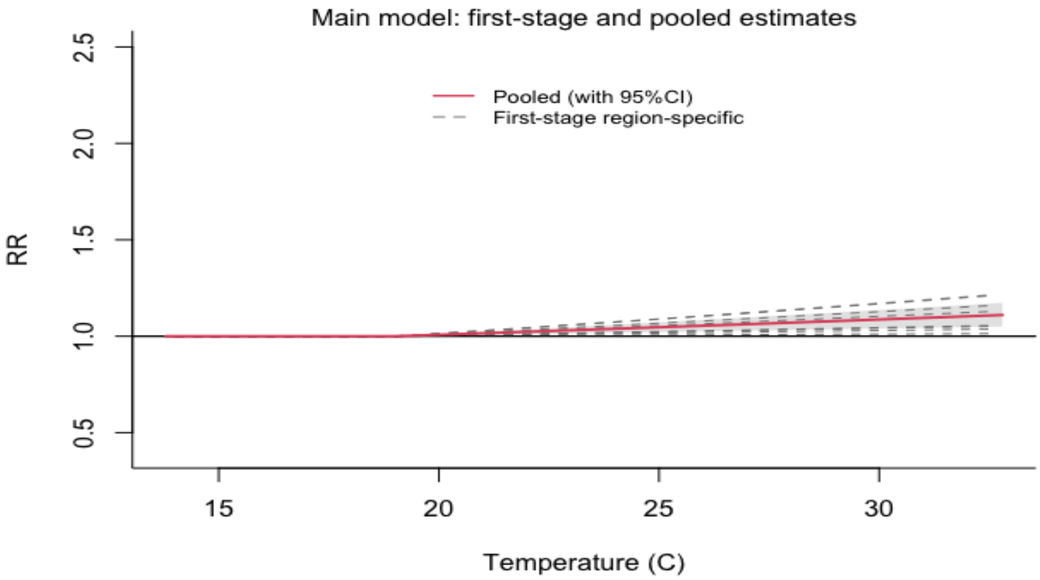
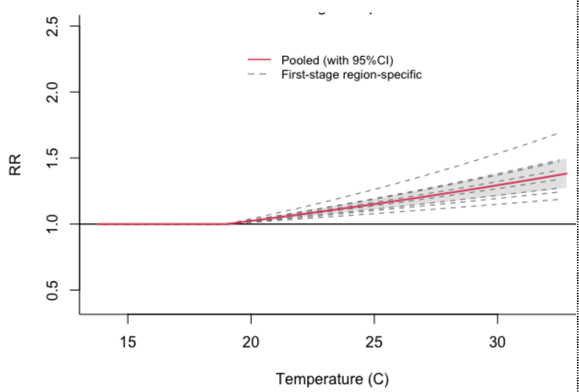
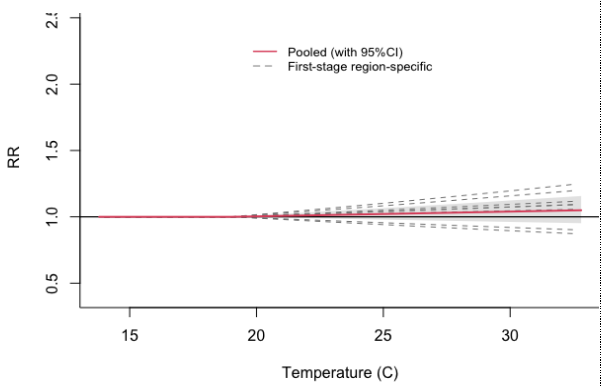
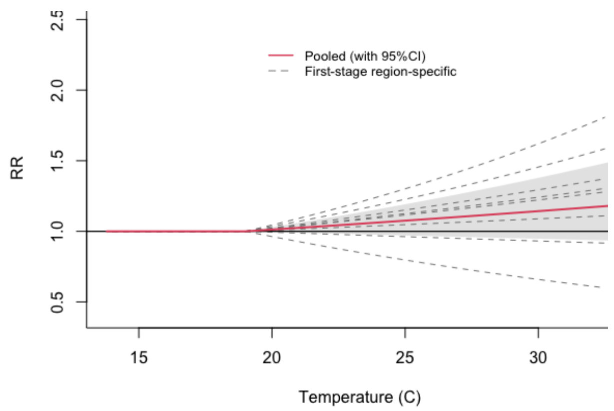


Figure 6. The pooled effect of temperature on all-cause admissions (OT=19)

Infectious diseases	**Respiratory diseases**
	
RR=1.024 (95%CI: 1.018-1.030)	RR=1.004 (95%CI: 0.996-1.011)

Mental health disorders



RR=1.012 (95%CI: 0.995-1.030)

Figure 7.The pooled effect of temperature on specific diseases (OT=19)

The pooled effect on specific disease groups is presented in Figure 7. The pooled estimate of temperature has significantly associated with 2.4% [1.8%-3.0%] corresponding to an increase in infectious diseases. The association between increasing 1°C in average temperature above the threshold and the risk of other diseases was relatively weak (RR=1.004 [0.996-1.011] for respiratory diseases and 1.012 [0.995-1.030] for mental health disorders).

3.2. Pooled effects of heatwaves

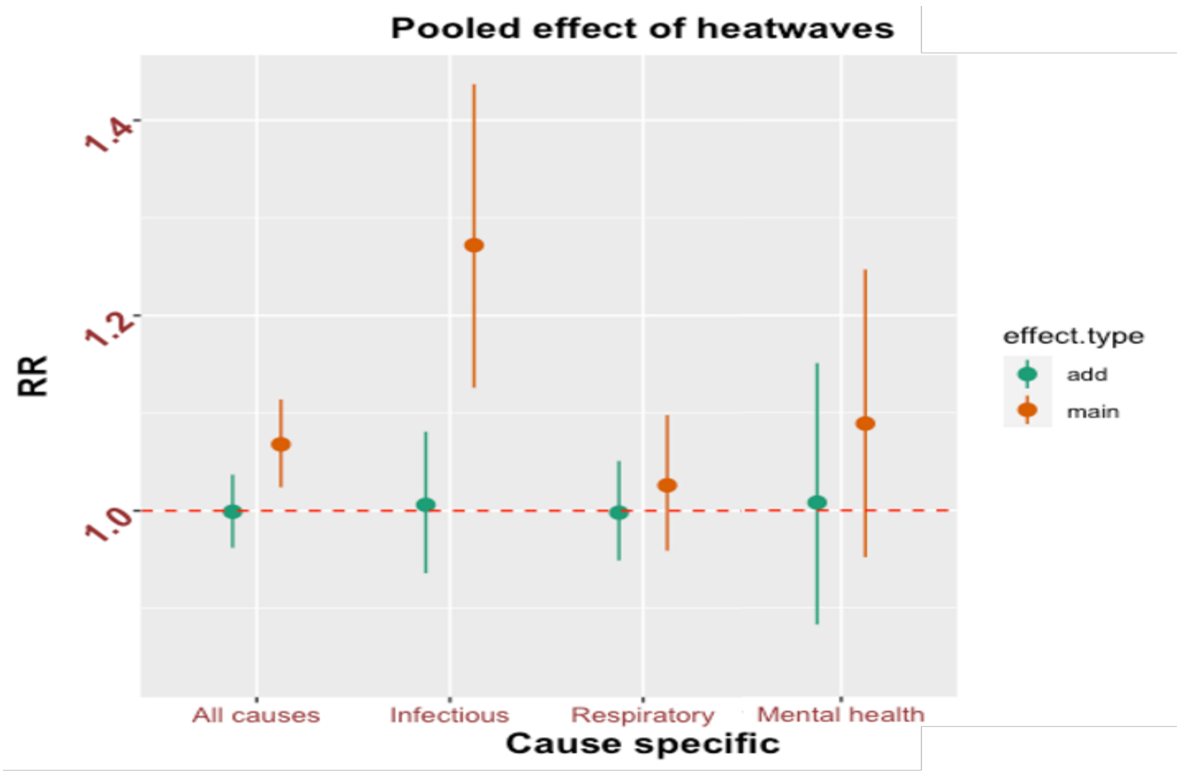


Figure 8. The country-level pooled main and added effect of heatwaves

The country-level pooled main and added effect of heatwaves on all-cause admissions and specific disease groups are illustrated in Figure 8. The main effect of heatwave for all-cause admission was RR = 1.07 (95% CI:1.02-1.11]. It means the risk of hospitalization for all causes increased by 7% during a heatwave event, compared with non-heatwave days. However, the added effect was not statistically significant (RR = 1, [0.96-1.04]). The main effect peaked at lag 0–3 and was highest for infectious diseases (1.27, [1.13-1.44]), followed by mental health (1.09 (0.95 - 1.25) and respiratory diseases 1.026 (0.96 -1.1). However, there is no statistically significant effect on the latter two diseases. Table 7 presents more detailed information.

Table 7. Pooled main and added effects across eight regions
(OT=19°C)

HW1	**Main effect (RR, 95%CI)**	**Test for heterogeneity**	**Added effect (RR, 95%CI)**
All-causes	**1.068 (1.024-1.114)**	0.035	0.999 (0.962-1.037)
Infectious	**1.272 (1.126-1.437)**	p≤0.001	1.006 (0.936-1.081)
Respiratory	1.026 (0.959 -1.098)	0.027	0.998 (0.949 - 1.051)
Mental health	1.089 (0.952 - 1.247)	0.396	1.008 (0.883 - 1.151)
HW1: 97th percentile with ≥2 days duration			

DISCUSSION

Main points

- This is a national-scale study conducted in Vietnam - among the most vulnerable countries to climate change but with low adaptive capacity.
- At a national level, high temperatures significantly increased the hospitalization risk for all causes and infectious diseases.
- The pooled main effects (daily high temperatures) of heatwaves were greater than the added effects (the duration of heat).
- The health effects of heat varied across eight regions, of which the Northern part tended to have a higher risk than the Southern.
- The differences in size effects among regions suggest the importance to identify heat-vulnerable regions and local-specific adaptation strategies.

1. Country-level pooled effects of high temperatures and heatwaves

This comprehensive study examined the short-term impacts of hot temperatures and heatwave events on the risk of hospital admission across eight ecological regions in Vietnam. We included 1,614,286 hospital admissions in the period from 2005 to 2021. For a given province, the data were available for between four and 10 years, depending on the availability and completeness of the data. The results contributed to evidence of the heat-health relationship in low- and middle-income countries with sub-tropical environments.

At a country level, the pooled estimates of high temperature showed a significant impact of same-day or after-one-day (lag 0-1) increase in temperature above threshold (19ºC) on hospital admission for all-cause and infectious diseases. However, the heat effects on respiratory, and mental health disorders were weak. The research findings on all-cause admission showed the same pattern as previous studies (Phung, Guo, Nguyen, et al., 2016; Talukder et al., 2022) while the finding for specific diseases varies across studies. A study in multi-provinces in northern Vietnam showed a significant impact of the increase in temperature above 24°C at the same day on hospitalization for all-cause, respiratory, and infectious (Talukder et al., 2022). A study in 16 climate zones throughout California reported that higher temperatures significantly increase admissions for mental health (RR=1.04, 95%CI: 1.01–1.07); nevertheless, for respiratory admissions, the study showed a negative association with high temperature (RR=0.93, 95% CI: 0.91–0.96) but a positive association with the heatwave effect (RR=1.09, 95%CI: 1.07–1.12) (Sherbakov et al., 2018).

The inconsistent conclusions about the association between temperature and specific diseases could be explained by the difference in age structures of certain populations where the aged population is more likely to have a high rate of chronic conditions such as respiratory diseases (Tran et al., 2020). Also, hospitalization could not be a sensitive indicator to assess the burden of some heat-sensitive diseases as severe cases may die before seeking care at the hospital. Furthermore, it is noted that, for each group of diseases, the impact of high temperature on specific sub-groups also may be different. For example, in a study in California, acute outcomes of respiratory hospitalizations were more sensitive to temperature than chronic outcomes (Sherbakov et al., 2018).

In addition to examining the effects of ambient temperature, the study also identified the impacts of heatwaves on all-cause and cause-specific admission across eight ecological regions. The research findings reported the hospitalization risk of both daily high temperatures (main effect) and the added effect due to the duration of extreme heat. The pool estimated for the whole country effect indicated that heatwave events significantly associate with an increase in all causes of hospitalization and infectious diseases on a concurrent day. The association between heatwaves and the hospitalization risk for all causes was confirmed by other previous studies in different areas. For example, the study in Vietnam by Phung et al. (2017) found that heatwaves increased the risk of all-cause admission by 2.5% at lag 0. Similarly, the study on the 2009 heatwave in Melbourne, Australia reported a significant increase in general medical admissions (IRR 1.81, $P < 0.01$) (Lindstrom et al., 2013).

Our study reported the main effect of heatwaves peaked at lag0–1 and decreased days after. This finding was in accordance with a majority of previous studies that reported a short-lag effect of heatwaves (Phung et al., 2017; Zeng et al., 2014; Zhao et al., 2019). The research also showed that the pooled main effects were greater than the added effects. This finding is in line with previous studies (Dang et al., 2022; Zeng et al., 2014). It is noted that differences in the definition of heatwaves add to the difficulty of assessing the health effects of heatwaves as well as challenges in comparing results among regions and countries. For example, the study by Dong et al. (2016) showed that using different definitions results in different estimates of the impact of the heatwave on cardiovascular mortality. In our study, we applied six different definitions of heatwaves and realized that HW.2.97 (97^{th} percentile with ≥2 days duration) had the greatest effect on hospitalization risk. See appendix 3 for a more detailed statistical analysis applying different heatwave definitions.

2. Region-level effects of high temperatures and heatwaves

At the region-level effect, high temperature affected all-cause admission higher in the Northern (including Northwest, Northeast, Red River Delta, and North Central Coast) than in the Southern (including Southern Centre Coast, Central Highland, Southeast, and Mekong River Delta). In terms of the heatwave effect, the main effect for all-cause admission was highest in the Northeast, followed by the Northwest, the Southeast, and the Mekong River Delta. There was no statistically significant effect of heatwaves on other regions including Red River Delta, North Central Coast, South Centre Coast, and Central Highland. The different effects may be partly explained by the difference in climate zones between North and South Vietnam. Unlike North Vietnam which has a humid and subtropical climate, South Vietnam has a tropical climate all year round so residents may have better heat acclimatization and be more able to cope with the hot climate. For this reason, the effect of high temperatures on health in South Vietnam maybe not observed clearly. This assumption was supported by a national-scale study in Brazin that the effect of high temperature on hospitalization risk was most pronounced in cold regions (Zhao et al., 2019). Another reason may be because of the impact of latitude on the temperature-hospitalization relationship. A study in the Eastern U.S. reported the health effect of high temperature increased with latitude increment (Xiao et al., 2015). In terms of province-level effects of high temperature on specific disease groups, non-significant effects of heatwaves on respiratory and mental health disorders in almost all provinces except the Northwest and North Central Coast. However, the level of effects in two of these regions is relatively small. The effect of high temperature on the risk of hospital admission in eight provinces was mostly observed for cumulative lag for 1 day (lag 0-1 day). The spatial and temporal differences in the heat-health relationship were found in some studies (Hondula & Barnett, 2014; Phung et al., 2015). In addition, the demographic characteristics, socio-economic features, healthcare systems, and adaptation capacity of communities vary from province to province and may also contribute to the differential health effects of heat. For example, provinces with high elderly populations or youth children under five years old are more likely to be sensitive to hot weather than others. This suggested the importance of location-specific studies in informing local policy in order to develop an appropriate heat-health action plan and identify vulnerable population sub-groups.

The temperature–morbidity relationship was often reported to be U-, V- or J-shaped, where threshold temperatures (a certain temperature or temperature range) were typically associated with the lowest morbidity risks and health risks increase when temperatures fall below or rise above the threshold (Lu et al., 2020; Phung, Guo, Thai, et al., 2016; Zhai et al., 2021). However, the temperature threshold varied by study and setting. For example, Phung et al. (2016b) in the Mekong Delta showed that when the average minimum temperature was over 21°C, the risk of all-cause hospital admissions increased by 1.3% per 1°C increase. Another study in sub-tropical Hong Kong stated that mean temperature increases of 1°C above 29.0°C were associated with 4.5% more hospitalizations (Chan et al., 2013). Our study identified the thresholds at 80 - 85 percentiles of daily mean temperature. For this definition, the Optimal Temperature (OT) in Northwest, Northeast, Red River Delta, and North Central Coast was 19ºC while South Central Coast, and Central Highland had OT at 20ºC; OT=25ºC in Mekong River Delta, and OT=26ºC in Southeast.

LIMITATIONS

This was a multi-province study representing eight ecological regions in Vietnam to quantify the effect of both high temperature and heatwave events on hospitalization risk. The study examined both all-cause admissions and heat-sensitive diseases including infectious diseases, respiratory diseases, and mental health disorders. Therefore, the findings provided evidence to extend our knowledge of the temperature-hospitalization relationship, especially the positive association between high temperature and infectious diseases. However, several limitations in this study should be mentioned. The first limitation relates to health data. The study used hospitalization data at the provincial level; therefore, some cases admitted to lower-level hospitals such as commune health centres and district hospitals were not taken into account. Also, some patients might visit lower-level healthcare centres before administering to provincial hospitals. For this reason, the date of admission to the provincial hospital might not represent the date of onset of the health problem, resulting in an inadequate estimate heat-health relationship. In addition, electronic health record storage in hospitals in Vietnam had some limitations due to the under-resourced context. Therefore, the information could be inaccurate and hard to verify. Despite this, the study remaind representative of the majority of severe admissions.

The second limitation regards meteorological data, in each province, temperature and humidity information was collected from the most central monitoring station. Therefore, the study's analysis assumed that all residents in each province were exposed to the same weather factors. As a result, it might not reflect the exact exposure of individuals due to variations in geographical and suburban features.

The third limitation is that the study did not control individual-level risk factors such as demographics, medical history, and duration and extent of heat exposure. For example, socio-economic status, distance from home to hospitals, and health insurance might affect the hospital delay time of patients. Likewise, other information such as air conditioning, occupation, duration spent outdoors, and individual risk factors (physical exercise, smoking, or alcohol consumption) also modified the heat-hospitalization association. However, these such data were not available in these electronic health records. In order to address this issue, the study applied time-series analysis which can minimise such bias in ecological designs. The reason is that individual factors do not seem to have changed within a short time period and in DLM models, the effects of these factors were filtered out through the smooth function of time.

Lastly, this study did not control modifying effect of air pollution in the heat-health association. It is noted that air pollution is often worse during hot weather, and it can be difficult to separate the health effects of heat and air pollution exposure. Unfortunately, the air pollution data was not available in the data set.

CONCLUSION AND RECOMMENDATION

This project was conducted in Vietnam - among the countries that are most vulnerable to climate change, natural disasters, and extreme temperature events while having limited resources and a disadvantaged healthcare system. The findings indicated the impacts of high temperatures and heatwaves on hospitalization risk for all-cause and heat-sensitive diseases across eight ecological regions in Vietnam. At the country level, the pooled estimates of high temperature showed a significant effect of an increase in temperature above the threshold (19ºC) at a lag of 0-1 day and heatwaves at a lag of 0–3 days on hospital admissions due to all causes and infectious diseases. However, the study did not find a clear association between heat exposure and hospitalization risk for respiratory diseases, and mental health disorders. At the region-level effect, the study also indicated the differences in the level effects of high temperatures and heatwaves across regions. The effect of heat on hospitalization risk in the Northern was higher than in the Southern. This finding suggested the importance of identifying heat-vulnerable regions and local-specific adaptation strategies. Given projections of the heat-vulnerable areas is important in climate change adaptation and response. For this reason, the findings contributed to expanding the understanding of heat's impact on human health, providing additional evidence-based information for the development of heat-health action plans, and promoting the capacity of Vietnamese residents to cope with extreme heat effects. For example, based on the temperature threshold of each region, heat-health warning systems can be applied differently. Furthermore, heat vulnerability maps that identify high-risk populations can be developed to give timely support to vulnerable groups.

For further studies, stratified analyses by demographic, socio-economic, geography, and latitude characteristics to assess the heat-health relationship are recommended to better identify vulnerable populations and high-risk regions. In addition, given the multi-factorial causes of certain diseases such as respiratory and mental health disorders, deeper classification and analyses are needed to examine the effect of high temperatures and heatwaves. Moreover, health and weather data need to be improved to provide better evidence of the heat-health association. During heatwave events, the use of real-time surveillance will allow for early detection of heat-related health threats thereby providing better response solutions.

To improve resilience to extreme heat, the local government should use scientific evidence-based information to develop specific plans for different ecological regions to adapt to heat. Establishing early warning systems, raising community awareness about heat-related health risks, and increasing vegetation and trees are some suggested solution

REFERENCES

Anderson, G. B., Dominici, F., Wang, Y., McCormack, M. C., Bell, M. L., & Peng, R. D. (2013). Heat-related emergency hospitalizations for respiratory diseases in the Medicare population. *American journal of respiratory and critical care medicine*, *187*(10), 1098-1103.

AusAID. (2017). *Australia – Vietnam Climate Change Delivery Strategy 2011- 2016*. https://dfat.gov.au/about-us/publications/Documents/vietnam-climate-change-strategy-2011-16.pdf

Azhar, G. S., Mavalankar, D., Nori-Sarma, A., Rajiva, A., Dutta, P., Jaiswal, A., Sheffield, P., Knowlton, K., Hess, J. J., & Group, A. H. S. (2014). Heat-related mortality in India: excess all-cause mortality associated with the 2010 Ahmedabad heat wave. *PLoS One*, *9*(3).

Bai, L., Ding, G., Gu, S., Bi, P., Su, B., Qin, D., Xu, G., & Liu, Q. (2014). The effects of summer temperature and heat waves on heat-related illness in a coastal city of China, 2011–2013. *Environmental research*, *132*, 212-219.

Benevolenza, M. A., & DeRigne, L. (2019). The impact of climate change and natural disasters on vulnerable populations: A systematic review of literature. *Journal of Human Behavior in the Social Environment*, *29*(2), 266-281.

Benmarhnia, T., Deguen, S., Kaufman, J. S., & Smargiassi, A. (2015). Vulnerability to heat-related mortality. *Epidemiology*, *26*(6), 781-793.

Bhaskaran, K., Gasparrini, A., Hajat, S., Smeeth, L., & Armstrong, B. (2013). Time series regression studies in environmental epidemiology. *International journal of epidemiology*, *42*(4), 1187-1195.

Campbell, S., Remenyi, T. A., White, C. J., & Johnston, F. H. (2018). Heatwave and health impact research: A global review. *Health & place*, *53*, 210-218.

Chan, E. Y., Goggins, W. B., Yue, J. S., & Lee, P. (2013). Hospital admissions as a function of temperature, other weather phenomena and pollution levels in an urban setting in China. *Bulletin of the World Health Organization*, *91*, 576-584.

Cheng, J., Xu, Z., Bambrick, H., Su, H., Tong, S., & Hu, W. (2019). Impacts of exposure to ambient temperature on burden of disease: a systematic review of epidemiological evidence. *International journal of biometeorology*, *63*(8), 1099-1115.

D'Ippoliti, D., Michelozzi, P., Marino, C., De'Donato, F., Menne, B., Katsouyanni, K., Kirchmayer, U., Analitis, A., Medina-Ramón, M., & Paldy, A. (2010). The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project. *Environmental Health*, *9*(1), 37.

Dang, T. N., Vy, N. T. T., Thuong, D. T. H., Phung, D., Van Dung, D., & Le An, P. (2022). Main and added effects of heatwaves on hospitalizations for mental and behavioral disorders in a tropical megacity of Vietnam. *Environmental Science and Pollution Research*, 1-10.

Deng, C., Ding, Z., Li, L., Wang, Y., Guo, P., Yang, S., Liu, J., Wang, Y., & Zhang, Q. (2019). Burden of non-accidental mortality attributable to ambient temperatures: a time series study in a high plateau area of southwest China. *BMJ open*, *9*(2), e024708.

Dong, W., Zeng, Q., Ma, Y., Li, G., & Pan, X. (2016). Impact of heat wave definitions on the added effect of heat waves on cardiovascular mortality in Beijing, China. *International journal of environmental research and public health*, *13*(9), 933.

Eckstein, D., Künzel, V., Schäfer, L., & Winges, M. (2019). Global climate risk index 2020. *Bonn: Germanwatch*.

Gasparrini, A. (2011). Distributed lag linear and non-linear models in R: the package dlnm. *Journal of statistical software*, *43*(8), 1.

General Statistics Office of Vietnam. (2019). *The Vietnam Population and Housing Census.* . Retrieved 15 Sep from https://www.gso.gov.vn/default_en.aspx?tabid=515&idmid=5&ItemID=19281

Global Facility for Disaster Reduction and Recovery (GFDRR). (2011). *Vulnerability, Risk Reduction, and Adaptation to Climate Change - Climate Risk and Adaptation Country Profile* http://sdwebx.worldbank.org/climateportalb/doc/GFDRRCountryProfiles/wb_gfdrr_climate_change_country_profile_for_VNM.pdf

Green, H., Bailey, J., Schwarz, L., Vanos, J., Ebi, K., & Benmarhnia, T. (2019). Impact of heat on mortality and morbidity in low and middle income countries: a review of the epidemiological evidence and considerations for future research. *Environmental research*, *171*, 80-91.

Guo, Y., Gasparrini, A., Armstrong, B. G., Tawatsupa, B., Tobias, A., Lavigne, E., Coelho, M. d. S. Z. S., Pan, X., Kim, H., & Hashizume, M. (2017). Heat wave and mortality: a multicountry, multicommunity study. *Environmental health perspectives*, *125*(8), 087006.

Hanna, E. G., Kjellstrom, T., Bennett, C., & Dear, K. (2011). Climate change and rising heat: population health implications for working people in Australia. *Asia Pacific Journal of Public Health*, *23*(2_suppl), 14S-26S.

Hondula, D. M., & Barnett, A. G. (2014). Heat-related morbidity in Brisbane, Australia: spatial variation and area-level predictors. *Environmental health perspectives*, *122*(8), 831-836.
Huang, C., Barnett, A. G., Wang, X., Vaneckova, P., FitzGerald, G., & Tong, S. (2011). Projecting future heat-related mortality under climate change scenarios: a systematic review. *Environmental health perspectives*, *119*(12), 1681-1690.
Jabeen, H., & Johnson, C. (2013). Perceptions of climate variability and coping strategies in informal settlements in Dhaka, Bangladesh. In *Cities at risk* (pp. 149-170). Springer.
Jackson, L. L., & Rosenberg, H. R. (2010). Preventing heat-related illness among agricultural workers. *Journal of agromedicine*, *15*(3), 200-215.
Kenny, G. P., Yardley, J., Brown, C., Sigal, R. J., & Jay, O. (2010). Heat stress in older individuals and patients with common chronic diseases. *Cmaj*, *182*(10), 1053-1060.
Lindstrom, S., Nagalingam, V., & Newnham, H. (2013). Impact of the 2009 M elbourne heatwave on a major public hospital. *Internal medicine journal*, *43*(11), 1246-1250.
Lu, P., Xia, G., Zhao, Q., Xu, R., Li, S., & Guo, Y. (2020). Temporal trends of the association between ambient temperature and hospitalisations for cardiovascular diseases in Queensland, Australia from 1995 to 2016: a time-stratified case-crossover study. *PLoS medicine*, *17*(7), e1003176.
McGregor, G. R., Bessmoulin, P., Ebi, K., & Menne, B. (2015). *Heatwaves and health: guidance on warning-system development*. WMOP.
Methner, M., & Eisenberg, J. (2018). Evaluation of heat stress and heat strain among employees working outdoors in an extremely hot environment. *Journal of occupational and environmental hygiene*, *15*(6), 474-480.
Mora, C., Dousset, B., Caldwell, I. R., Powell, F. E., Geronimo, R. C., Bielecki, C. R., Counsell, C. W., Dietrich, B. S., Johnston, E. T., & Louis, L. V. (2017). Global risk of deadly heat. *Nature climate change*, *7*(7), 501-506.
Müller, N., Kuttler, W., & Barlag, A.-B. (2014). Counteracting urban climate change: adaptation measures and their effect on thermal comfort. *Theoretical and applied climatology*, *115*(1), 243-257.
Nachmany, M., Fankhauser, S., Davidová, J., Kingsmill, N., Landesman, T., Sundaresan, J., & Townshend, T. (2015). *Climate Change Legislation in Vietnam*. https://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2015/05/VIETNAM.pdf
Nguyen, D. Q., Renwick, J., & McGregor, J. (2014). Variations of surface temperature and rainfall in Vietnam from 1971 to 2010. *International Journal of Climatology*, *34*(1), 249-264.
Nutong, R., Mungthin, M., Hatthachote, P., Ukritchon, S., Imjaijit, W., Tengtrakulcharoen, P., Panichkul, S., Putwatana, P., Prapaipanich, W., & Rangsin, R. (2018). Personal risk factors associated with heat-related illness among new conscripts undergoing basic training in Thailand. *PloS one*, *13*(9), e0203428.
Opitz-Stapleton, S. (2014). *Da Nang, Vietnam: Climate Change Impacts on Heat Stress by 2050* (Boulder, CO: Institute for Social and Environmental Transition-International, Issue. https://www.rockefellerfoundation.org/wp-content/uploads/Climate-Change-Impacts-on-Heat-Stress-by-2050.pdf
Phung, D., Chu, C., Rutherford, S., Nguyen, H. L. T., Do, C. M., & Huang, C. (2017). Heatwave and risk of hospitalization: A multi-province study in Vietnam. *Environmental Pollution*, *220*, 597-607.
Phung, D., Guo, Y., Nguyen, H. T., Rutherford, S., Baum, S., & Chu, C. (2016). High temperature and risk of hospitalizations, and effect modifying potential of socio-economic conditions: A multi-province study in the tropical Mekong Delta Region. *Environment international*, *92*, 77-86.
Phung, D., Guo, Y., Thai, P., Rutherford, S., Wang, X., Nguyen, M., Do, C. M., Nguyen, N. H., Alam, N., & Chu, C. (2016). The effects of high temperature on cardiovascular admissions in the most populous tropical city in Vietnam. *Environmental Pollution*, *208*, 33-39.
Phung, D., Huang, C., Rutherford, S., Chu, C., Wang, X., & Nguyen, M. (2015). Climate change, water quality, and water-related diseases in the Mekong Delta Basin: A systematic review. *Asia Pacific Journal of Public Health*, *27*(3), 265-276.
Robinson, P. J. (2001). On the definition of a heat wave. *Journal of applied Meteorology*, *40*(4), 762-775.
Sherbakov, T., Malig, B., Guirguis, K., Gershunov, A., & Basu, R. (2018). Ambient temperature and added heat wave effects on hospitalizations in California from 1999 to 2009. *Environmental research*, *160*, 83-90.
Stanke, C., Kerac, M., Prudhomme, C., Medlock, J., & Murray, V. (2013). Health effects of drought: a systematic review of the evidence. *PLoS currents*, *5*.
Steffen, W., Hughes, L., & Perkins, S. (2014). Heatwaves: hotter, longer, more often.
Talukder, M. R., Chu, C., Rutherford, S., Huang, C., & Phung, D. (2022). The effect of high temperatures on risk of hospitalization in northern Vietnam. *Environmental Science and Pollution Research*, *29*(8), 12128-12135.
Thang, N. V., Nga, P. T. T., Huong, H. T. L., & Hien, N. X. (2020). *Kich Ban Bien Doi Khi Hau (Climate Change Scenario)*. http://www.imh.ac.vn/files/doc/2020/KB%20BDKH%202912.pdf

Thao, N. D., Takagi, H., & Esteban, M. (2014). *Coastal disasters and climate change in Vietnam: Engineering and planning perspectives*. Elsevier.
The World Bank. (2018). *Vietnam Overwiew*. Retrieved 10 Sep from http://www.worldbank.org/en/country/vietnam/overview
The World Bank. (2020). *CO2 emissions (metric tons per capita)*. Retrieved 15 Sep from https://data.worldbank.org/indicator/EN.ATM.CO2E.PC
Tong, S., Wang, X. Y., & Barnett, A. G. (2010). Assessment of heat-related health impacts in Brisbane, Australia: comparison of different heatwave definitions. *PLoS One*, *5*(8).
Tran, D. N., Doan, V. Q., Nguyen, V. T., Khan, A., Thai, P. K., Cunrui, H., Chu, C., Schak, E., & Phung, D. (2020). Spatial patterns of health vulnerability to heatwaves in Vietnam. *International journal of biometeorology*, *64*(5), 863-872.
Tuyet Hanh, T. T., Huong, L. T. T., Huong, N. T. L., Linh, T. N. Q., Quyen, N. H., Nhung, N. T. T., Ebi, K., Cuong, N. D., Van Nhu, H., & Kien, T. M. (2020). Vietnam Climate Change and Health Vulnerability and Adaptation Assessment, 2018. *Environmental Health Insights*, *14*, 1178630220924658.
USAID. (2017). *Climate change risk profile: Vietnam.* . https://www.climatelinks.org/sites/default/files/asset/document/2017_USAID_Vietnam%20climate%20risk%20profile.pdf
Watts, N., Amann, M., Ayeb-Karlsson, S., Belesova, K., Bouley, T., Boykoff, M., Byass, P., Cai, W., Campbell-Lendrum, D., & Chambers, J. (2018). The Lancet Countdown on health and climate change: from 25 years of inaction to a global transformation for public health. *The Lancet*, *391*(10120), 581-630.
Xiang, J., Hansen, A., Pisaniello, D., & Bi, P. (2015). Extreme heat and occupational heat illnesses in South Australia, 2001–2010. *Occupational and environmental medicine*, *72*(8), 580-586.
Xiao, J., Peng, J., Zhang, Y., Liu, T., Rutherford, S., Lin, H., Qian, Z., Huang, C., Luo, Y., & Zeng, W. (2015). How much does latitude modify temperature–mortality relationship in 13 eastern US cities? *International journal of biometeorology*, *59*(3), 365-372.
Xu, Z., FitzGerald, G., Guo, Y., Jalaludin, B., & Tong, S. (2016). Impact of heatwave on mortality under different heatwave definitions: a systematic review and meta-analysis. *Environment international*, *89*, 193-203.
Yin, Q., & Wang, J. (2017). The association between consecutive days' heat wave and cardiovascular disease mortality in Beijing, China. *BMC public health*, *17*(1), 1-9.
Yu, W., Mengersen, K., Wang, X., Ye, X., Guo, Y., Pan, X., & Tong, S. (2012). Daily average temperature and mortality among the elderly: a meta-analysis and systematic review of epidemiological evidence. *International journal of biometeorology*, *56*(4), 569-581.
Zeng, W., Lao, X., Rutherford, S., Xu, Y., Xu, X., Lin, H., Liu, T., Luo, Y., Xiao, J., & Hu, M. (2014). The effect of heat waves on mortality and effect modifiers in four communities of Guangdong Province, China. *Science of The Total Environment*, *482*, 214-221.
Zhai, G., Zhang, K., & Chai, G. (2021). Lag effect of ambient temperature on the cardiovascular disease hospital admission in Jiuquan, China. *Air Quality, Atmosphere & Health*, *14*(2), 181-189.
Zhao, Q., Li, S., Coelho, M. S., Saldiva, P. H., Hu, K., Huxley, R. R., Abramson, M. J., & Guo, Y. (2019). The association between heatwaves and risk of hospitalization in Brazil: A nationwide time series study between 2000 and 2015. *PLoS medicine*, *16*(2), e1002753.

Appendix 1. Cause-specific hospital admissions increase in per cent per 1oC increase by mean, by lag period

Cumulative lag models**	All causes		Infectious		Respiratory		Mental health	
	RR	95%CI	RR	95%CI	RR	95%CI	RR	95%CI
Northwest (Dien Bien) (OT=19°C)								
Lag 0-1	**1.012**	**1.005-1.020**	**1.025**	**1.006-1.046**	**1.014**	**1.003-1.025**	1.007	0.977-1.039
Lag 0-2	**1.011**	**1.003-1.019**	**1.027**	**1.006-1.048**	**1.016**	**1.004-1.027**	0.999	0.967-1.031
Lag 0-3	**1.009**	**1.001-1.017**	**1.029**	**1.007-1.051**	**1.013**	**1.002-1.025**	0.994	0.960-1.028
Lag 0-4	1.006	0.998-1.015	**1.033**	**1.010-1.057**	1.011	0.999-1.024	0.992	0.957-1.028
Lag 0-5	1.003	0.995-1.012	**1.031**	**1.007-1.055**	1.008	0.995-1.021	0.988	0.952-1.026
Lag 0-6	1.002	0.993-1.011	**1.029**	**1.004-1.055**	1.007	0.993-1.020	0.993	0.955-1.033
Lag 0-7	1.000	0.990-1.010	**1.027**	**1.001-1.054**	1.005	0.991-1.019	0.995	0.955-1.036
Northeast (Bac Giang) (OT=19°C)								
Lag 0-1	**1.010**	**1.005-1.016**	**1.028**	**1.013-1.044**	0.992	0.980-1.005	0.979	0.931-1.029
Lag 0-2	**1.012**	**1.006-1.018**	**1.028**	**1.012-1.044**	0.991	0.978-1.004	0.969	0.920-1.022
Lag 0-3	**1.014**	**1.008-1.020**	**1.030**	**1.013-1.047**	0.992	0.979-1.007	0.963	0.911-1.018
Lag 0-4	**1.015**	**1.009-1.022**	**1.031**	**1.014-1.049**	0.993	0.978-1.008	0.960	0.906-1.017
Lag 0-5	**1.016**	**1.009-1.022**	**1.032**	**1.014-1.051**	0.993	0.978-1.008	0.956	0.900-1.015
Lag 0-6	**1.015**	**1.008-1.022**	**1.030**	**1.011-1.050**	0.992	0.976-1.008	0.953	0.895-1.015
Lag 0-7	**1.013**	**1.006-1.021**	**1.028**	**1.009-1.048**	0.990	0.974-1.007	0.952	0.891-1.016
Red River Delta (Ha Noi) (OT=19°C)								
Lag 0-1	**1.004**	**1.000-1.009**	**1.023**	**1.013-1.033**	0.997	0.991-1.004	1.000	0.974-1.027
Lag 0-2	1.003	0.998-1.008	**1.023**	**1.012-1.034**	0.993	0.986-1.000	1.002	0.975-1.031
Lag 0-3	1.001	0.996-1.006	**1.022**	**1.010-1.033**	**0.990**	**0.983-0.997**	1.008	0.978-1.038
Lag 0-4	0.999	0.994-1.005	**1.021**	**1.009-1.033**	**0.988**	**0.981-0.996**	1.005	0.974-1.038
Lag 0-5	0.998	0.992-1.004	**1.019**	**1.007-1.032**	**0.986**	**0.978-0.994**	1.003	0.970-1.037
Lag 0-6	0.996	0.990-1.002	**1.019**	**1.006-1.033**	**0.983**	**0.975-0.991**	0.997	0.963-1.033
Lag 0-7	0.995	0.988-1.001	**1.019**	**1.006-1.034**	**0.980**	**0.971-0.989**	0.994	0.958-1.031
North Central Coast (Ha Tinh) (OT=19°C)								
Lag 0-1	**1.008**	**1.001-1.016**	**1.037**	**1.022-1.052**	**1.013**	**1.004-1.022**	**1.047**	**1.011-1.085**
Lag 0-2	1.006	0.998-1.014	**1.037**	**1.022-1.052**	**1.010**	**1.001-1.019**	**1.044**	**1.007-1.083**
Lag 0-3	1.004	0.996-1.012	**1.040**	**1.024-1.056**	1.008	0.998-1.018	**1.045**	**1.006-1.086**
Lag 0-4	1.002	0.994-1.011	**1.043**	**1.027-1.060**	1.006	0.996-1.017	1.039	0.998-1.082
Lag 0-5	1.001	0.992-1.010	**1.048**	**1.030-1.066**	1.004	0.993-1.015	1.031	0.988-1.075
Lag 0-6	1.0002	0.990-1.009	**1.051**	**1.032-1.070**	1.001	0.990-1.013	1.020	0.976-1.067
Lag 0-7	0.998	0.988-1.008	**1.053**	**1.034-1.073**	1.001	0.988-1.013	1.011	0.964-1.059
South Central Coast (Binh Dinh) (OT=20°C)								
Lag 0-1	1.001	0.991-1.010	**1.022**	**1.009-1.035**	1.002	0.988-1.017	1.006	0.943-1.074
Lag 0-2	1.001	0.992-1.011	**1.021**	**1.008-1.035**	1.005	0.990-1.020	1.022	0.954-1.095
Lag 0-3	1.004	0.994-1.014	**1.025**	**1.011-1.040**	1.006	0.990-1.022	1.034	0.962-1.112
Lag 0-4	1.004	0.994-1.015	**1.028**	**1.013-1.043**	1.005	0.989-1.022	1.044	0.967-1.127
Lag 0-5	1.006	0.994-1.017	**1.031**	**1.015-1.047**	1.004	0.986-1.021	1.042	0.962-1.129
Lag 0-6	1.007	0.995-1.018	**1.035**	**1.018-1.051**	1.001	0.983-1.020	1.034	0.951-1.125
Lag 0-7	1.009	0.997-1.021	**1.039**	**1.022-1.056**	1.001	0.982-1.020	1.028	0.941-1.122
Central Highland (Dak Lak) (OT=20°C)								

Cumulative lag models**	All causes		Infectious		Respiratory		Mental health	
	RR	95%CI	RR	95%CI	RR	95%CI	RR	95%CI
Lag 0-1	1.002	0.988-1.017	1.014	0.995-1.033	1.005	0.987-1.023	1.007	0.929-1.092
Lag 0-2	1.000	0.985-1.015	1.011	0.992-1.031	1.001	0.983-1.020	1.004	0.923-1.091
Lag 0-3	1.001	0.985-1.016	1.010	0.990-1.031	1.002	0.983-1.021	1.015	0.931-1.107
Lag 0-4	1.002	0.986-1.019	1.010	0.989-1.031	1.001	0.981-1.021	1.027	0.938-1.124
Lag 0-5	1.003	0.986-1.020	1.009	0.987-1.031	1.000	0.979-1.021	1.028	0.936-1.129
Lag 0-6	1.004	0.986-1.021	1.008	0.986-1.031	1.000	0.979-1.022	1.026	0.931-1.131
Lag 0-7	1.005	0.987-1.024	1.007	0.984-1.030	1.000	0.978-1.023	1.020	0.922-1.129
Southeast (Binh Phuoc) (OT=26^{o}C)								
Lag 0-1	**1.016**	**1.003-1.030**	1.013	0.989-1.037	1.020	0.997-1.044	1.012	0.944-1.084
Lag 0-2	**1.016**	**1.003-1.029**	1.014	0.991-1.039	1.018	0.995-1.043	1.016	0.947-1.090
Lag 0-3	1.012	0.998-1.026	1.012	0.988-1.037	1.016	0.992-1.040	1.004	0.935-1.079
Lag 0-4	1.009	0.995-1.023	1.008	0.984-1.034	1.015	0.990-1.040	0.992	0.922-1.068
Lag 0-5	1.007	0.993-1.022	1.007	0.982-1.033	1.016	0.991-1.042	0.975	0.904-1.052
Lag 0-6	1.007	0.992-1.021	1.008	0.982-1.035	1.014	0.988-1.041	0.962	0.891-1.040
Lag 0-7	1.005	0.990-1.020	1.010	0.984-1.038	1.014	0.988-1.042	0.958	0.886-1.037
Mekong River Deltal (Dong Thap) (OT=25)								
Lag 0-1	**1.015**	**1.009-1.021**	**1.018**	**1.006-1.029**	1.010	0.998-1.023	1.035	0.997-1.075
Lag 0-2	**1.011**	**1.005-1.017**	**1.015**	**1.003-1.026**	1.007	0.995-1.020	1.022	0.984-1.062
Lag 0-3	**1.010**	**1.003-1.016**	**1.015**	**1.003-1.027**	1.004	0.991-1.017	1.024	0.984-1.065
Lag 0-4	**1.010**	**1.003-1.016**	**1.016**	**1.004-1.029**	1.003	0.990-1.016	1.027	0.986-1.069
Lag 0-5	**1.010**	**1.003-1.017**	**1.018**	**1.006-1.030**	1.003	0.989-1.016	1.026	0.984-1.070
Lag 0-6	**1.010**	**1.003-1.016**	**1.019**	**1.006-1.032**	1.001	0.987-1.015	1.031	0.988-1.076
Lag 0-7	**1.010**	**1.003-1.017**	**1.021**	**1.008-1.034**	1.001	0.986-1.015	1.033	0.989-1.078

Appendix 2. The pooled main and added effects under different heatwave definitions.

	Heatwave Type	Main effect (RR, 95%CI)	Test for heterogeneity	Added effect (RR, 95%CI)	Test for heterogeneity
All-causes	**hw.2.97**	1.068 (1.024-1.114)	0.035	0.999 (0.962-1.037)	0.014
	hw.2.98	1.072 (1.030-1.116)	0.064	0.984 (0.950-1.019)	0.21
	hw.2.99	1.073 (1.031-1.116)	0.094	0.983 (0.933-1.037)	0.245
	hw.4.97	1.068 (1.031-1.108)	0.128	0.998 (0.957-1.040)	0.308
	hw.4.98	1.070 (1.033-1.109)	0.148	0.991 (0.943-1.042)	0.307
	hw.4.99	1.070 (1.030-1.112)	0.114	1.024 (0.946-1.109)	0.268
Infectious	**hw.2.97**	1.272 (1.126-1.437)	p≤0.001	1.006 (0.936-1.081)	0.021
	hw.2.98	1.278 (1.127-1.448)	p≤0.001	1.011 (0.948-1.078)	0.29
	hw.2.99	1.288 (1.133-1.465)	p≤0.001	1.013 (0.942-1.088)	0.521
	hw.4.97	1.265 (1.124-1.424)	p≤0.001	1.045 (0.977-1.117)	0.792
	hw.4.98	1.275 (1.129-1.439)	p≤0.001	1.031 (0.947-1.123)	0.596
	hw.4.99	1.282 (1.133-1.450)	p≤0.001	1.053 (0.941-1.180)	0.672
Respiratory	**hw.2.97**	1.026 (0.959 to 1.098)	0.027	0.998 (0.949 - 1.051)	0.2
	hw.2.98	1.030 (0.963 - 1.101)	0.039	0.971 (0.907 - 1.039)	0.106
	hw.2.99	1.031 (0.962 - 1.106)	0.035	0.939 (0.840 - 1.050)	0.062
	hw.4.97	1.028 (0.960 - 1.102)	0.022	0.982 (0.925 - 1.043)	0.672
	hw.4.98	1.031 (0.962 - 1.105)	0.027	0.936 (0.866 - 1.010)	0.365
	hw.4.99	1.030 (0.958 - 1.107)	0.022	0.921 (0.792 - 1.071)	0.416
Mental health	**hw.2.97**	1.089 (0.952 - 1.247)	0.396	1.008 (0.883 - 1.151)	0.965
	hw.2.98	1.088 (0.948 - 1.249)	0.402	1.043 (0.893 - 1.218)	0.919
	hw.2.99	1.087 (0.943 - 1.253)	0.38	1.181 (0.923 - 1.511)	0.353
	hw.4.97	1.087 (0.949 - 1.245)	0.35	1.065 (0.877 - 1.292)	0.692
	hw.4.98	1.085 (0.945 - 1.245)	0.322	1.154 (0.872 - 1.528)	0.385
	hw.4.99	1.087 (0.944 - 1.252)	0.29	1.516 (1.055 - 2.177)	0.754