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Vietnam in the face of extreme heat events

A literature review

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Vietnam in the face of extreme heat events

A literature review

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Abstract
Some of the greatest impacts of climate change worldwide arise from increasing extreme weather events, including hot temperature extremes. As global warming is projected to further intensify in future decades, Vietnam will face increasing extreme heat events. In order to contribute to identify potential knowledge gaps on this issue and better inform adaptation policies, we performed a literature review of 61 documents published between 2005 and 2024 and dealing with extreme temperatures and heat stress in Vietnam. We found that actually the two main topics of these documents are the urban heat island effect and the negative health impacts of high temperatures, but without taking climate change into account. Climatological studies focusing on hot extremes in Vietnam appear rather rare. The few studies identified all report increasing trends over the past decades, and the rare studies providing climate projections for Vietnam specifically or for vietnamese cities all point out to further increases. Hence, dangerous hot weather could occur up to several months per year. Overall, our review highlights the need for further research on this issue in Vietnam in order to better anticipate potential heat-related damages and build relevant adaptation policies.

Keywords
Climate change, Vietnam, extreme events, heat stress, high temperature

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Résumé
L'augmentation des événements climatiques extrêmes, dont les extrêmes de température, font partie des facteurs d'impact majeurs du changement climatique à l'échelle mondiale. Avec l'intensification du niveau de réchauffement global au cours des prochaines décennies, le Vietnam sera de plus en plus confronté à des épisodes de chaleur extrêmes. Afin de contribuer à l'identification des potentielles lacunes dans les connaissances sur cette question et de mieux informer les politiques d'adaptation, nous avons effectué une revue de littérature sur 61 documents publiés entre 2005 et 2024 et traitant des températures extrêmes et du stress thermique au Vietnam. Nous avons constaté que les deux principaux sujets abordés dans ces documents sont l'effet d'îlot de chaleur urbain et les impacts négatifs des températures élevées sur la santé, mais sans prise en compte du changement climatique. Les études climatologiques portant sur les extrêmes de chaleur au Vietnam semblent plutôt rares. Pourtant, les quelques travaux identifiés font tous état de tendances à la hausse au cours des dernières décennies, et les rares études fournissant des projections climatiques spécifiquement pour le Vietnam ou une ville vietnamienne soulignent toutes la poursuite de cette hausse. A l'avenir, des niveaux de chaleur dangereux pourraient ainsi perdurer jusqu'à plusieurs mois par an. Dans l'ensemble, notre revue souligne la nécessité de poursuivre les recherches sur cette question au Vietnam afin de mieux anticiper les dommages potentiels liés aux chaleurs intenses et élaborer des politiques d'adaptation pertinentes.

Mots-clés
Changement climatique, Vietnam, événements extrêmes, stress thermique, température élevée

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Introduction

Climate change and hot extremes

Increasing trends in hot extremes

One of the most striking consequences of anthropogenic global warming is the increased frequency and/or intensity of some extreme weather events in many regions of the world. IPCC (2021) assessed that hot extremes (including heatwaves) and heavy precipitations have become more frequent and more intense across most land regions since the 1950s, while agricultural and ecological droughts have also increased in some regions. The confidence in human contribution to observed changes in hot extremes is assessed as "high" in most IPCC AR6 reference regions. Over the past few years, several severe hot extreme events have been observed worldwide, such as the extraordinary heatwave on the Pacific coast of the United States and Canada in June 2021, with temperatures far above 40°C for a few days and records broken in multiple cities, including a new all-time Canadian temperature record of 49.6°C in the village of Lytton (Philip *et al.*, 2021). Recorded temperatures laid far outside the range of historical temperatures, and the event was estimated to be virtually impossible without anthropogenic climate change. Impacts were catastrophic, including hundreds of deaths, mass-mortality in marine life and a dramatic increase in wildfires (White *et al.*, 2023). In 2015, a wet-bulb temperature of 34.6°C was recorded in Iran (Schär, 2016), i.e. a value very close to the critical threshold for human survivability of 35°C proposed by Sherwood & Huber (2010) (see below). Southern Europe was hit by an exceptional summer heat wave in 2017, with records broken in southern France, Corsica, and Croatia, where nighttime temperatures exceeded 30°C (Kew *et al.*, 2019). Historical temperature records were further broken in Western Europe during summer 2019 during two extreme heat waves which would have had extremely small odds in the absence of climate change (Vautard *et al.*, 2020). In 2019, India experienced its second-longest heat wave with temperatures reaching up to 50.8 °C in Rajasthan (Dube *et al.*, 2021), while central and eastern China experienced unprecedented and long-lasting heatwaves in July and August 2022 (Wang *et al.*, 2023).

Heat stress impacts

Increased heatwave frequency, duration, and magnitude worldwide already result in significant damages on work capacity, human health and mortality, infra-structures and ecosystems. The different impact channels of heat stress on human performances and occu-pational health have been reviewed by

Kjellstrom *et al.* (2016) (see references therein; see also Mora *et al.* (2017b)). These include direct health impacts, with physiological and/or psychological changes, such as clinical damage to organ function which can lead to acute heat stroke and chronic diseases (e.g. kidney disease, see also Hansson *et al.* (2021), Sasai *et al.* (2023), Wesseling *et al.* (2020)), and hence increased mortality or hospital admissions. Psychological and physiological changes can both drive diminished human performance capacity, leading to reduced work capacity and increased accident risk. Elderly people, those with impaired health, and workers performing heavy labor appear as the most vulnerable. Beyond impacts at the individual level, heat stress may have wider social implications, through negative impacts on population health status and/or on the community economy, through loss of income for instance. In addition to direct impacts on health and work capacities, high temperatures also accelerate pollutant formation reactions and may modify air-pollution-related health effects, for instance through increased effects of ozone-mortality (e.g. Shi *et al.*, 2020).

Increased heat hazards in urban area

Extreme temperature hazards and heat stress are further increased in urban areas because of the urban heat island (UHI) effect, compounded by recent rapid urbanization in many parts of the world. This well-documented effect can increase air temperatures in cities by several Celsius degrees compared to the surrounding sub-urban or rural areas (Chapman *et al.* 2017). It is caused by the physical changes to the surface energy balance in built areas compared to vegetated areas and anthropogenic heat release. As assessed in the 2022 IPCC report (Dodman *et al.*, 2022), the risks to cities, settlements, and infrastructures from heatwaves will worsen in future decades. Future urbanization will further amplify projected local air temperature increase, particularly by strong influence on minimum temperatures. Cities in mid-latitudes would potentially be subject to twice the levels of heat stress compared with their rural surroundings under all climate scenarios by 2050. A disproportionate level of exposure exists in subtropical cities subject to year-round warm temperatures and higher humidity. For instance, in the cities of Gorakhpur (India), Islamabad, Lahore, and Multan (Pakistan), the increase in mean temperature could reach 2-3°C by 2050 compared to the late 20th century under the RCP8.5 scenario, while the heat index could rise by 4 to 7°C over the same time span (Amman *et al.*, 2014). Hot extremes in these cities, already have negative impacts, especially on the poor population lacking appropriate shelter and access to basic water and energy. These heat-related challenges will further rise in the coming decades as both daily and nighttime temperatures will reach unprecedented levels. Even if the local population has a long historical experience in dealing with very warm climate conditions, Amman *et al.* (2014) concluded that a form of active cooling will be necessary in both urban and rural areas to help the population cope with these new climate conditions. The big challenge will be to find clean and low-energy solutions to avoid a large increase in greenhouse gas emissions which could be triggered by a massive use of air-conditioning systems.

Heat indices

While the adverse impacts triggered by heat stress have been studied for decades, the assessment of the stress and its translation in terms of physiological and psychological strain is complex. As a result, more than 30 different heat indices have been developed since the beginning of the 20th century (Epstein & Moran, 2006). Those indices differ in both input variables and the way their effects are parametrized (Kjellstrom *et al.*, 2016). Some integrate both environmental and physiological variables, but are usually difficult to calculate and not appropriate for easy daily use, while some others are based only on measured basic environmental variables such as air temperature and humidity. No temperature index out-performs the others at predicting mortality in all age groups, seasons, or regions (Barnett *et al.*, 2010), which makes projections of heat impacts on population all the more difficult. Commonly used indices include the Heat Index (HI) (Steadman, 1979), employed operationally by the US National Weather Service (NWS), the wet-bulb temperature (T_w) (Haldane, 1905) or the wet-bulb globe temperature (WBGT) (Yaglou & Minaed, 1957). HI is based on a physiological model and its implementation is rather complex. However, the NWS provides a polynomial fit, which depends only on air temperature and relative humidity, and simple charts to assess the likelihoods of heat disorders with prolonged exposure. Hence, this index is widely used in both scientific literature and for warning systems. T_w is defined as the lowest air temperature that would be reached through water evaporation only until saturation (Im *et al.*, 2017). It is measured by covering a standard thermometer bulb with a wetted cloth and fully ventilating it. WBGT includes air temperature, relative humidity, air movement and adds radiant heat as a 4th factor. T_w and WBGT are always lower or equal to the air temperature. As high-lighted by Kjellstrom *et al.* (2016), the WBGT significant advantages: it was designed to represent heat effects on working people, is widely used in national and international guidelines and standards, and has been extensively tested in laboratories and in fields by the US army.

A limit to adaptation?

Metabolic heat produced by a human body (~100 W at rest) has to be evacuated in order to keep core body temperature near 37°C and avoid adverse health outcomes. Heat dissipation can be achieved through three mechanisms: heat conduction, evaporative cooling, and net infrared cooling. When air temperature rises above 34-37°C, the only efficient mechanism of body heat loss is the evaporation of sweat. Therefore, air humidity can have a major impact on the body's ability to cool and is an important variable for assessing exposure to heat stress in a humid environment. Indeed, under high humid conditions, heat loss through sweating may become insufficient and the core body temperature can rise to a dangerous level (Kjellstrom *et al.*, 2016). In their seminal publication Sherwood & Huber (2010) raised the issue of an adaptability limit to climate change due to heat stress. As they argued, net conductive and evaporative cooling can occur only if the body remains warmer than the environment's wet-bulb temperature (T_w). It is thermodynamically impossible for an object to lose heat to an environment whose T_w exceeds the object's temperature. Which means that T_w allows to establish a limit on heat transfer from a human's body, no matter how well hydrated and ventilated it is. Given that the human's core body temperature must remain around 37°C, corresponding to skin temperature at 35°C, they considered that a prolonged exposure to T_w>35°C would induce hyperthermia and be intolerable, even for someone in good health, at rest, fully wet and well-ventilated. Their analysis of the annual maximum air temperature (T_{max}) and maximum T_w on land between 1999-2008 according to ERA-Interim reanalysis shows that while T_{max} could reach 50°C in some parts of the world, the highest maximum T_w anywhere on Earth was ~30°C, with most common values at 26-27°C. Hence, the theoretical threshold of 35°C was never reached under historical climate. However, this may change in the future. A global warming of 3-4°C would in some locations halve the "safety margin", i.e. the difference between maximum T_w and 35°C, leaving not much room for additional burdens to cooling such as sustained physical activity. In a worst-case scenario of 7°C global warming, some areas would face climate conditions where metabolic heat dissipation would become impossible, calling their habitability into question.

Reaching a global warming level as high as 7°C currently appears unlikely, at least for the 21st century. The highest greenhouse gas (GHG) emission scenario (SSP5-8.5) considered in the 6th IPCC report (2021) would lead to a warming of 4.4°C in 2081-2100 (very likely range: 3.3-5.7°C). However, recent publications (Hansen *et al.*, 2023; Schneider *et al.*, 2019) argued that the climate sensitivity to GHG emissions might be underestimated and that higher levels of warming might be possible. In any case, even for global warming levels below 4°C, heat conditions in some regions in the tropics and sub-tropics could make them very inhospitable for humans already during this century. WBGT projections point out the tropical regions as being at risk of significant reductions in labour capacity from heat stress in peak months (*Dunne et al.*, 2013). At the global scale, Mora *et al.*, (2017a) conducted a literature survey to identify locations and timing of past hot events that caused heat-related death. Using about 2000 case studies, mostly from cities in the mid-latitudes, they defined empirically temperature-humidity deadly thresholds. They calculated that historically (1995-2005), about 13.2% of the planet's area and 30.6% of the world's population were exposed more than 20 days/year to temperature-humidity conditions above the deadly threshold. According to the projections from the general circulation models (GCMs) of the Coupled Model Intercomparison Project phase 5 (CMIP5), these values could increase to ~27% (resp. ~47%) of land area and ~47% (resp. ~74%) of the world's population by 2100 under low GHG emission scenario RCP2.6 (resp. high emission scenario RCP8.5). Most strikingly, most tropical regions may face deadly heat conditions nearly year-round under RCP8.5 scenario. Some regions, including parts of Southeast Asia and West Africa, may be exposed to such dangerous conditions most of the year by the end of the century even under the medium-range emission scenario RCP4.5 or as early as mid-century under RCP8.5.

Subsequently, several papers have refined projections of exposure to heat stress, using regional climate models (RCMs). Pal & Eltahir (2016) showed that extremes of T_w in the region around the Arabian Gulf are likely to approach and exceed the critical threshold of 35°C under RCP8.5 scenario. In addition, the effect of humidity brought from water bodies or irrigation can significantly increase heat stress in this region, highlighting the need to include irrigation in future climate projections to assess heat stress (Safieddine *et al.*, 2022). Im *et al.* (2017) projected that extremes of T_w in South Asia (India, Pakistan, Sri Lanka) are likely to approach and, in a few locations, exceed the critical threshold of 35°C by the late 21st century under RCP8.5 scenario. The pattern of these climate projections at a higher spatial resolution than Mora *et al.* (2017a) pointed at the Indus and Ganges river valleys as being the regions most at risk. Under RCP8.5, approximately 75% of the South Asian population is projected to experience maximum T_w > 31°C, which is considered as a dangerous level for most humans, compared to 15% in the current climate and 55% under RCP4.5. Under RCP8.5 scenario, the North China Plain, currently home to 400 million people and a major agricultural area with extensive irrigation, is also likely to experience deadly heatwaves, with T_W exceeding the tolerance threshold for farmers while working outdoors (Kang & Eltahir, 2018).

Furthermore, the theoretical limit of T_w = 35°C proposed by Sherwood & Huber (2010) might actually significantly underestimate the critical T_w threshold above which steady-state core body temperature can no longer be maintained, even for a young, healthy adult at a low activity level (Vecellio *et al.*, 2022; Lu and Romps, 2023). Experiments in a controllable environmental chamber suggested that the critical T_w actually ranges rather from 25°C to 28°C in a hot-dry environment and from 30°C to 31°C in a warm-humid environment (Vecellio *et al.*, 2022). Vecellio *et al.* (2022) concluded that "*not only is the 35°C theoretical threshold untenable under real-world testing, […] one universal wet-bulb temperature cannot be used to quantify human thermal tolerance across the world*". The heat-stress risk for more vulnerable populations or at more intense activity levels would also be higher than for the subjects of the experiments. One of the limitations of the study though, is the fact that it was conducted in Pennsylvania. The repeatability with subjects living in warmer climates, and therefore better acclimatized to such conditions, remains to be further investigated.

Southeast Asia in the face of increased extreme heat conditions

IPCC AR6 (Cissé *et al.*, 2022) assessed that Southeast Asia will be one of the world's regions "*most affected by climate change in terms of heat-related mortality (high confidence). Similarly, projections of the impacts of future heat on occupational health, worker productivity and workability point to [this] region as problematic under climate change (high confidence).*" Exposure to heatwaves in Southeast Asia could increase from 37 million person-days nowadays to 247 million person-days in 2061-2080 under SSP3-4.5 scenario and to 1,158 million person-days under SSP5-8.5 scenario. However, over the past decade, only a few publications have investigated the issue of future heat stress levels in Southeast Asia specifically.

According to Climatic Research Unit (CRU) data for 1961-1990, most parts of the region already experienced high levels of maximum WBGT in the afternoon in March over this period, with values ranging from 29°C to 33°C (Kjellstrom *et al.*, 2013). The southern regions of Vietnam were exposed to values above 27°C, even up to 31°C for the Mekong Delta. Kjellstrom *et al.* (2013) estimated that such values triggered a workloss of 10-40% for heavy work in shade and 40-60% in the sun.

A 1°C increase in WBGT would lead to a further 10% increase in workloss. Also using WBGT to compute work capacity, Kjellstrom *et al.* (2017) investigated the impact of heat stress on occupational health in South and Southeast Asia in the context of climate change, using two different GCMs. For India, they found that the increase in heat stress at 2.5°C global warming level could lead to an increase of daylight work hours lost from historical levels of <1% and 6% for light and heavy work respectively to 4% and 15%. As they argued, reductions of workplace heat stress could be achieved in several ways: providing shade cover, reducing work intensity via mechanization, using air conditioners and fans, and ensuring access to sufficient drinking water. They stressed that it is crucial for both work supervisors and workers to be trained on heat stress risks, associated symptoms, and prevention methods. Li (2020) investigated heat wave trends in Southeast Asia during 1979-2018 using the ERA5 reanalysis data. Results show an increasing trend in the frequency, number, and amplitude of heatwaves. For instance, the trend in heatwave frequency[1] for the Indochina Peninsula is +7.78 (resp. +8.78) days/decade for TX90pct (resp. TN90pct)[2] and +7.56 (resp. +11) days/decade for TWX90pct (resp. TWNpct)[3]. It should be noticed that heatwaves based on minimum temperature are increasing at a much higher rate than those based on maximum temperature. Heatwave trends in Southeast Asia have been further investigated by Li *et al.* (2022), using observations (SA-OBS), reanalyses (ERA5), and their combination (CHIRTS database). Results from the three datasets confirmed that heatwaves based either on maximum temperature or minimum temperature have increased during 1983-2016. The increase in minimum temperature is of special health concern, since anomalously warm nighttime minimum temperatures have been linked to increased mortality and detrimental health effects in high-impact heatwaves across the globe.

According to the bias-corrected projections of the CESM GCM for Southeast Asia (Dong *et al.*, 2021), median values of heat wave frequency could increase from 51.5 days/year at 1°C global warming level (GWL) to 141.7 and 220.8 days/year at 2°C and 3°C GWL respectively, while heatwave duration could increase from 13.6 days at 1°C GWL to 57 days at 3°C GWL. The projections of heatwave frequency and duration with GWL are non-linear, and the increase is faster above 1°C of GWL. It should be noted that these projections are

1 i.e. the number of days per year spent in a heatwave.

2 TX90pct (TN90pct): the threshold is the calendar-day 90th percentile based on a 15-day moving average for daily maximum (minimum) temperature.

3 TWX90pct (TWN90pct): the threshold is the calendar-day 90th percentile based on a 15-day moving average for daily maximum (minimum) wet-bulb temperature.

based only on dry heat, therefore it would be most important to also take humidity into account in future studies. The projections from 7 CMIP6 GCMs under SSP2-4.5 and SSP5-8.5 climate scenarios and SSP3 population scenario (Sun *et al.*, 2022) show that the median total exposure to heat extreme[4] in Southeast Asia could increase by 205% under 2°C GWL and by 337% under 3°C GWL, with the largest part of the signal being due to climate change. The level of exposure depends on the sub-region, with the largest increases projected over the Philippines. While the above-mentioned projections are already a source of concern, it should be noted that climate models may underestimate extreme temperature indices over Southeast Asia, as is observed for the RegCM4.3 regional climate model for instance (Ngo-Duc *et al.*, 2017).

Increasing exposure to heat extremes may drive increasing human mobility in future decades, as pointed out by Zander *et al.* (2019) in their survey of urban populations of Indonesia, Malaysia, and the Philippines. No surprise, almost all (98%) respondents reported having experienced heat stress. Nearly a quarter (23%) reported being "very likely" to move away from their current locations because of heat, and 50% that they « probably would ». The authors highlighted that "*Moving away to cooler places as an adaptation strategy to heat may be challenging to foresee in terms of timing, capabilities, destination and potential costs […] While many people move back after sudden onset disasters, heat potentially leads to permanent movements given it is likely to be better planned, and as the habitability of some places is increasingly compromised.*"

Objectives of the study

Hence, Southeast Asia appears as one of the world's regions most exposed to extreme heat, an exposure projected to further rise in future decades. Given the large negative socio-economic impacts extreme heat may have and the relatively limited amount of literature on the subject focusing on the region, it appears that the issue warrants more research attention. Kjellstrom *et al.* (2017) for instance recommended that any national analysis on the impact of climate change includes: a background statement and listing of publications on the topic of heat effects on work; a quantitative assessment of current and future heat stress levels year-round (including maps); an analysis of the health risks and productivity impacts; a listing of the potential heat-effect prevention methods and discussion of how best to develop strategies to deal

[4] Percentage of days when daily maximum temperature is above 90th percentile.

with heat threats, a step-by-step plan for country-level policies and programs. In Vietnam, average, temperatures have already increased by ~0.78°C from 1981 to 2018, i.e. about 0.21°C/decade (Ngo-Duc *et al.*, 2021).

Since seemingly moderate changes in the mean temperature can significantly increase the risk of extreme events (IPCC, 2021) and as illustrated by the publications for Southeast Asia mentioned above, Vietnam will face increasing extreme heat hazards in future decades, as anthropogenic global warming is expected to further intensify. Indeed," *global surface temperature will continue to increase until at least mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades*." (IPCC 2021, SPM, p.14).

Therefore, following some of the above-listed recommendations of Kjellstrom *et al.* (2017), we conducted a literature review to answer the following questions:

- What is the current level of knowledge on historical and future trends of extreme temperatures and heat in Vietnam? Are quantitative assessments of current and future heat stress levels and exposure available?
- Does exposure to extreme heat already have negative impacts in Vietnam?
- Are there quantitative assessments of potential future socio-economic impacts of increasing exposure to extreme heat in Vietnam?

This literature review is intended as a first step to identify the main knowledge gaps on this issue of heat hazards in Vietnam and where further research is needed to better inform adaptation policies.

1. Methodology

A Web search was conducted in September 2024 using Google Scholar, in order to retrieve literature related to extreme temperature and/or heat exposure, trends and impacts in Vietnam. We selected the references based on keywords occurrence in the title only, using heat/temperature-related keywords combined with geographical keywords (Table 1). The search was restricted to documents published in English between 2005 and September 2024.

Table 1. List of keywords used for the literature search with Google Scholar

Heat/temperature-related keywords	Heat, heatwave(s), extreme temperature(s), high temperature(s), wet-bulb temperature, wet temperature, humidity AND temperature
Geographical keywords	Vietnam, Viet Nam, Hanoi, Mekong delta, Ho Chi Minh City

Note: The heat/temperature-related keywords and geographical keywords were combined in pairs.

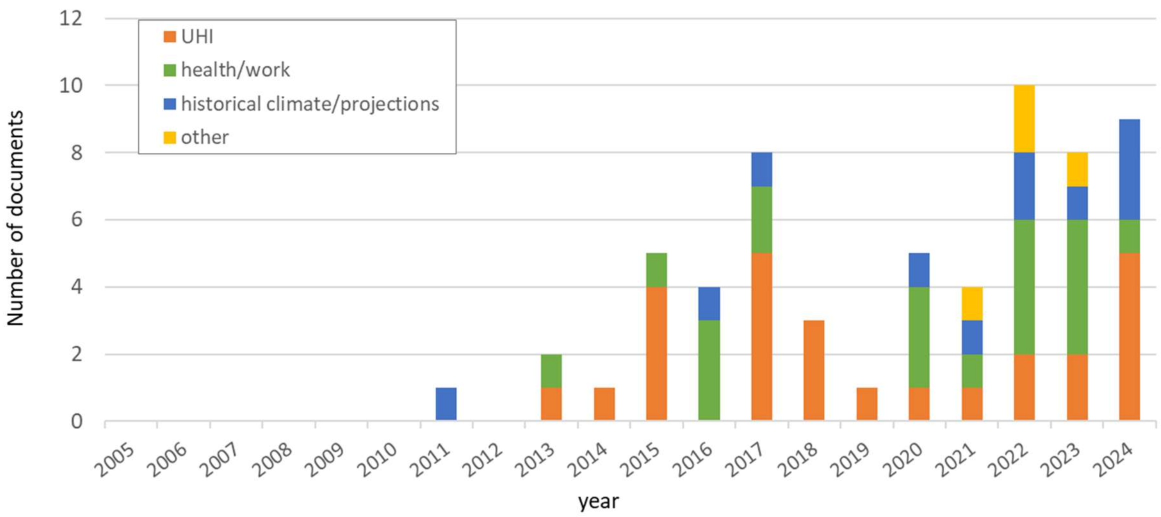
The search returned a total of 147 references of peer-reviewed articles, conference abstracts or articles, doctoral/master dissertations or book chapters. A first screening on the title and type of resources was performed to exclude out-of-subject publications, conference abstracts and duplicates, and a few articles actually in Vietnamese. The number of references was thus narrowed down to 57 documents, which entered the review process. Four additional relevant documents were added to the list based on the authors' knowledge, although their titles do not include the chosen keywords (see Supplementary Material for the detailed list of documents).

2. Results

2.1. Overview of topics and geographical scope

A first screening on the year of publication for the selected documents shows that no publications meeting the selection criteria are found between 2005 and 2010. After 2010, the number of publications shows an increasing trend (Figure 1), suggesting increasing scientific interest in the issue of extreme temperatures and heat stress in Vietnam, although the annual number of publications remains small, with a maximum of 10 documents in 2022. However, the two main topics are the urban heat island (UHI) effect and the health impacts of high temperatures, while climatological studies appear rather rare over the period considered.

Figure 1. Number of documents meeting the selection criteria published between 2005 and September 2024, per year, with main topic



The screening on the titles to identify both the geographical scope and main angle of approach of the publication (Table 2) shows that 13 publications consider the whole Vietnam. About one third (23) of the selected documents focus on the case of Hanoi, and among these 14 deal with the issue of the UHI effect. This topic appears as the most studied, with a total of 25 documents, while heat-related health/work capacity issues come second with 20 documents. By contrast, only 11 documents investigate historical trends and/or climate projections in heat extremes (Table 2), and among the whole selection only 11 documents include some climate change projections, suggesting that climate change impact on future heat stress in Vietnam remains under-studied.

Table 2. Number of documents retrieved, by main topic and geographical scope

Main topic/ geographical scope	Health/ work capacity	Urban heat island effect	Historical climate trends and/or climate projections	Other	Total
Vietnam (whole country)	5 Including 1 with CC projections		7 Including 3 with CC projections	1	**13**
Hanoi	6	14 Including 2 with CC projections (same study)	1 Including 1 with CC projections	2	**23**
Ho Chi Minh City	4 Including 1 with CC projections	7	-	-	**11**
Mekong delta or other regions/cities	5	4	3 Including 2 with CC projections	2 1 with CC projections	**14**
Total	**20**	**25**	**11**	**5**	**61**

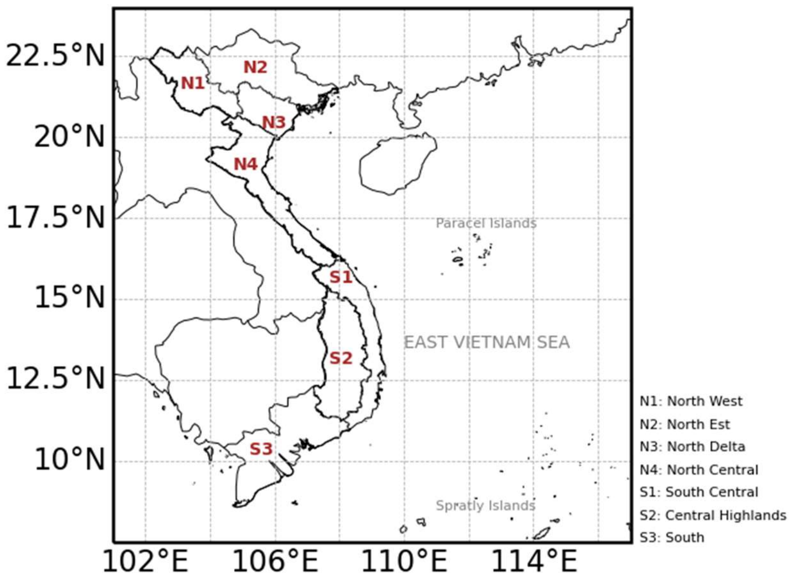
2.2. Historical climate and projections

Historical trends

Ho *et al.* (2011) investigated the evolution of extreme climatic events, including hot summer days, for the seven climatic sub-regions in Vietnam (Figure 2), based on the data from 58 meteorological stations for 1961-2007. Data show increasing trends for all regions but one in the value of daily maximum temperature, with 0.4°C/decade over 5 regions. The study also provides climate projections performed with the RegCM3 RCM for 2001-2050 under A1B (medium GHG emissions) and A2 (high GHG emissions) SRES climate scenarios. Results show an increase of 5-9% in the number of hot summer days compared with the baseline period.

A publication by the Vietnamese Institute of Meteorology, Hydrology and Climate Change (IMHEN) (Nguyen *et al.*, 2016) extended the number of stations and the period considered (82 stations, period 1961-2014) and studied the evolution of the highest maximum temperature and the number of hot (T>35°C) and very hot (T>39°C) days. Results show an increasing trend in all three variables in the North of Vietnam, but contrasting trends in the South, with most stations recording decreasing trends. However, for the South only few station data are available over the period considered, and data quality of the records might have been affected by the war.

Figure 2. Vietnam and its seven climatic sub-regions. Source: Thanh Ngo-Duc



Increasing trends in the frequency of heatwaves, number of hot days, maximum duration, mean and maximum severity of heatwaves were also reported in the master's thesis of Vu (2020). Ngo-Duc *et al.* (2021) also provided a synthesis of the evolution of daily maximum temperature and the number of hot or very hot days over 1981-2018 based on the data from 150 meteorological stations. The daily maximum temperature records show increasing trends over the whole country, at a rate of 0.11 to 0.32°C/decade in almost all regions except for a few stations recording a decrease. The warming trends appear higher in the North Delta, southern North East, northern Central, and eastern Southern Vietnam. The evolution of hot and very hot days appears more heterogeneous and depends on the region considered. The southern North East, North Delta, North Central, and South Central regions show an increasing trend of ~2.6-10.5 days/decade in the number of hot days, while a decrease of 2.6-5.3 days/decade was recorded in some areas of the North West and Central Highlands and in the eastern part of South Vietnam. Contrasting trends in the Southern part of the country seems in agreement with Nguyen *et al.* (2016). However, the higher number of stations included allows to show that some close stations may show an opposite trend, a finding which requires more investigation. The number of very hot days has also increased, but at a lower rate than for hot days.

Vu & Ngo-Duc (2024) further investigated the issue of spatial distribution and trends of heat stress in Vietnam at the country scale. They used the daily maximum temperature (Tx) and daily relative humidity (RH13, recorded at 1 p.m.) during 1979–2018 recorded at 68 meteorological stations spanning the seven Vietnamese sub-regions, providing useful benchmark values for future research on heat stress in Vietnam. They found that annual averages of Tx ranges from 19°C to 31.8°C, with higher values in the South and seasonal variations. Tx increased over almost all areas of Vietnam over the period considered. The highest average trend is recorded in the North Delta, with 0.32°C/decade, followed by the South with 0.24°C/decade. Contrary to Tx, RH13 trends appear more spatially variable, and both negative and positive trends are recorded, depending on the region and stations. In this study, heat stress is defined as a daily maximum wet-bulb temperature (TWmax) above the local 95th percentile for the baseline period 1979–1998. Results show that TWmax variations are closely tied to Tx rather than to RH13. The highest values of TWmax (>28°C) are observed in the North Delta and Central regions, and the lowest ones (<26°C) in high-elevation areas. The study reveals that a significant increase in the annual number of heat stress days is observed at most stations. The interquartile range of values across all stations ranges from 0.8 to 4.2 days/decades, but much higher values are observed at some stations, such as 28.9 days/decade at NamDong station (North Central region), 12.5 days/decade at TraMy station in the Central Highlands and 11.4 days/decade at BachLongVi station in the North Delta. It is worth noting that statistical significance of the trend is provided for each station.

Two recent articles investigated more specifically the issue of summer heatwaves over the past decades at the country scale. Pham Thi *et al.* (2023) assessed summer heatwaves characteristics and trends, based on the daily maximum temperature recorded at 144 meteorological stations over 1980-2018. Heatwaves were identified using a local relative threshold of 90th percentile of maximum temperature. Results show that heatwaves are "*more frequent, intense, severe and longer-lasting in the North Delta and North Central sub-regions compared to the others*". Increasing trends in heatwave frequency and severity are recorded across the whole country, and most particularly in the two above-mentioned regions. Pham-Than *et al.* (2024) provided a detailed analysis on summer heatwaves characteristics in Vietnam and some key large-scale atmospheric drivers, in particular ENSO, as a first contribution towards the development of seasonal heatwave prediction system. Their study relied on the data of 102 weather stations over 1980-2020 and investigated 4 heatwave characteristics for the seven climatic sub-regions of the country: 1) the annual number of heatwave events (HWN), 2) the annual number of heatwave days (HWL), 3) the annual heatwave duration (HWD) and 4) the annual heatwave magnitude (HWM). They chose to apply a relative temperature threshold for the definition of a heatwave event, which is defined as at least 3 consecutive days with a daily maximum temperature above the local 90th percentile. While results show differences in heatwaves characteristic from one region to the other, these differences do not appear very large: HWN ranges from 1.7 to 2.3 events/year and HWL from 7.8 to 9.4 days/year. Heatwave events are more frequent in the Red River delta and the North Central, but their duration is relatively short. On the contrary, less events occur in the Central highlands and the South, but they last longer. Magnitude also varies depending on the region. It can be noticed that in this study the choice of a relative temperature threshold for heatwave definition allows a more flexible definition taking into account the background climate but does not allow to assess the number of days per year with uncomfortable or even dangerous heat levels. Pham-Than *et al.* (2024) also performed a principal component analysis on the temperature data. Results reveal that several teleconnection factors have a statistically significant impact on heatwaves in Vietnam. Among these drivers, ENSO appears as the primary driver of variability of these events. The difference between El Niño and La Niña years range from +1.42 to +2.39 for HWN and from +6.19 to +11.03 for HWL among the sub-regions. However, ENSO does not appear to influence HWD or HWM. The study does not investigate the evolution of heatwaves with global warming over the period considered.

Only four other publications focusing on past heat exposure in Vietnamese cities or regions have been found, with three of them taking into account air humidity, through the choice of the Heat Index (HI). Phuong *et al.* (2022) analyzed the evolution of observed daily mean, maximum, and minimum temperatures at 12 sites located in the Central Highlands of Vietnam during 1980–2019. Significant warming trends in all three variables are recorded, with the estimated trend slopes varying mainly from 0.30–0.43, 0.09–0.25, and 0.41–0.52°C/decade, respectively. Most extreme temperature indices are characterized mainly by positive trends. Opitz-Stapleton *et al.* (2016) addressed historical trends in the city of Da Nang (central Vietnam coast) of day- and night-time HI, which was considered as the most understandable and easiest to implement in workplaces. Indeed, while WBGT is used by the Ministry of Health and the Vietnam Standard and Quality Institute for guidelines on heat-humidity thresholds for workplaces in Vietnam, many workplaces actually do not have the specific WBGT thermometers required. Historical trends in HI are computed using daily meteorological station data from 1970 to 2011, completed by ERA-Interim and NCEP reanalyses to overcome the issue of missing data over some years between 1973-1993 as a legacy of the American/Vietnam War. The mixing of these datasets inevitably introduces some errors. Therefore, the reported trends, or absence of trends in daytime and nighttime HI values are to be considered with the most caution. For instance, the number of days exceeding 37 °C has been increasing at a rate of 0.3 days/per decade but average night-time air temperatures declined by about 0.3°C between 1970 and 2011, which is not in agreement with expectations in a warming world. This decreasing trend may be due to the issue of missing data prior to 1993. New analyses with more recent data covering 2011-2023 would allow an improved assessment. Two other studies investigate the past trends of the HI in urban areas of the Red River Delta, with similar methodologies. Hoang *et al.* (2022) focused on Hanoi and Chien *et al.* (2024) on Thai Binh City, a coastal province. Both studies rely on daily temperature and relative humidity data from a meteorological station for the historical period (past 30 years[5]). In both cities, meteorological data show an upward trend of HI_{max} and of the number of days with HI_{max} at dangerous level (>41°C), which reached about 100 days/year over the past decade.

Climate projections

Among above-cited publications at the country scale, only two provided also projections of hot extremes in the context of climate change. According to the projections from 5 different climate models, the mean maximum temperature would increase by 1.7-2.7°C compared to 1986-2005 by the end of the century under RCP4.5 scenario, with the greatest increase in the Northeast and Northern delta. The number of hot and very hot days would both increase, by 25-35 days under RCP4.5 and 35-45 days under RCP8.5 scenario respectively (Nguyen *et al.*, 2016). Ngo-Duc *et al.* (2021) applied another approach and performed a statistical downscaling of the outputs of 31 CMIP5 GCMs. Results show that the daily maximum temperature would increase on average by 1.3-1.9°C (resp. 1.8-2.6°C) by mid-century and by 1.7-2.6°C (resp. 3.2-4.7°C) by the end of the century under RCP4.5 (resp. RCP8.5) scenario. In agreement with Nguyen *et al.* (2016), the warming would be larger in the North than in the South.

None of these two studies took into account the impact of air humidity on future heat stress. To the best of our knowledge, currently only Opitz-Stapleton *et al.* (2016), Hoang *et al.* (2022) and Chien *et al.* (2024) provided HI projections for Da Nang, Hanoi and Thai Binh City respectively. In agreement with global trends, the climate projections for Da Nang from 6 GCMs downscaled and bias-corrected with a quantile mapping approach show an increase in the number of hot days, with +28 days/year for days with a median HI>37°C for instance in 2020-2049 compared to 1970-1999. The length of the hot season, when daytime

[5] Hanoi: Lang station, period 1991-2020. Thai Binh station: period 1991-2021.

HI remains above 32°C (i.e. "extreme caution" category) may extend by 2-3 months. However, here again, the values are to be considered with caution given the potential significant biases in the historical dataset used to downscale and bias-correct the GCM outputs. The authors indicated that potential impacts of climate change on occupational heat-health risk were not yet within general occupational safety officer awareness at the time of their study, but that the issue was gradually gaining attention from policy-makers. The Center for Community Health Development (COHED), the Ministry of Labor, Invalids and Social Affairs (MOLISA), and Department of Labor, Invalids and Social Affairs of Da Nang (DOLISA) were expanding training programs and introducing occupational heat exposure guidelines to enterprises in the city. Hoang *et al.* (2022) and Chien *et al.* (2024) relied on the climate projections under RCP4.5 and RCP8.5 scenarios issued by the MONRE in 2020 for future decades. However, relative humidity was not a variable available in these projections. Therefore, it had to be computed from other variables. In Hoang *et al.* (2022), relative humidity is computed based on temperature and precipitation, while in Chien *et al.* (2024) it is computed based on maximum, minimum and average temperature, which potentially introduces some biases in the modeled maximum HI (HI_{max}) values, especially for high values. Projected trends are similar for both cities, with an upward trend in annual average HI_{max} of ~0.8°C/decade in Hanoi and ~0.9°C/decade in Thai Binh. The number of days with HI_{max} at dangerous level are also projected to increase and could reach about 120-140 days/year in Hanoi and 140-160 days/year in Thai Binh by mid-century. The authors concluded that days likely to cause heat stroke will increase in future decades, highlighting the need to develop plans and policies to protect vulnerable populations such as outdoor workers, elderly and very young people, and people with pre-existing medical conditions.

2.3. Health or work capacity

Whole Vietnam

Five publications only tackle the issue of heatwave impacts on health or work capacity for the whole country. Phung *et al.* (2017) investigated the statistical relationship between heatwaves and the risk of hospitalization in 25 cities representing different ecological regions of Vietnam, using generalized linear models with Poisson family and distributed lag models. Their pooled estimates show that heatwaves significantly increase all causes and infectious admissions by 2.5% (95%CI: 0.8-4.3) and 3.8% (95%CI: 1.5-6.2) at lag 0 respectively, with a higher risk in the North than in the South of Vietnam for all causes. On the contrary, cardiovascular and respiratory admissions were not significantly increased after a heatwave event. Similarly, Tran *et al.* (2023b) investigated the statistical relationship between temperature and risk of hospitalization in 8 Vietnamese provinces representative of the different ecological regions. They used daily hospitalization and meteorological data from provincial hospitals and provincial meteorological stations collected over 5 to 10 years between 2005 and 2020 – depending on the province – and applied a time-series analysis (generalized linear and distributed lag models with a quasi-Poisson family). The results for the country-level pooled effect show that a 1°C increase in the daily mean temperature above a threshold[6] lead to a 0.8% [0.4%-1.2%, 95% CI] increase in hospital admissions for all causes, and a 2.4% [1.8%-3%] increase for infectious disease. But no significant trend was found for respiratory or mental health disease. Consistent with Phung *et al.* (2017), the magnitude and statistical significance of the trends depends on the region considered. Hence, the positive correlation between temperature increase and hospital admission for all causes is significant in only 3 regions over 8. For infectious diseases, the risk of hospitalization when daily temperature increases is higher in the northern provinces. As highlighted by Tran *et al.* (2023), those differences could be related to demographic characteristic of the population, socioeconomic conditions, quality of the healthcare system, adaptability or the level of heat acclimatization of people. Therefore, they conclude on the importance of conducting studies at both national and subnational level in order to develop local adaptation strategies and define heat-health warning systems.

Nguyen *et al.* (2023) reported higher mortality rates in Vietnam at the provincial level during both cold and heat waves over 2000-2018. They established a statistical relationship between temperature and mortality rates, which is then used to project future deaths due to cold and heatwaves under the four RCP climate scenarios (RCP2.6, 4.5, 6.0, and 8.5), assuming no changes in people's health and economic conditions. Results show a slight decreasing trend in mortality related to cold events and a significant increasing trend in mortality due to heatwaves. These projections are in qualitative agreement with expectations in a warming world. However, the publication does not provide the methodological assumptions for the climate projections (type and number of climate models, spatial resolution, bias corrections) which prevent further discussion of the results. It should also be noted that, as for the three other studies mentioned above, the quantitative relationships established by Nguyen *et al.* (2023) relies on daily temperature data recorded at meteorological stations, with only a few stations for each province, which is only a proxy of population exposure and does not account for spatial variability, including the difference between urban and rural areas.

[6] The temperature threshold if defined as the daily mean temperature associated with the lowest hospitalisation risk for each province.

In addition to health impacts, one study reported negative temperature effect on cognitive performances. Vu (2022) studied the impact of temperature on mathematic test performance of all Vietnamese students at the entrance examination for colleges and universities in 2009. Results suggest a decrease of 1.64% of the raw score for a ~3°C temperature increase from 25.5°C to 28.2°C but these values have to be taken with caution since the temperature was measured at the nearest weather station, i.e. several km from the exam site, which could have introduced biases of several degrees in the actual exposure of the students during their exams. To the best of our knowledge, this study is the only one available on the impact of heat on cognitive performances in Vietnam.

Finally, Phan (2024) investigated the relationship between temperature shocks and the human development index (HDI) at the household level in Vietnam. This study relies on socio-economic data from four waves of the Vietnam Household Living Standard Survey (VHLSS), conducted between 2012 and 2018, and on daily climate data from the ERA5 dataset[7]. The accuracy of the health index is enhanced by using also a nighttime lights dataset. The author developed a new method to construct the household-based HDI, and propose an econometric model linking HDI and temperature at the district level. Despite some acknowledged limitations, results suggest a negative correlation between temperature shocks and HDI[8], particularly through impacts on health and income. However, these findings show spatial heterogeneity across regions and urban vs rural settings: negative impacts on HDI appears more pronounced in the Central Highlands and South Vietnam and HDI losses also appears greater in urban area. This latest finding is consistent with higher temperatures in urban areas because of the UHI effect (which cannot be captured in the ERA5 dataset).

Hanoi

More publications on heat impacts on health under present-day climate at the city or provincial level were identified. Among these, six focused on Hanoi. Trang *et al.* (2016) and Trang (2017) reported that elevated temperature is significantly related to increasing admissions at the Hanoi Mental Hospital for depressive disorders and that heatwave periods are associated to increasing risk of admission for the whole group of mental disorder. Men, residents in rural regions and elderly population over 60 years appeared to be the most sensitive groups. Nguyen *et al.* (2022) reported a significant increase in heat-related respiratory hospitalization among children under 5 years-old in the central districts of Hanoi

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7 Climate reanalysis at 31 km of spatial resolution, aggregated at the district level.

8 HDI at the household level decreases by 2 to 3.5% if temperature deviate from the long-run average by more than two standard deviations.

at temperatures > 34°C, between 2010 and 2014. Indirect heat-related health impacts are highlighted by Cheng *et al.* (2020), who investigated the statistical relationships between heatwaves and dengue outbreaks between 2008 and 2016. Available data suggest that the relationship between temperature and dengue incidence is non-linear, with both short-term and long-term effects, and also depends on the categories of outbreak (small, medium, large). Higher temperatures increase the number of dengue cases, but the effect is more pronounced for large outbreaks. However, the drivers remain unclear and could be due to temperature effects on mosquito population or on changing in human activities (e.g. time spent outside). The authors concluded that further investigations are required to facilitate the development of early warning systems for controlling and preventing dengue transmission. Only one study on heat-related symptoms among workers was identified (Lohrey *et al.*, 2021). The field survey conducted among outdoors workers in Hanoi suggested limited knowledge of the heat-related risks and preventive actions. Although most of the respondents reported having experienced heat-related illness symptoms such as tiredness (78%), headache (57%), and for a few of them fainting (4,1%), only 17.8% respondents could name any heat exhaustion symptoms and 66% could not name any stroke symptoms. These results highlight that public policies should be developed to increase the level of awareness among this much-exposed population and implement preventive actions such as cooling tents, provision of drinks, and health advice. Such policies have actually been recently tested in the city. In 2018, the Vietnam Red Cross with the German Red Cross and IMHEN pioneered the implementation of a Forecast-Based-Financing approach on heatwaves in an urban context for Hanoi, with the main objective to reduce the impact of heatwaves on the most vulnerable populations. The protocol and results are presented by Dinnissen *et al.* (2020). They set up a warning system based on the heat index and maximum temperature forecasts, and implemented early actions including cooling centers and buses. In 2020, the scaling up of this approach was planned in other cities in Vietnam (i.e. Da Nang, Hai Phong).

Ho Chi Minh City

Four publications focusing on Ho Chi Minh City (HCMC) also studied heat-related impacts on health. Phung *et al.* (2016b) reported an increase of 12.9% in the overall risk of cardiovascular hospital admission during heatwaves. Using dynamical downscaling to calculate district-level temperatures in the city between 2010 and 2013 and the mortality data from the HCMC health department, Dang *et al.* (2018) showed a significant increase in heat-related mortality risk when the temperature rises above 30°C. The estimated fraction of mortality resulting from total heat in the central area was estimated to 1.42%, with 0.42% attributable to the UHI effect. Heatwaves also appear to have caused an increase in all-cause mental and behavioral disorder admissions at the HCMC Mental Health Hospital over 2017-2019 (Dang *et al.*, 2022). Nhat *et al.* (2022) also found a positive relationship between heatwaves and hospital admissions for cardiovascular disease over 1997-2018 when temperatures exceed ~26°C, though with large uncertainties. The statistical model was then applied to future decades to investigate changes in cardiovascular admissions with global warming, based on temperature projections from the PRECIS GCM, dynamically downscaled with two different RCMs. Results suggest that the number of hospitalizations in 2050 would be multiplied by 2 or 2.3 under the RCP4.5 and RCP8.5 climate scenarios, respectively. However, the model assumes no changes in population, health services, and treatment, thus not accounting for population growth, ageing, potential changes in health services, or changes in exposure due to air-conditioning development. Moreover, the spatial resolution of the RCMs is only 25 km, i.e. approximately the size of the city, which does not allow for correctly capturing the UHI effect or temperature differences between city districts. The potential increase in the UHI effect due to city growth in future decades is also not taken into account.

Mekong delta and other cities or regions

Phung *et al.* (2016a) examined the statistical relationship between temperature and hospitalizations in the Mekong Delta Region over 2002-2014, using Generalized Linear and Distributed Lag Models. They found that a 1°C increase in daily average temperature was associated with a 1.3% increase in the risk of hospital admissions for all causes, 2.2% for infectious diseases, and 1.1% for respiratory disease. Contrary to the findings of the above-mentioned studies focusing on Hanoi or HCMC, results are inconsistent for cardiovascular diseases. However, the relationships for all causes appear heterogeneous across the provinces of the delta, ranging from 0.05% increase in Tra Vinh to 3.6% in An Giang. A meta-regression shows that population density, poverty rate, and illiteracy rate increased the risk of hospitalization due to high temperature in the region, while higher household income, access to safe water, and hygienic toilets reduce this risk. In a later study, Phung *et al.*, (2018) examined the temperature-hospitalizations statistical relationship over 2010-2013 with a series of hierarchical Bayesian models. Consistent with Phung, *et al.*, (2016a), they found that a 5°C increase in average temperature is associated with a 6.1% increase in region-wide hospital admissions in the Mekong Delta Region. However, the magnitudes of temperature-hospitalization risk are highly heterogeneous across districts, ranging from -55.2% to +24.4%. The effects of heatwaves on hospital admissions for cardiovascular and respiratory disease are also investigated in Ninh Thuan province (coastal area, south-central Vietnam) and Ca Mau (Mekong delta) by Nhung *et al.*, (2023). Daily hospital admissions at the two provincial hospitals between 2010 and 2017 show an increase in respiratory diseases during heat events in Ninh Thuan, but a negative correlation for cardiovascular diseases in Ca Mau.

Table 3. Qualitative overview of the type of correlation between high temperature and health impacts found in the literature

Reference	Geographical scope	Period	Type of impact	Correlation
Phung *et al.* (2017)	25 cities	*	hospitalization, all causes	+
			hospitalization, infectious disease	+
			hospitalization, cardiovascular disease	ns
			hospitalization, respiratory disease	ns
Tran *et al.* (2023b)	8 provinces	2005-2020	hospitalization, hospital admission all causes	+
			hospitalization, infectious disease	+
			hospitalization, respiratory disease	ns
			hospitalization, mental health	ns
Nguyen *et al.* (2023)	Vietnam	2000-2018	mortality	+
Vu (2022)	Vietnam	2009	cognitive performance (mathematical tests)	-
Phan (2024)	Vietnam	2012-2018	HDI	-
Trang *et al.* (2016, 2017)	Hanoi	2008-2012	hospitalization, mental disorders	+
Nguyen *et al.* (2022)	Hanoi	2010-2014	hospitalization respiratory disease, children <5 years	+

Cheng *et al.* (2020)	Hanoi	2008-2016	dengue outbreaks	+
Lohrey *et al.* (2021)	Hanoi	2018	heat-related illness, outdoor workers	+
Phung *et al.* (2016b)	HCMC	2002-2014	hospitalization, cardiovascular disease	+
Dang *et al.* (2018)	HCMC	2010-2013	heat-related mortality risk	+
Nhat *et al.* (2022)	HCMC	1997-2018	hospitalization, cardiovascular disease	+
Phung *et al.* (2016a)	Mekong Delta	2002-2014	hospitalization, all causes	+
			hospitalization, infectious disease	+
			hospitalization, respiratory disease	+
			hospitalization, cardiovascular disease	inconsistent
Phung *et al.* (2018)	Mekong Delta	2010-2013	hospital admissions	+
Nhung *et al.* (2023)	Ninh Thuan	2010-2017	hospitalization, respiratory disease	+
	Ca Mau	2010-2017	hospitalization, cardiovascular disease	-
Tran *et al.* (2023a)	Ha Tinh	2021	heat-related illness, rice farmers	+

Note: Positive correlation: + ; negative correlation: -; non significant: ns.
(* : this publication is not in open access, the period of the study could not be identified).

Hoa *et al.,* (2013) conducted a study on heat stress and adaptive capacity among low-income outdoor workers in the coastal city of Da Nang (central Vietnam). They used a survey with pre-designed questionnaires, more in-depth interviews with some key informants, and reviewed current policies or regulations to protect the health of the outdoor workers as well as the city's resilience to climate change plan. The main findings are as follows: prevalent and serious heat exposure in workplaces; heat stress impacts include physical symptoms, losses in productivity, and financial strain; lack of knowledge on adaptive behavior in the face of heat events. Poverty appears as one of the key drivers of vulnerability, as the workers tend to put their health at risk to maintain their income. In addition, despite existing legislation on the issue of heat stress, the lack of resources and regulation leads to a clear absence of measures to address heat stress by employers and authorities. Heat stress impacts are also recorded among rice farmers, as shown by the survey of Tran *et al.* (2023a) in Ha Tinh province (north-central coast of Vietnam). 83.4% of the respondents reported to have experienced at least one heat-related illness symptom, and 55.1% reported two or more symptoms during the harvesting season.

2.4. Urban heat island effect

Hanoi

The total urban population of Hanoi city increased from about 0.9 million to over 3 million between 1990 and 2010. The rapid urbanization drives a gradual decrease in areas of vegetation and water and an increase in urban structures such as roads and buildings. In addition, population growth has increased the energy demand, and thus the amount of anthropogenic heat released into the air, contributing to the local UHI effect (Doan *et al.*, 2019). In 2011, the Vietnam government implemented a long-term urban development plan, named the Hanoi Master Plan 2030 (HMP), with the aim to develop Hanoi as a sustainable city, while the population is expected to further increase to ~10 million by 2030. To meet the demand of urban development, 28% of the city's natural land will be urbanized by 2030, leading to a 3 times increase in constructed land. The largest changes would occur in the surrounding agricultural land, which would be reduced from 49% of the city area in 2009 to 34% by 2030 (Trihamdani *et al.*, 2013).

Among the selected documents, 14 deal with the UHI effect in Hanoi city. Four of them assessed the UHI effect on land surface temperature, using remote sensing data. Thanh Hoan *et al.* (2018) used the land surface temperature (LST) from satellite data combined with a land use map to assess the impact of land-use type (urban, vegetation, water) on LST during two heatwave days in 2016 and 2017. LST results show a difference of ~7°C between

100% urban built-up cover and 100% vegetative cover. According to this study, converting only 20% of an urban built-up area into a mix of vegetative and water bodies could reduce LST by 2.43°C, showing their importance in reducing LST. Hanh & Chuc (2022) also found large LST differences between high-density urban areas – with LST ranging from 37°C to 43°C – and vegetated areas – with LTS ranging from 26°C to 29°C – based on Landsat images for 2009, 2011, 2016, and 2021. Using satellite images acquired during the wet summer seasons of 1996, 2007, and 2016, Nguyen (2020) confirmed the negative effect of build-up areas versus the positive effect of vegetation on local temperatures. Similarly, Liou *et al.* (2021) studied the impact on LST of decreasing green spaces in Hanoi between 2016 and 2018 and showed that urban green spaces significantly reduce heat, but the effect appears as very local and decrease quickly with distance: beyond 300 m, no cooling effect can be observed.

Other studies rely on regional climate modelling to further investigate the past and future evolution of the UHI in Hanoi city. Doan *et al.* (2019) used the WRF regional climate model coupled with an urban canopy model to perform temperature simulations for the city for 1990, 2010, and 2030, taking into account the projections of urbanization for 2030 according to the current HMP. Results show that land use change and anthropogenic heat will further increase the UHI effect during 2010-2030 compared to 1990-2010. In the urban-core, the monthly mean surface air temperature in July for instance is projected to increase by 0.7°C. However, climate change is not taken into account in these projections. A series of publications from a team of Japanese researchers in collaboration with the Vietnam Institute of Urban and Rural Planning also applied mesoscale urban climate modelling with WRF to Hanoi. Trihamdani *et al.* (2013) investigated the impact of the different green strategies of the HMP. Results show that major hotspots would occur in newly constructed areas and that the expansion of urban areas would increase the intensity of the UHI and both air and surface temperatures in the urban center by 1°C during typical summer weather. Trihamdani *et al.* (2015a) further studied the impact of UHI effect on the indoor thermal comfort and cooling loads in the urban row houses of the city. The authors tested three different land-use configurations: present-day, the HMP scenario, which includes large and centralized green areas, and the same amount of greenbelts as in the HMP but relocated to form smaller green spaces equally distributed in the city. They showed that the third scenario lead to lower average air temperature in built-up areas than in the HMP scenario, but the reduction is limited to 0.5°C during night-time and 0.3°C during daytime under the hottest period, illustrating the limited impact of green areas on their urban surroundings. In a row house located in rural areas at present-day which would then be included in a new urban areas, the energy demand for cooling would increase by 179%. This study was further developed by Trihamdani, *et al.* (2015b), who included additional land-use scenarios, with different vegetation types. A greater reduction of hotspot areas is modelled when the mixed forest is employed as the land cover in the green spaces instead of mixed shrub/grassland. Nam *et al.* (2015) also further investigated the influence of the UHI under the HMP on energy consumption for space cooling in residential buildings. The total cooling load would increase from 683 to 903 Terajoule between 2010 and the HMP conditions. However, this increase is mainly due to the increasing number of households (92%) while the increase in the UHI effect because of land-use changes would account for only 8%. Among potential adaptation strategies to reduce heat exposure indoors, model results from Van Thin & Huu (2021) for Hanoi indicate that installing solar panels on rooftops can reduce indoor air temperature by up to 12°C, hence improving thermal comfort and saving electricity consumption from fans or air conditioners.

It is important to note that none of the above studies on UHI effect projections for Hanoi includes climate change impacts on temperature. This question was addressed in a study whose results were published in several papers. A first part (Kubota *et al.*, 2017) presented further results on the impacts of different future land-use scenarios in Hanoi. High-temperature areas, with temperatures of 40–41°C, would expand widely over the planned built-up areas and the green strategies would not necessarily be effective at cooling all of the built-up areas, although largely reducing the air temperature within the green spaces, particularly at night. A second part (Lee *et al.*, 2017) included climate change impacts and analysed the respective contributions of land use changes and global warming on urban temperatures by 2030, using the WRF regional climate model forced by the MIROC5 GCM. Average air temperature projections show an increase of up to 2.1°C in existing urban areas, of which up to 1.5°C and 0.6°C are attributable to global warming and land use changes, respectively. Results from the same study are also presented in Trihamdani *et al.*, (2017, 2018) who concluded that the future increase in urban temperature will likely exceed the cooling effects of any UHI mitigation measures.

Ho Chi Minh City

HCMC is also a fast-growing city. Impervious surface was estimated to ~10,000 ha in 1996 and ~27,000 ha in 2016 by Son *et al.* (2017). These values were recently revised upwards by Pham *et al.* (2024) who estimated the impervious surface at 43,387 ha in 2016 and 61,886 ha in 2020, based on satellite data. As for Hanoi, the UHI effect in HCMC is also clearly visible on land surface temperature maps based on Landsat data, as shown in Tran Thi *et al.* (2017), Son *et al.* (2017), Nguyen (2023), Do *et al.* (2024) and Pham *et al.* (2024). Let us mention also a publication investigating different strategies to reduce heat and improve thermal comfort through urban design in HCMC (Huynh & Eckert, 2012). Possible strategies include building orientation, type of paving and roof material, green roofs, and street greenery or combinations of these. Results show in particular that the most efficient strategy to reduce air temperature at pedestrian level is street greenery. Light or green roofs do not have a significant effect at pedestrian level, but can reduce indoor temperature and help to reduce energy consumption for building cooling, with green roof being much more efficient than light roof. Huynh & Le (2024) also showed the effectiveness of green infrastructures to reduce UHI.

Other cities

Three publications focusing on the issue of UHI effect in other Vietnamese cities were also identified. Nguyen *et al.* (2022) investigated the relationship between land-use change and temperature, evaporation, and humidity in Da Nang city and Quang Nam province (central Vietnam) between 1979 and 2021. Built-up areas have increased for both areas during 2000-2020, from 77.24 km^2 to 96.92 km^2 for Da Nang and from 183 km^2 to 226 km^2 for Quang Nam. In the mean time, the temperature data from two meteorological stations show an increasing trend in maximum, minimum, and mean annual temperatures between 1979 to 2020, with 0.16°C/decade and 0.30°C/decade for the maximum temperature at Da Nang and Tam Ky stations respectively. The authors found a positive correlation between temperature and built-up areas, which they attributed to an increase in the UHI effect. However, it is doubtful that the temperature data from a single station can be representative of the whole areas, and, most importantly, despite the fact that a large part of the temperature increase may be due to climate change, the relative contribution of climate change and land-use change on temperature changes over the period is not assessed.

Can Tho city, the largest urban area in the Vietnamese Mekong Delta and a fast growing city has also experienced an important increase of UHI extent and intensity, due to increased urbanization (Diem *et al.*, 2023). Diem *et al.* (2024) assessed the variation in land surface temperature (LST) for different structure types in the city. LST were computed from Lansat satellite imagery dated in 2020; urban structure types were derived from a previous dataset and grouped into four main categories (residential, industrial, public and special use, green and open space). UHI effect is observed over 26% of Can Tho City area, with a LST increase up to >5°C in parts of urban area compared with rural areas. The maximum UHI intensity is observed over "industrial" and "public and special use" groups.

Finally, Scheuer *et al.* (2024) proposed a systematic assessment of different greening strategies to mitigate the UHI in the city of Huê (North-Central Vietnam). The case study is a small area of 2.53 ha located in a newly developed residential area and considered representative of urban expansion projects in the city. The ENVI-met model was used to simulate the impact of different greening scenarios on the outdoor thermal comfort at the pedestrian level during a hot day of November 2021. Green infrastructures include grassy areas, green verge, vertical greenery systems and Palm or Deciduous trees. Results confirmed that tree-based interventions are the most efficient to reduce heat stress. However, some adverse effects — such as trapping of outgoing longwave radiations below tree canopy — are also simulated during certain times of the day, highlighting the importance of tree species choice, planting configurations and the need to properly consider local wind patterns. Moreover, while tree planting decreases the Universal Thermal Climate Index by several Celcius degrees thanks to the shading effect, its effect on air temperature is more limited (maximum 1.3°C). Hence, the cooling effect obtained in the tested scenarios appears insufficient when compared to temperature increases projected for Vietnam under global climate change. The authors stressed that in their modelled setting no scenario could achieve a reduction of heat stress large enough to reach comfort levels, calling for "*additional measures [...] to be identified*" beyond greening strategies.

2.5. Other topics

Tran *et al.* (2020) combined a heatwave exposure index, to a sensitivity and adaptive capacity index to assess the spatial pattern of health vulnerability to heatwaves at the provincial level. In their study, a heatwave is defined as at least 3 days with an average temperature above the 95th percentile at the provincial weather station. This relative threshold value differed depending on the province considered, ranging from only 24.5°C in mountainous areas to 32.4°C in the Red River delta. The exposure index was computed using the ERA-Interim reanalysis (~80 km of spatial resolution) between 2005 and 2017. Results show that the southern part of the country is more exposed to heatwaves than the northern part. The largest average number of heatwaves ranged from 122 days in south-eastern provinces to only 18-30 days in northern mountainous regions. However, it should be noticed that potential biases in the ERA-Interim dataset compared to meteorological station data are not assessed, which can lead to biases in the assessment of the number of heatwaves over the period. The sensitivity index was based on 9 indicators of population characteristics, such as population density and percentages of elderly and children for instance. The adaptive capacity index was based on 3 indicators: the number of health staff among the population, the percentage of households with air-conditioning, and the percentage of green areas. Contrary to the exposure index, no north-south gradient is found for the sensitivity and adaptive index, whose spatial pattern is more heterogeneous across the country. The combination of the 3 indexes in a single vulnerability index partly reflects the exposure gradient: the most vulnerable provinces are in the south-central region and in the south-eastern and south-western, while the least vulnerable provinces are the mountainous and north-eastern provinces. Some areas, such as big cities classified as highly sensitive because of their population density may not be the most vulnerable because of higher adaptive capacities, through a high availability of air conditioners for instance. While this study provides useful information to tailor different strategies to deal with heatwave impacts depending on the region, it does not provide information on how vulnerability will evolve in future decades because of: 1) increased exposure to heatwaves because of both climate change and land-use changes, especially increasing urban heat island effect in spreading urban areas, and 2) socio-economic changes in the population which may increase or decrease sensitivity and adaptive capacity.

We identified one study on the cost of heat-related damages and potential adaptation strategies. This study, from the United Nations University deals with the compound risk of floods and heat waves in Can Tho (Mekong Delta) in the context of climate change (Behre *et al.*, 2021). They estimated that heat-related damages in the city could increase from USD 87 million and ~540 000 people impacted to USD 341 (resp. 439) million and 628 000 (resp. 1 million) people in 2050 under RCP4.5 (resp. RCP8.5) climate scenario. Interestingly, in the RCP8.5 scenario, the impact of economic development alone accounted for USD 222 million for the modeled economic damages compared to USD 129 million for climate change. On the contrary, climate change was the main driver of impacts on people (+410 000). The study also provided a cost-benefit analysis of some adaptation options such as green or white roofs, "climate smart agriculture" or cooling centers. However, the available document is only an Executive Summary, and no details on methodologies and limitations are available, neither for damage projections nor for the cost-benefit analysis.

Let us also mention the doctoral dissertation of Le (2022) and related publication (Le *et al.*, 2022) on the relationship between temperature, heat waves, crime, and injury in Hanoi over 2013-2019. They 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. However, the risk plateaued at 30°C and decreased at higher exposures, probably because people will interact less at high temperatures to avoid heat. The inverted U-shape response presents a large statistical uncertainty.

As explained by Kien *et al.* (2023), in the face of health adverse effects triggered by heatwaves, heat-wave early warning systems (HEWSs) may be promising mitigation tools. HEWs implies forecasting the occurrence and severity of heatwaves, predicting potential health outcomes and sending timely notifications to people. Kien *et al.* (2023) is the 1st study in Vietnam investigating the individual willingness to pay for an SMS-based early warning system. Their work, based on the Contingent Valuation Method, targeted a most vulnerable group, i.e. hospitalized patients experiencing heat-related illness. After designing a questionnaire with local authorities, policymakers, experts and participants, they conducted interviews with 400 patients from hospitals located in four central provinces, representative of the climate zones in the north and south-central Coast regions. The findings show an average willingness to pay of VND 283,110 (~USD 11) per person per year. Assuming that 50% of the heat-vulnerable population would pay for HEWSs, the total willingness to pay in central Vietnam would reach about USD 37 million per year.

3. Discussion

In agreement with the increase in hot extremes observed worldwide over the last decades, increasing trends in high temperatures and heatwaves are observed in Vietnam. Seven publications reported increasing trends in various extreme temperature indices, such as maximum temperatures, the number of hot days, heat stress, heatwave duration and frequency, at the country scale. At a more local scale, the retrieved literature in English is rather scarce, with only four documents identified, for the Central highlands, Da Nang, Hanoi and Thai Binh City respectively. Despite these relatively limited literature, the increasing trends in hot extremes in Vietnam appears well established, especially in the most recent studies relying on data including the past decade. However, only the study of Vu & Ngo-Duc (2024) at the country scale and the studies of Opitz-Stapleton *et al.* (2016), Hoang *et al.* (2022) and Chien *et al.* (2024) at the city scale took into account air humidity in their assessment of heat stress trends. To be noticed, all of these studies relied on meteorological stations data and no assessment of past changes in extreme temperatures using a temperature gridded dataset could be found in our review. This lack of gridded data is an issue for both the assessment of climate change impacts on hot extremes in Vietnam over the past decades and for the assessment of historical heat-related impacts on the Vietnamese population.

The literature on future extreme temperature and heat stress in Vietnam specifically appears even more limited, with only four studies providing projections in the context of climate change. These findings suggest that the issue of future heat hazards is currently understudied and related emerging risks are probably underestimated, especially in the case of compounded meteorological hazards (Nguyen-Duy *et al.* 2024). The few studies identified all reported increasing levels of heat stress with higher levels of global warming, in agreement with climate projections for other regions in the world. In some places, the Vietnamese population might be exposed to dangerous levels of heat stress up to several months per year, an issue which deserves more attention from both the scientific community and the public authorities.

Actually, the issue of heat exposure in Vietnam appears to be addressed in the scientific literature mainly through the prism of the urban heat island effect, which is well documented. UHI intensity as high as 7°C are reported in some places. Most of the available studies focus on Hanoi, with some of them investigating the greening strategy of the Hanoi Master Plan at time horizon 2030 through urban mesoscale modelling. However, only one study, with only one climate model also includes climate change impacts on air temperatures in the temperature projections. No scientific literature with projections including both the UHI and climate change impacts on temperature and heat stress for time horizons beyond 2030 - now a close time horizon - seems to be currently available. The evaluation of future heat hazards in urban areas is thus probably significantly underestimated. In particular, available studies suggest that no greening strategies in Vietnamese cities has a potential cooling effect large enough to counteract the compounded effects of UHI and climate change and protect the population from dangerous heat stress. Although they are by no doubt an essential component of future adaptation strategies in the face of global warming, greening policies are no silver-bullets and will need to be accompanied by other adaptation and mitigation strategies.

Increasing heat stress appears as a serious issue for Vietnam, as all publications investigating heat impacts on health or work capacities reported negative impacts over the last decades (Table 3), with increased hospital admissions for various causes (e.g. cardiovascular and infectious diseases, mental health disorders) and increased mortality during heatwaves, although the statistical relationships depend on the region or city considered. Temperature-cardiovascular diseases relationship even shows an opposite correlation depending on the region considered, highlighting the need for further research on this topic to better inform local strategies adapted to the local demographic and socio-economic context. More generally, the assessment of heat-related health impacts in Vietnam would benefit from improved spatial resolution of the underlying temperature dataset and hence the population's exposure. Increased dengue outbreaks are also reported in Hanoi but the role of temperature seems to be complex and here also further research is needed. Heat illness symptoms are also reported by outdoor workers, either in urban (Da Nang) or rural areas (rice farmers). However, all of these studies consider only air temperature as the predicting variable, and none include air humidity although it is a crucial factor to evaluate heat stress level. In addition, to date only two studies (Nguyen *et al.*, 2023; Nhat *et al.*, 2022) considered the potential health or mortality impacts of increased heat stress with global warming, but both assume that people's health and economic conditions remain unchanged, thus probably leading to important biases in the projections.

No study assesses the potential socio-economic impacts and damages of extreme heat in Vietnam in future decades, which remains a very challenging task, as it is in general for future climate damages (e.g. Pindick, 2013; DeFries *et al.*, 2019; Woillez *et al.*, 2020). Indeed, it would require not only to identify all direct and indirect impact channels of extreme heat (e.g. health, diseases, work capacity, income, crops and livestock, etc.), but also how these impacts interact with multiple vulnerabilities and how compound or cascading impacts can spread across sectors. In this respect, assessments of observed impacts over the historical period can provide a qualitative overview of what could occur in the future, but not a quantitative assessment, because we cannot extrapolate observations to climate conditions outside the historical range and in a different socio-economic context. More research on this issue is needed to inform as much as possible public policies and help policy makers to make decisions in a context of uncertainty.

Generally speaking, it appears from the reviewed documents that the question of exposure to heat stress and related issues are slightly gaining public interest over the past few years, but the level of awareness among the population seems to remain low. Only a handful of experimental warning systems in case of heatwave events including early actions to reduce the impact of heatwaves on the most vulnerable populations were mentioned in the reviewed literature.

4. Conclusions

Our review is limited to publications in English and for a more thorough assessment should be completed by a review of available documents in Vietnamese. In particular, more information on current and planned public policies in the face of increasing heat hazards might be available in Vietnamese official documents. More data and climate projections on hot extremes in Vietnam might also be available in publications addressing not only hot extremes but also other types of extreme weather events, which did not enter the review because of the lack of explicit referenced to temperature or heatwaves in their title. Despite these limitations in our review's scope, we can make the following conclusions:

- Increasing trends in high temperature and heatwave events are well recorded in Vietnam, although the literature for Vietnam specifically remains limited. The assessment of historical trends is based on meteorological station data, which in some cases may suffer from a large amount of missing data prior to 1993, especially in the Southern part of the country. Outside of global datasets such as Climate Reanalyses, no historical gridded temperature dataset that would cover the whole Vietnam and include some indices of hot extremes is available.

- Similarly, heat hazards in Vietnam will increase with the levels of global warming, but only a handful of publications tackle this issue, which remains under-studied so far. In particular, no study is available on future heat hazards at the country's scale taking into account air humidity through heat indices such as the heat index or the wet-bulb temperature. In cities, while the issue of UHI and potential mitigation strategies receive growing attention, no study but one investigate heat hazards combining both the UHI effect and climate change.

- Exposures to heat stress already have observed negative impacts on health and work capacity in Vietnam, but further research is needed to improve the evaluation of the relationship between heat exposure and health issues or loss of work capacity.

- No study but one, limited to Da Nang city, deals with potential future socio-economic impacts of heatwaves in Vietnam. Given the major impact of demography and socio-economic changes on vulnerability to heat stress, assessing heat-related impacts is very challenging. However, omitting this dimension in assessments of potential climate change impacts in Vietnam may lead to significant underestimations.

Therefore, we recommend to address the following issues in future research:

- Build a historical gridded climate database of daily temperature in Vietnam, based on available meteorological data and Climate Reanalyses, in order to assess the impact of climate change on hot extremes over the past decades. Depending on data availability, this database should also include air relative humidity data, to investigate the evolution of heat stress indices such as the heat index or the wet-bulb temperature.

- Perform and/or analyze climate projections at high spatial resolution from dynamical and/or statistical downscaling of the CMIP6 climate dataset to assess future heat hazards and exposure to heat stress in Vietnam (including air humidity). The assessments should take into account different climate models and consider different levels of global warming, to account for the range of possible futures, including low-probability but high-impact climate scenarios.

- Similarly, perform new climate projections at very high spatial resolution for the main Vietnamese cities, taking into account both climate change and urban heat island effect, in order to assess the population's exposure at the district level as well as the efficiency of potential UHI mitigation strategies at horizon 2050 and beyond.

- Based on improved historical climate data and climate projections, provide new assessments of heat impacts on health and work capacities, taking into account the projected changes in demography and socio-economic status of the population. This would be a first step towards improved assessment of climate-change potential damages in the country.

Research programs following the above recommendations are currently in progress, such as the GEMMES Vietnam 2 program which started end of 2023[9]. In particular, new high-resolution climate projections, expected at both the country scale and for specific cities, will be highly valuable to inform future public policies and adaptation plans to protect vulnerable populations in the face of increasing heat hazards.

[9] https://www.afd.fr/en/gemmes-vietnam-analysis-socio-economic-impacts-climate-change-vietnam-and-adaptation-strategies

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List of acronyms and abbreviations

AFD	Agence française de développement
CMIP	Climate Models Intercomparison Project
CRU	Climatic Research Unit (University of East Anglia)
ENSO	El Niño Southern Oscillation
ERA	European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5
GHG	Greenhouse gas
GCM	Global climate model
GWL	Global warming level
HCMC	Ho Chi Minh City
HDI	Human development index
HI	Heat index
HMP	Hanoi Master Plan
IMHEN	Vietnam Institute of Meteorology, Hydrology and Climate Change
LST	Land Surface Temperature
MONRE	Ministry of Natural Resources and the Environment (Vietnam)
NWS	US National Weather Service
RCM	Regional climate model
RCP	Representative Concentration Pathway
RH	Relative humidity
SRES	Second report on emission scenario
SSP	Shared Socioeconomic Pathway
TW	Wet-bulb temperature
UHI	Urban heat island
VHLSS	Vietnam Household Living Standard Survey
WBGT	Wet-bulb globe temperature

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