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Mortality burden attributable to heatwaves in Thailand: A systematic assessment incorporating evidence-based lag structure

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ABSTRACT

Background: Available information on the acute and cumulative effects of heatwaves on cause-specific mortality in Thailand is scarce.

Objectives: To quantify the acute and cumulative effects of heatwaves on mortality in Thailand, and assess heatwave-related mortality burden.

Methods: Thirty heatwave definitions were used and categorized into three groups: low intensity heatwaves (HW_{low}), middle intensity heatwaves (HW_{middle}), and high intensity heatwaves (HW_{high}). Time-series analyses were conducted to examine the acute and cumulative effects of HW_{low}, HW_{middle}, and HW_{high} on total and cause-specific mortality in 60 provinces of Thailand, incorporating an optimal lag for each cause and each province. Random-effects meta-analyses were performed to pool provincial estimates to national estimates for both acute and cumulative effects. Meta-regressions were conducted to identify the possible factors contributing to the spatial heterogeneity of heatwave vulnerability.

Results: The cumulative effects of HW_{low} and HW_{middle} on total and cause-specific mortality were greater than HW_{high}. Both acute and cumulative effects of HW_{low}, HW_{middle} and HW_{high} on neoplasms and certain infectious and parasitic diseases were among the highest across all death causes. Effects of heatwaves on deaths from endocrine, nutritional and metabolic diseases appeared to be longer-lasting, and effects of heatwaves on deaths from ischaemic heart diseases and pneumonia occurred more rapidly. Northern and Central Thailand were the regions vulnerable to heatwaves, and proportion of elderly population was the major driver behind the spatial heterogeneity of heatwave vulnerability.

Conclusions: More attention needs to be paid to mild heatwaves. Future heatwave-related mortality burden due to neoplasms and infectious diseases in Thailand may increase as climate change continues.

1. Introduction

Climate change has been considered as the biggest global health threat in the 21st century (Watts et al., 2018), and properly tackling its adverse impacts can be the greatest opportunity to improve public health (Wang and Horton, 2015). Increasing global surface temperature is the most symbolic parameter of climate change (IPCC, 2014) and ambient high temperature, especially prolonged extreme high temperature (i.e., heatwave) (Anderson and Bell, 2011; Basagaña et al., 2011; Ma et al., 2015), has caused substantial health burden globally (Gasparrini et al., 2015). There is no universal consensus on how to well define heatwaves so far (Xu et al., 2016) and a slight change in heatwave definition may have a considerable impact on the estimated health effect (Tong et al., 2010). A recent multicountry study which used four temperature thresholds to define heatwaves have observed that the association between heatwaves and total mortality increased with increasing temperature thresholds (Guo et al., 2017). To better facilitate the development of tailored and cost-effective heatwave-prevention strategies (e.g., heatwave early warning system), it is judicious to categorize heatwaves of various intensities into several groups while

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evaluating the health effects of heatwaves (Tong et al., 2014; Xu et al., 2016).

The effect of heatwaves on mortality appeared not just on the same day of exposure, but also lasted for few days (i.e., lag effect) (Guo et al., 2017). Further, mortality increase during heatwaves in some regions may be followed by a mortality decrease after heatwaves due to the decrease in the population of susceptible pool (i.e., harvesting effect) (Hajat et al., 2005). The widely-observed harvesting effects could, to some extent, affect or bias the assessment of the overall heatwave-related health burden (Baccini et al., 2013). It is possible that spatially variable population vulnerability to heatwaves due to different contexts, such as demographic characteristics (Schifano et al., 2009) and adaptation capacities (Huang et al., 2013), results in the heterogeneity of heatwave effects across different regions, mainly in terms of lag structure and effect size. Also, the lag structure of health effects of different-intensity heatwaves on the same city may also be different as more intense heatwaves may trigger deaths more promptly and have a longer-lasting harvesting effect (Guo et al., 2017). Therefore, it is desirable to scientifically consider evidence-based lag structure so as to accurately assess heatwave-related health burden. For example, Hertel et al. have used generalized cross validation to determine the optimal lag period when looking at heatwave effect on cause-specific mortality in Essen, Germany (Hertel et al., 2009).

A population/community's heatwave vulnerability is mainly determined by three factors: exposure, sensitivity, and adaptive capacity. Thus, heatwave vulnerability varies considerably across different communities due to their various exposure levels, as well as different demographic and adaptation characteristics (Guo et al., 2017). It is crucial to identify those communities/populations which are more vulnerable to heatwave impacts for wisely allocating limited health resources to help those who are most in need (Benmarhnia et al., 2015).

The heatwave definition of World Meteorological Organization is "when the daily maximum temperature of more than five consecutive days exceeds the maximum normal temperature by 5 °C, the "normal" period being defined as 1961–1990". This definition has been adopted by Thai Meteorological Department and thus Thailand has been considered as rarely experiencing heatwaves. However, heatwaves should not be assessed without reference to its human health impacts although it is generally considered as a meteorological event (Robinson, 2001), and prior studies have observed considerable adverse effects of heat and heatwaves (using a few widely used definitions) on mortality in Thailand (Guo et al., 2017; Guo et al., 2012). However, to the best of our knowledge, no study has characterized the effects of heatwaves on cause-specific mortality in Thailand.

This study aimed to quantify the effects of heatwaves on total and cause-specific mortality in 60 provinces of Thailand, a country where health effects of heatwaves have not been adequately evaluated. Specifically, this study attempted to answer four research questions: 1). How did different-intensity heatwaves affect total and cause-specific mortality in Thailand? 2). What were the total and cause-specific mortality burdens attributable to different-intensity heatwaves after incorporating evidence-based lag structure? 3). What was the spatial distribution of the heatwave effects on mortality in Thailand? And 4). What were the possible factors contributing to the heterogeneity of heatwave effects across different provinces of Thailand?

2. Methods

2.1. Study site

Thailand is located in the tropical area, with latitudes ranging from 5° 37′ N to 20° 27′ N and longitudes ranging from 97° 22′ E to 105° 37′ E. Upper part of Thailand, e.g., Northern Thailand and Northeastern Thailand, usually experiences a long period of warm weather, and maximum temperatures can reach 40 °C or more. As a developing country, public health resources in Thailand, especially those used for preventing and controlling heat impact, are limited. The great exposure to heat and the relatively low adaptive capacity may make Thailand residents vulnerable to the adverse impact of heatwaves.

2.2. Data collection

Daily data on non-external cause-specific deaths (International Statistical Classification of Diseases and Related Health Problems 10th Revision (ICD-10): A00-R99) from 1st January 1999 to 31st December 2008 in 60 provinces of Thailand were obtained from Ministry of Public Health, Thailand. To specifically analyze the relationship between heatwaves and cause-specific deaths, we extracted the daily number of deaths due to the following diseases: certain infectious and parasitic diseases (A00-B99), neoplasms (C00-D48), malignant neoplasms (C00-97), endocrine, nutritional and metabolic diseases (E00-90), diabetes mellitus (E10-14), diseases of the circulatory system (I00-99), ischaemic heart diseases (I20-25), diseases of the respiratory system (J00-99), pneumonia (J12-18), diseases of the digestive system (K00-93), diseases of the genitourinary system (N00-99), and renal failure (N17-19). Daily climatic data for each province which covered the same period of time, including maximum temperature, minimum temperature, mean temperature and relative humidity, were provided by Meteorological Department, Ministry of Digital Economy and Society, Thailand.

Data on the possible factors contributing to the heterogeneity of heatwave effects on deaths across provinces (population heatwave sensitivity modifiers), including population density, average years of education attainment of population aged 15 years and over, proportion of people aged ≥ 60 years, proportion of people aged ≥ 65 years, proportion of people aged ≥ 70 years, proportion of people aged ≥ 75 years, and proportion of one-person households, were obtained from the results of Thailand 2000 Population and Housing Census (National Statistical Office, 2000). There were three censuses in Thailand (year 1990, year 2000 and year 2010) from year 1990 until now, and we chose the information from year 2000 Census because our study period covered this year and also because this census results included the most relevant/thorough information on possible factors associated with heatwave effect. No information on gross provincial product per capita (GPPPC) (heatwave adaptive capacity modifier) was found in this census results and thus we used the GPPPC in 2013 as a proxy (NESDB, 2015). We also used the average values of mean temperature as well as relative humidity in each province as the indicators for heatwave exposure level modifiers. The details of these factors were presented in Table S1 (supplementary material). Ethics approval was granted by the Ethics Committee of Sun Yat-sen University prior to the data collection.

2.3. Heatwave definitions

The four hottest months (March to June) from 1999 to 2008 were chosen as the study period in this study. Heatwave was defined by incorporating duration and intensity (Xu et al., 2016). To comprehensively explore how different heatwaves affect mortality in Thailand, we adopted the most-commonly used 10 intensities (90th, 91st, 92nd, …, or 99th percentile of the mean temperature across the study period) and three durations (i.e., ≥2, 3 or 4 consecutive days) in the existing literature to define a heatwave. Thus, we used a total of 30 heatwaves definitions. For the development of cost-effective heatwave early warning system, it is desirable to categorize heatwaves into different groups according to its intensity. Our prior work has observed that grouping heatwaves into three categories seemed reasonable (Tong et al., 2014), and Nairn has also proposed to group heatwaves into three categories (Nairn and Fawcett, 2015; Wang et al., 2018). We categorized these 30 heatwave definitions into three groups: low intensity heatwaves (HW_{low}), middle intensity heatwaves (HW_{middle}), and high intensity heatwaves (HW_{high}). This classification may provide practical evidence to development of heatwave early warning system as policy makers can decide when to trigger the system based on heatwave intensity and it is easy for public to understand the classification.

2.4. Statistical analysis

Three-stage analyses were conducted in this study. In the first stage, we quantified the effects of 30 different heatwaves on total and cause-specific deaths in each province (i.e., relative risk (RR)). In the second stage, in each province, we pooled the RRs of 30 heatwaves into three different intensity heatwave groups (i.e. HW_{low}, HW_{middle}, and HW_{high}), and also calculated the attributable fraction (AF) and attributable death numbers (AN) (Cheng et al., 2017) under three different intensity heatwave groups accordingly (Gasparrini et al., 2012). Finally, we pooled RRs and summed ANs of all provinces and obtained national estimates of RRs and ANs for three different intensity heatwave groups. In the third stage, we used meta-regression to identify the possible factors contributing to the heterogeneity of heatwave effects across different provinces under HW_{low}, HW_{middle}, and HW_{high} using RR of each province as the outcome variable.

2.4.1. First-stage analysis

A quasi-Poisson generalized additive model was used to quantify the effects of heatwaves on total and cause-specific deaths in each province (Bhaskaran et al., 2013). A natural cubic spline with three degrees of freedom (*df*) was used to control for the long-term trend and with-in season variation (Xu and Tong, 2017). A categorical variable was used to control for day of the week (Guo et al., 2017). Relative humidity was also controlled for in the model with linear function for the current day's value (lag 0) as our primary analyses showed that using spline function with different *df*s and for different lag days did not change the main results.

We conducted two different types of analyses using distributed lag non-linear model (DLNM) (Gasparrini et al., 2010) to specifically quantify the acute effects of heatwaves and to assess the cumulative effects of heatwaves (considering prolonged effect of heatwaves or harvesting effect) (Cheng et al., 2018). To capture the acute effects of heatwaves on deaths, we used a fix lag for 0–1 days (i.e., the current day of exposure and the next day). To investigate the cumulative effects of heatwaves, we used generalized cross validation (GCV) (Hertel et al., 2009) to identify an optimal lag within a range of lag 1 day to lag 21 days (Gasparrini et al., 2015), and then calculated the effect of each heatwave on deaths under the optimal lag. This approach to capture the cumulative effects of heatwaves has been well used in our prior work (Cheng et al., 2018).

2.4.2. Second-stage analysis

To pool the RRs of 30 heatwaves into three different intensity heatwave groups in each province, we used random-effects meta-analysis through maximum likelihood (Viechtbauer, 2010). To pool RRs of all provinces together for a national estimate, we also used the same meta-analysis approach. The detailed equations for calculating the AF and AN were:

$$AF_{ij} = \frac{RR_{ij} - 1}{RR_{ij}}$$

$$AN_{ij} = AF_{ij} * \sum\nolimits_{1}^{n} D_{ijn}$$

where: AF_{ij} indicates the attributable fraction in region (i, range:1–60) under the heatwave definition (j, rang1–60); RR_{ij} is the estimated relative risk obtained from the first-stage analysis; AN_{ij} indicates the attributable number; $\sum_{1}^{n} D_{ijn}$ is the total deaths (D) summed over all identified heatwave episodes (n, range ≥ 1) in region (i) under the heatwave definition (j). The attributable fraction and attributable number for one heatwave category (low, medium or high) was computed with the averaged AF_{ij} and AN_{ij} across all heatwave definitions that conditions on the significant RR_{ij} above 1.0. In other words, when heatwave effects under a certain heatwave definition were not statistically significant, the AF and AN would be assumed to be zero. The national attributable number was calculated by summing up all regional specific estimates. This approach has been well utilized in our previous study (Cheng et al., 2017).

2.4.3. Third-stage analysis

Potential factors contributing to the heterogeneity of heatwave effects across different provinces (Table S1) were assessed using random-effects meta-regression single predictor models (Cheng et al., 2017; Guo et al., 2017). Residual heterogeneity was examined and then quantified by the Cochran Q test and I^2 statistic.

All statistical analyses were conducted in R (version 3.4.0), and the visual mappings were done in ArcGIS (version 10.5). The packages "dlnm" and "metafor" were used to conduct distributed lag non-linear models and meta-regression analyses (Gasparrini, 2011; Viechtbauer, 2010).

3. Results

3.1. Summary statistics

Table 1 showed the details of these heatwave definitions and categories. Fig. S1 (supplementary material) presented the values of mean temperature for each heatwave definition in each province and in Thailand. The bold black line and points represent the mean temperatures averaged across 60 province of Thailand. Other lines and points in different colors represent the province-specific mean temperatures.

Table 2 presented the average values of climatic factors and cause-specific deaths of all provinces in the study period. The average value of mean temperature ranged from 25.07 °C in Chiang Rai to 29.26 °C in Bangkok. Neoplasms, certain infectious and parasitic diseases, and diseases of the circulatory systems were the three leading causes of deaths in Thailand in the study period, followed by diseases of the respiratory system.

3.2. Acute effects of heatwaves on total and cause-specific deaths

Table 3 showed the pooled acute effects of HW_{low}, HW_{middle} and HW_{high} on total and cause-specific deaths in Thailand, suggesting that deaths from certain infectious and parasitic diseases, ischaemic heart diseases, and pneumonia were the three leading causes which were most sensitive to HW_{low}, HW_{middle} and HW_{high}. The acute effects of HW_{low} on deaths from diseases of the respiratory system and diseases of the circulatory system were not very high compared with deaths from other diseases. The acute effect of heatwaves on deaths from endocrine, nutritional and metabolic diseases was relatively high under HW_{low}, but was not high under HW_{middle} or HW_{high}.

3.3. Cumulative effects of heatwaves on total and cause-specific deaths

The pooled cumulative effects of HW_{low}, HW_{middle}, and HW_{high} on total and cause-specific deaths in Thailand, which were shown in Table 4, were higher than the acute effects in Table 3, indicating that heatwave effects in Thailand occurred beyond one to two days (Fig. S2 (supplementary material)). Intriguingly, the pooled cumulative effects on total and cause-specific deaths decreased when heatwave intensity increased. Further, the ranks of cause-specific deaths also changed in Table 4 compared with Table 3. Deaths from certain infectious and parasitic diseases were still the leading cause of deaths which was most sensitive to HW_{low}, HW_{middle}, and HW_{high}, but the cumulative effects of HW_{low} and HW_{middle} on diabetes mellitus ranked very high, compared with the acute effects. Comparing the ranks of cause-specific deaths across HW_{low}, HW_{middle}, and HW_{high} in Table 4, we observed that the

Table 1
Heatwave definitions used in this study.

Heatwave types	Specific definitions	Categories
Heatwave type 1	90th percentile & 2 days	Low intensity heatwaves (HW_{low})
Heatwave type 2	90th percentile & 3 days	
Heatwave type 3	90th percentile & 4 days	
Heatwave type 4	91th percentile & 2 days	
Heatwave type 5	91th percentile & 3 days	
Heatwave type 6	91th percentile & 4 days	
Heatwave type 7	92th percentile & 2 days	
Heatwave type 8	92th percentile & 3 days	
Heatwave type 9	92th percentile & 4 days	
Heatwave type 10	93th percentile & 2 days	
Heatwave type 11	93th percentile & 3 days	
Heatwave type 12	93th percentile & 4 days	
Heatwave type 13	94th percentile & 2 days	Middle intensity heatwaves (HW_{middle})
Heatwave type 14	94th percentile & 3 days	
Heatwave type 15	94th percentile & 4 days	
Heatwave type 16	95th percentile & 2 days	
Heatwave type 17	95th percentile & 3 days	
Heatwave type 18	95th percentile & 4 days	
Heatwave type 19	96th percentile & 2 days	
Heatwave type 20	96th percentile & 3 days	
Heatwave type 21	96th percentile & 4 days	
Heatwave type 22	97th percentile & 2 days	High intensity heatwaves (HW_{high})
Heatwave type 23	97th percentile & 3 days	
Heatwave type 24	97th percentile & 4 days	
Heatwave type 25	98th percentile & 2 days	
Heatwave type 26	98th percentile & 3 days	
Heatwave type 27	98th percentile & 4 days	
Heatwave type 28	99th percentile & 2 days	
Heatwave type 29	99th percentile & 3 days	
Heatwave type 30	99th percentile & 4 days	

ranks of cause-specific deaths sensitive to HW_{low} and HW_{middle} were similar, but it changed substantially under HW_{high}.

3.4. Number of deaths attributable to heatwaves

Table 5 showed the rounded number of deaths attributable to HW_{low}, HW_{middle}, and HW_{high} in Thailand. Deaths from neoplasms and certain infectious and parasitic diseases were the major mortality burdens attributable to HW_{low}, HW_{middle}, and HW_{high}, followed by deaths from diseases of the respiratory system, and deaths from diseases of the circulatory system.

3.5. Spatial distribution of the heatwave effects on mortality

Fig. 1 illustrated the acute effects of HW_{low}, HW_{middle}, and HW_{high} on total deaths across different provinces. We found that the effects of HW_{low} on total deaths in provinces in Northern and Central Thailand (e.g., Kamphaeng Phet, and Nakhon Sawan) were the highest, and the geographical scale spread when heatwave intensity increased from HW_{low} to HW_{middle} (Phichit, Chai Nat, and Suphan Buri) and HW_{high}. Interestingly, we also observed that there were provinces which were vulnerable to HWl_{ow} and/or HW_{middle}, but not to HW_{high} (e.g., Prachuap Khiri Khan, and Yala). Fig. S3 (supplementary material) illustrated the effects of HW_{low}, HW_{middle}, and HW_{high} on cause-specific deaths across different provinces of Thailand, implying that heatwave-vulnerable provinces varied by cause and heatwave intensity.

3.6. Factors contributing to the heterogeneity of heatwave effects across different provinces

Fig. 2 showed the factors contributing to the heterogeneity of the acute effects of heatwaves on total deaths across different provinces. Table S2 (supplementary material) presented the details of Cochran Q test and I^2 statistic. For HW_{low}, a higher latitude, a lower longitude, and a higher proportion of elderly people, corresponded to a greater effect of heatwaves on total deaths. For HW_{middle}, a lower relative humidity, a lower education attainment, and a higher proportion of elderly people, corresponded to a greater effect of heatwaves on total deaths. For HW_{high}, no factors significantly contributed to the heterogeneity, suggesting that all subgroups were vulnerable to HW_{high}. Fig. S4 (supplementary material) showed the factors contributing to the heterogeneity of the effects of heatwaves on cause-specific deaths across different provinces, suggesting that the proportion of elderly people was the most consistent factor influencing people's vulnerability to heatwaves across different provinces.

4. Discussion

This study, for the first time, grouped the most widely used heatwave definitions into three categories and quantified the mortality burden attributable to heatwaves in Thailand after incorporating evidence-based lags. It has yielded several notable findings: 1). The acute effect of heatwaves on total deaths increased when heatwave intensity increased, but this pattern did not apply to cause-specific deaths, and interestingly, the cumulative effects of heatwaves on total and cause-specific deaths decreased when heatwave intensity increased (Table 4); 2). The acute and cumulative effects of HW_{low}, HW_{middle} and HW_{high} on deaths from certain infectious and parasitic diseases and neoplasms ranked among the highest, causing considerable mortality burden; 3). HW_{low} and HW_{middle} effects on deaths from endocrine, nutritional and metabolic diseases (e.g., diabetes mellitus) may last way beyond one to two days. On the contrary, the effects of HW_{low}, HW_{middle} and HW_{high} on the commonly recognized heatwave-related death causes, such as ischaemic heart diseases and pneumonia, seemed to occur more rapidly; 4). Deaths from diseases of the circulatory system and diseases of the respiratory system appeared to be more sensitive to HW_{high} (Table 4), but HW_{low} and HW_{middle} also caused substantial mortality burden from diseases of the circulatory system and diseases of the respiratory system, due to the high prevalence of these diseases; 5). The effects of HW_{low}, HW_{middle}, and HW_{high} on total deaths were the highest

Table 2
Mean values of daily climatic factors and cause-specific mortality in 60 communities of Thailand, from 1999 to 2008.

	T_{max} (°C)	T_{mean} (°C)	T_{min} (°C)	RH (%)	Total	AB	C00D48	C0097	E	E1014	I	I2025	J	J1218	K	N	N1719
Bangkok	33.37	29.26	25.34	70.57	58.31	12.49	15.00	14.90	1.75	1.56	11.63	0.76	7.39	4.34	3.07	2.66	2.27
Nakhon Ratchasima	32.21	27.09	22.28	71.75	19.20	4.02	4.71	4.68	0.82	0.72	3.86	0.32	2.60	1.29	1.26	0.93	0.78
Ubon Ratchathani	33.08	27.53	22.34	71.17	13.43	2.54	3.37	3.35	0.73	0.67	2.22	0.17	1.54	0.75	0.77	1.07	0.96
Khon Kaen	32.75	27.23	22.11	72.03	16.13	2.81	4.38	4.36	1.13	1.07	2.52	0.22	1.67	0.69	1.03	1.15	1.02
Chiang Mai	32.18	26.27	20.68	72.00	19.30	3.93	4.85	4.83	0.73	0.65	3.21	0.30	2.43	1.03	1.14	1.36	1.17
Buriram	32.94	27.43	22.31	8.81	1.80	2.38	2.38	2.37	0.42	0.38	1.39	0.12	1.00	0.48	0.57	0.59	0.51
Udon Thani	32.63	27.13	21.95	72.19	12.02	1.97	3.68	3.67	0.79	0.74	1.85	0.16	1.19	0.48	0.75	0.91	0.82
Nakhon Si Thammarat	32.41	27.62	23.16	78.92	10.66	2.04	2.47	2.46	0.41	0.36	2.34	0.14	1.37	0.56	0.55	0.60	0.50
Surin	32.91	27.54	22.53	72.89	8.78	1.70	2.43	2.43	0.43	0.37	1.47	0.12	0.93	0.47	0.60	0.56	0.50
Songkhla	32.46	27.95	23.85	79.43	9.53	1.94	2.21	2.20	0.38	0.33	1.99	0.15	1.15	0.50	0.54	0.46	0.39
Roi Et	32.25	27.16	22.36	72.29	10.60	1.63	3.34	3.32	0.74	0.71	1.68	0.15	1.04	0.46	0.66	0.76	0.69
Chonburi	32.14	28.41	24.76	74.79	12.89	2.93	2.93	2.92	0.48	0.43	2.58	0.15	1.59	0.78	0.75	0.70	0.60
Chiang Rai	30.94	25.07	19.67	76.78	13.01	2.51	3.19	3.19	0.46	0.40	2.28	0.23	1.60	0.68	0.90	1.05	0.87
Samut Prakan	30.46	28.33	26.26	71.31	8.42	2.00	1.92	1.92	0.29	0.26	1.64	0.18	1.00	0.56	0.49	0.45	0.39
Chaiyaphum	32.96	27.75	22.89	70.03	7.90	1.37	2.43	2.42	0.49	0.45	1.15	0.11	0.82	0.35	0.53	0.55	0.49
Sakon Nakhon	31.81	26.52	21.65	72.97	8.50	1.45	2.72	2.71	0.47	0.44	1.28	0.10	0.77	0.32	0.50	0.72	0.66
Nakhon Sawan	33.78	28.51	23.60	71.41	10.41	2.05	2.27	2.26	0.37	0.33	2.28	0.13	1.36	0.65	0.64	0.57	0.50
Phetchabun	33.57	27.85	22.49	73.76	7.30	1.39	1.70	1.69	0.34	0.31	1.32	0.10	0.94	0.40	0.58	0.48	0.41
Surat Thani	32.04	27.55	23.38	80.86	6.27	1.21	1.48	1.47	0.27	0.24	1.18	0.13	0.86	0.36	0.36	0.34	0.28
Kalasin	32.13	27.34	22.19	70.86	8.27	1.36	2.35	2.34	0.59	0.56	1.24	0.11	0.88	0.38	0.54	0.70	0.63
Maha Sarakham	33.78	27.70	21.97	74.87	6.90	1.26	2.03	2.03	0.49	0.45	0.95	0.10	0.74	0.31	0.43	0.53	0.49
Pathum Thani	33.79	28.84	24.14	70.39	6.34	1.47	1.43	1.42	0.22	0.19	1.32	0.08	0.81	0.46	0.37	0.31	0.26
Nong Khai	32.32	26.96	22.02	74.76	5.62	1.03	1.59	1.58	0.35	0.32	0.84	0.08	0.62	0.28	0.35	0.51	0.47
Nakhon Pathom	33.00	27.91	23.14	74.47	7.16	1.52	1.59	1.59	0.28	0.25	1.52	0.10	0.92	0.50	0.42	0.37	0.31
Suphan Buri	33.57	28.38	23.46	71.99	6.92	1.30	1.49	1.48	0.30	0.27	1.63	0.12	0.86	0.42	0.41	0.36	0.31
Phitsanulok	33.19	27.93	22.92	72.71	8.98	1.92	1.65	1.64	0.30	0.26	2.15	0.14	1.08	0.55	0.53	0.42	0.36
Ratchaburi	33.27	28.08	23.45	72.93	8.60	1.77	1.85	1.84	0.30	0.27	1.77	0.13	1.13	0.58	0.48	0.40	0.34
Phra Nakhon Si Ayutthaya	33.64	28.33	23.29	71.18	6.95	1.49	1.31	1.31	0.23	0.20	1.51	0.10	0.98	0.51	0.42	0.33	0.29
Lampang	33.14	26.80	20.94	72.57	10.13	2.02	2.33	2.32	0.37	0.31	1.94	0.19	1.27	0.55	0.55	0.71	0.63
Lopburi	33.71	28.39	23.42	72.84	8.10	1.76	1.71	1.70	0.25	0.22	1.66	0.09	1.02	0.56	0.51	0.41	0.36

Mean values of climatic factors and cause-specific mortality in 60 communities of Thailand

	T_{max}	T_{mean}	T_{min}	RH	Total	AB	C00D48	C0097	E	E1014	I	I2025	J	J1218	K	N	N1719
Kamphaeng Phet	33.23	27.96	23.16	77.62	4.02	0.89	0.79	0.79	0.14	0.12	0.78	0.05	0.56	0.26	0.29	0.23	0.20
Narathiwat	31.40	27.33	23.50	81.06	4.42	0.77	0.74	0.73	0.23	0.21	1.05	0.25	0.65	0.26	0.22	0.23	0.19
Nakhon Phanom	31.74	26.40	21.44	75.10	4.57	0.69	1.43	1.42	0.23	0.21	0.65	0.04	0.46	0.19	0.27	0.44	0.40
Chachoengsao	33.11	27.72	22.94	72.58	5.81	1.14	1.28	1.27	0.24	0.22	1.14	0.06	0.82	0.43	0.35	0.32	0.27
Pattani	32.46	27.80	23.57	81.36	3.60	0.64	0.66	0.65	0.20	0.19	0.81	0.18	0.52	0.17	0.15	0.18	0.14
Loei	32.05	26.17	20.76	72.68	3.98	0.67	0.96	0.96	0.22	0.20	0.67	0.06	0.46	0.20	0.27	0.35	0.31
Trang	32.98	27.81	22.95	81.81	3.83	0.72	0.80	0.80	0.13	0.12	0.82	0.05	0.52	0.23	0.19	0.23	0.19
Sukhothai	33.18	27.63	22.43	77.56	5.19	0.94	1.16	1.15	0.21	0.19	0.98	0.08	0.70	0.36	0.32	0.32	0.29
Rayong	32.86	28.69	24.87	74.61	5.24	1.12	1.05	1.05	0.19	0.18	0.99	0.07	0.71	0.37	0.29	0.27	0.24
Phichit	32.75	27.91	23.37	75.26	4.33	0.84	0.90	0.90	0.14	0.12	0.82	0.05	0.59	0.35	0.30	0.26	0.22
Sa Kaeo	33.49	28.34	23.63	75.58	3.88	0.77	0.99	0.98	0.14	0.11	0.64	0.04	0.50	0.26	0.25	0.19	0.16
Tak	31.53	25.82	20.57	75.20	3.33	0.66	0.79	0.79	0.10	0.09	0.59	0.05	0.52	0.23	0.19	0.15	0.13
Chanthaburi	32.90	27.84	23.16	75.75	6.08	1.41	1.39	1.38	0.18	0.15	1.10	0.07	0.80	0.41	0.35	0.30	0.25
Prachuap Khiri Khan	32.34	27.67	23.36	75.89	4.07	0.95	0.95	0.94	0.15	0.13	0.71	0.05	0.55	0.27	0.23	0.23	0.20
Phatthalung	32.26	28.02	24.11	80.00	3.11	0.67	0.73	0.72	0.13	0.12	0.60	0.05	0.42	0.19	0.17	0.17	0.14
Phayao	31.79	25.79	20.33	77.10	6.32	1.41	1.56	1.56	0.23	0.21	1.04	0.09	0.75	0.30	0.39	0.46	0.39
Chumphon	31.89	27.37	23.16	78.69	3.50	0.69	0.77	0.77	0.11	0.09	0.77	0.05	0.53	0.25	0.18	0.16	0.13
Yala	32.99	27.89	23.35	77.42	3.16	0.58	0.58	0.57	0.15	0.14	0.73	0.10	0.40	0.16	0.16	0.15	0.12
Nan	32.01	25.85	20.08	76.37	5.47	0.95	1.23	1.22	0.17	0.15	0.99	0.09	0.89	0.31	0.31	0.45	0.40
Uttaradit	33.83	28.14	22.93	73.68	5.58	1.10	1.20	1.19	0.21	0.18	1.16	0.10	0.75	0.34	0.38	0.31	0.26
Phrae	32.89	27.16	21.97	75.57	6.28	1.15	1.75	1.75	0.29	0.26	1.07	0.12	0.73	0.28	0.38	0.47	0.41
Prachinburi	33.99	28.64	23.76	75.05	4.29	0.92	0.98	0.98	0.13	0.11	0.83	0.05	0.61	0.34	0.28	0.25	0.21
Lamphun	32.90	26.65	20.82	72.91	4.61	0.89	1.17	1.17	0.19	0.17	0.83	0.08	0.56	0.23	0.26	0.37	0.32
Mukdahan	32.90	27.30	22.23	73.57	2.67	0.45	0.62	0.62	0.13	0.12	0.34	0.03	0.25	0.12	0.14	0.20	0.17
Chai Nat	33.21	28.14	23.56	70.28	3.17	0.72	0.69	0.68	0.12	0.11	0.63	0.04	0.42	0.22	0.22	0.15	0.13
Phuket	32.15	28.46	24.94	78.25	2.57	0.60	0.55	0.54	0.10	0.09	0.52	0.03	0.32	0.16	0.16	0.15	0.14
Satun	32.60	27.96	23.69	79.19	1.20	0.26	0.25	0.25	0.06	0.05	0.26	0.04	0.15	0.06	0.06	0.06	0.05
Mae Hong Son	32.95	26.35	20.35	76.38	1.20	0.27	0.27	0.27	0.04	0.04	0.21	0.03	0.17	0.07	0.07	0.06	0.05
Trat	31.77	27.53	23.57	80.42	2.12	0.43	0.52	0.52	0.08	0.07	0.37	0.03	0.29	0.15	0.13	0.13	0.12
Ranong	32.06	27.76	23.78	79.08	1.11	0.26	0.26	0.26	0.05	0.05	0.23	0.04	0.14	0.07	0.06	0.05	0.05

Tmax, maximum temperature; **Tmean**, mean temperature; **Tmin**, minimum temperature; **RH**, relative humidity; **Total**, total deaths; **AB**, certain infectious and parasitic diseases; **C00D48**, neoplasms; **C0097**, malignant neoplasms; **E**, endocrine, nutritional and metabolic diseases; **E1014**, diabetes mellitus; **I**, diseases of the circulatory system; **I2025**, ischemic heart diseases; **J**, diseases of the respiratory system; **J1218**, pneumonia; **K**, diseases of the digestive system; **N**, diseases of the genitourinary system; **N1719**, renal failure.

Table 3
The pooled acute effects of heatwaves on cause-specific mortality in 60 communities of Thailand, from 1999 to 2008.

Disease	Rank	RR (95% CI)[a]	Rank	RR (95% CI)[a]	Rank	RR (95% CI)[a]
		HW_{low}[b]		HW_{middle}[b]		HW_{high}[b]
Total deaths		1.113 (1.097, 1.130)		1.120 (1.103, 1.138)		1.126 (1.103, 1.150)
Certain infectious and parasitic diseases	1	1.183 (1.146, 1.221)	2	1.190 (1.144, 1.238)	2	1.176 (1.114, 1.241)
Ischaemic heart diseases	2	1.171 (1.116,1.229)	1	1.195 (1.137, 1.256)	1	1.219 (1.134, 1.311)
Pneumonia	3	1.150 (1.096, 1.207)	3	1.184 (1.104, 1.269)	3	1.132 (1.032, 1.242)
Malignant neoplasms	4	1.139 (1.101, 1.179)	4	1.138 (1.097, 1.182)	4	1.128 (1.083, 1.175)
Neoplasms	5	1.139 (1.100,1.179)	5	1.137 (1.095, 1.180)	5	1.127 (1.082, 1.174)
Diseases of the digestive system	6	1.132 (1.080, 1.186)	7	1.120 (1.068, 1.173)	7	1.103 (1.038, 1.173)
Endocrine, nutritional and metabolic diseases	7	1.127 (1.077, 1.180)	9	1.103 (1.032, 1.178)	10	1.059 (0.970, 1.156)
Diabetes mellitus	8	1.125 (1.070, 1.182)	6	1.121 (1.053, 1.192)	9	1.074 (0.984, 1.171)
Diseases of the respiratory system	9	1.105 (1.068, 1.143)	8	1.118 (1.070, 1.168)	6	1.116 (1.053, 1.182)
Diseases of the circulatory system	10	1.079 (1.051, 1.108)	10	1.092 (1.063, 1.121)	8	1.095 (1.051, 1.141)
Renal failure	11	1.037 (0.975, 1.103)	12	0.996 (0.928, 1.170)	11	1.038 (0.970, 1.111)
Diseases of the genitourinary system	12	1.036 (0.981, 1.095)	11	1.000 (0.941, 1.062)	12	1.028 (0.967, 1.091)

[a] RR, relative risk; CI, confidence interval.
[b] HW_{low}, low intensity heatwaves; HW_{middle}, middle intensity heatwaves; HW_{high}, high intensity heatwaves.

in provinces of Western Thailand. Further, this heatwave-vulnerable region spread to Midwestern Thailand when heatwave intensity increased from HW_{low} and HW_{middle} to HW_{high}; 6). The proportion of elderly population was the most consistent factor which contributed to the spatial heterogeneity of heatwave effects, and education attainment, relative humidity, and latitude, may also play a role in influencing the heatwave vulnerability across different provinces.

There is evidence suggesting that mild heat caused more mortality burden (attributable fraction) than extreme heat globally because mild heat occurred much more frequently than extreme heat (Gasparrini et al., 2015). In our study, surprisingly, we found that in Thailand mild heatwaves (HW_{low} and HW_{middle}) not just caused more mortality burden (i.e., attributable fraction and attributable death number) than extreme heatwaves (HW_{high}) (Table 5), but also had greater cumulative effects (i.e., RR) on total and cause-specific mortality (Table 4), although the acute effect of heatwaves on total mortality increased with heatwave intensity (Table 3). A study of Guo et al. which examined how heatwaves affected mortality acutely in 18 countries/regions (including Thailand) using 90th, 92.5th, 95th and 97.5th as the temperature thresholds to define heatwaves observed that the effect of heatwaves on total mortality was higher when using higher temperature thresholds (Guo et al., 2017). Our finding on the acute effect of heatwaves on total mortality echoed the finding of Guo et al. and proved their argument that this finding might be driven by the fact that the acute effect of heatwaves on deaths from diseases of the circulatory system increased with heatwave intensity (Table 3) (Madaniyazi et al., 2016). Nevertheless, our findings also call for attention to the greater cumulative effects of mild heatwaves on total and cause-specific mortality than extreme heatwaves given that these mild heatwaves happened much more frequently, and this finding might partially be explained by the longer harvesting effect of extreme heatwaves (Guo et al., 2017).

Although the past few decades have witnessed declining rates of infectious, maternal, neonatal, and nutritional diseases globally, neoplasms and infectious diseases still caused a huge disease burden, especially in under-developed countries (GBD 2016 Causes of Death Collaborators, 2017a, b). In this study, we observed the considerable acute and cumulative effects of heatwaves on deaths from neoplasms and certain infectious and parasitic diseases under all different intensity heatwaves, indicating that future burden of neoplasms and infectious and parasitic diseases due to heatwaves may keep increasing as heatwaves will become more frequent, more intense and longer-lasting (IPCC, 2014). It is delightful that Global Burden of Disease Risk Factor Collaborators will add temperature as a risk factor in their future work given the massive health effects of climate change and the increasing global policy focus on this field (Gakidou et al., 2017). Previous studies have found increases in deaths from neoplasms during heatwaves in Belgrade (Serbia) (Bogdanović et al., 2013), Essen (Germany) (Hoffmann et al., 2008), Catalonia (Spain) (Basagaña et al., 2011), and the Netherlands (Huynen et al., 2001), and they attributed this increase to short-term harvesting effect. Our findings on the acute and cumulative effects of heatwaves on deaths from neoplasm suggested that heatwaves may trigger existing issues of cancer patients, and the

Table 4
The pooled cumulative effects of heatwaves on cause-specific mortality in 60 communities of Thailand, from 1999 to 2008.

Disease	Rank	RR (95% CI)[a]	Rank	RR (95% CI)[a]	Rank	RR (95% CI)[a]
		HW_{low}[b]		HW_{middle}[b]		HW_{high}[b]
Total deaths		1.169 (1.131, 1.208)		1.155 (1.110, 1.201)		1.126 (1.069, 1.186)
Certain infectious and parasitic diseases	1	1.268 (1.175, 1.369)	1	1.248 (1.145, 1.359)	1	1.203 (1.080, 1.340)
Diabetes mellitus	2	1.260 (1.141, 1.390)	2	1.235 (1.100, 1.386)	7	1.100 (0.943, 1.283)
Neoplasms	3	1.222 (1.132, 1.320)	3	1.200 (1.105, 1.303)	4	1.117 (1.025, 1.218)
Endocrine, nutritional and metabolic diseases	4	1.220 (1.108, 1.344)	5	1.179 (1.057, 1.316)	8	1.093 (0.949, 1.259)
Malignant neoplasms	5	1.211 (1.118, 1.312)	4	1.199 (1.105, 1.302)	2	1.121 (1.030, 1.220)
Ischemic heart diseases	6	1.187 (1.082, 1.301)	6	1.161 (1.045, 1.290)	5	1.106 (0.946, 1.294)
Diseases of the digestive system	7	1.175 (1.087, 1.270)	7	1.136 (1.044, 1.235)	10	1.031 (0.918, 1.157)
Pneumonia	8	1.155 (1.052, 1.267)	9	1.124 (0.997, 1.268)	9	1.084 (0.950, 1.237)
Diseases of the respiratory system	9	1.145 (1.081, 1.212)	10	1.122 (1.043, 1.208)	6	1.102 (1.014, 1.197)
Diseases of the circulatory system	10	1.129 (1.070, 1.190)	8	1.129 (1.062, 1.200)	3	1.119 (1.019, 1.228)
Diseases of the genitourinary system	11	1.012 (0.937, 1.092)	11	0.946 (0.853, 1.049)	11	0.904 (0.795, 1.027)
Renal failure	12	1.010 (0.910, 1.121)	12	0.901 (0.788, 1.031)	12	0.869 (0.752, 1.004)

[a] RR, relative risk; CI, confidence interval.
[b] HW_{low}, low intensity heatwaves; HW_{middle}, middle intensity heatwaves; HW_{high}, high intensity heatwaves.

Table 5
The number of deaths attributable to heatwaves in Thailand under optimal lags (cumulative), from 1999 to 2008.

Disease	Rank	Attributable number	Rank	Attributable number	Rank	Attributable number
		HW_{low}[a]		HW_{middle}[a]		HW_{high}[a]
Total deaths		19,686		12,329		5687
Neoplasms	1	6622	1	3977	1	1867
Malignant neoplasms	2	6544	2	3926	2	1813
Certain infectious and parasitic diseases	3	4566	3	3199	3	1345
Diseases of the respiratory system	4	2751	5	1569	5	781
Diseases of the circulatory system	5	2556	4	2125	4	1081
Pneumonia	6	1480	6	1000	7	433
Endocrine, nutritional and metabolic diseases	7	1364	7	859	8	430
Ischemic heart diseases	8	1341	8	837	6	576
Diabetes mellitus	9	1147	9	694	9	377
Diseases of the digestive system	10	1091	10	608	10	313
Diseases of the genitourinary system	11	512	11	231	11	127
Renal failure	12	464	12	175	12	110

[a] HW_{low}, low intensity heatwaves; HW_{middle}, middle intensity heatwaves; HW_{high}, high intensity heatwaves. The national attributable number was calculated by summing up all regional specific estimates (refer to equations described in the Methods section).

reasons behind the effect of heatwaves on neoplasm warrant more research attention. The underlying mechanisms of heatwave effects on infectious diseases (e.g., intestinal infectious diseases) have been well documented in the existing literature. High temperature promotes the growth of bacteria (Hashimoto et al., 2004), affects food chain (D'Souza et al., 2004), and alters people's hygiene behavior (Xu et al., 2014b). The increase in infectious diseases during heatwaves also remind the health sector of infectious disease control and prevention in Thailand to be better prepared in the face of heatwaves.

In this study, we found that acute effect of heatwaves on deaths from endocrine, nutritional and metabolic diseases was not high, but the cumulative effects of HW_{low} and HW_{middle} on deaths from endocrine, nutritional and metabolic diseases (especially diabetes mellitus) ranked very high among all death causes, implying that the control and prevention of heatwave-related deaths from endocrine, nutritional and metabolic diseases rely not just on heatwave early warning but also upon a constant protection on patients with pre-existing severe endocrine, nutritional and metabolic diseases before, during and after heatwaves. The compromised thermoregulatory function of diabetic patients due to autonomic neuropathy (Sun et al., 2008), as well as the effects of high temperature on glucose tolerance (Akanji and Oputa, 1991) and insulin absorption (Koivisto et al., 1981), may explain the effect of heatwaves on deaths from diabetes. We noticed that, different from endocrine, nutritional and metabolic diseases, effects of HW_{low}, HW_{middle}, and HW_{high} on deaths from ischaemic heart diseases and pneumonia occurred relatively acutely. The physiological mechanisms explaining the effects of heatwaves on ischaemic heart diseases and pneumonia have been widely described (Chen et al., 2015; Oudin Åström et al., 2015; Xu et al., 2014a). Briefly, increased respiratory and heart rate, and increased surface blood circulation etc., put extra pressure on cardiovascular and respiratory systems, triggering the deaths of those patients with pre-existing severe ischaemic heart diseases or pneumonia. Ischaemic heart diseases has been the number one cause of years of life lost in Thailand in 2016 (GBD 2016 Causes of Death Collaborators, 2017a), and our finding reminds the caretakers of patients with severe ischaemic heart diseases or pneumonia to take protective measures (e.g., let those patients stay in cool places and stay hydrated) on heatwaves days.

For the acute effect of heatwaves on total mortality, the vulnerable provinces were largely located in Western Thailand, and the

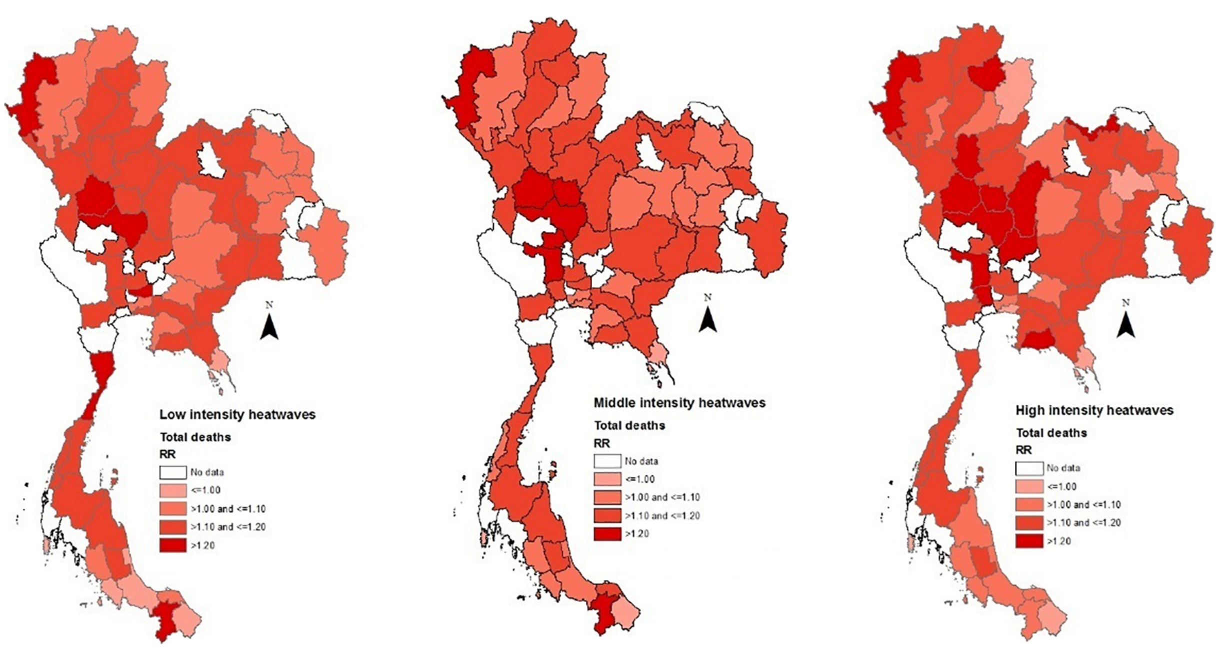

Fig. 1. Heatwave effects on total deaths in 60 Thailand provinces.

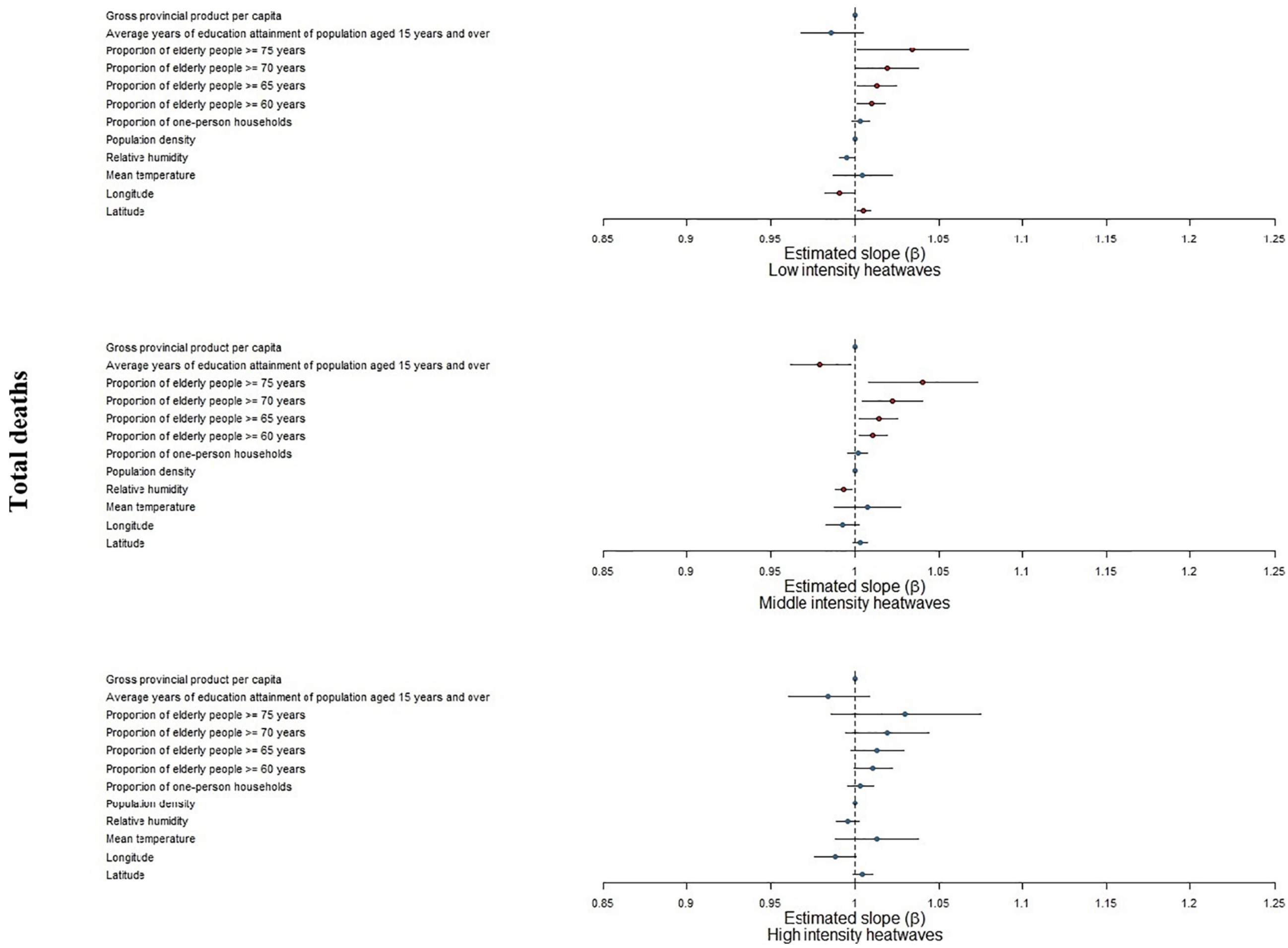

Fig. 2. Factors contributing to the spatial heterogeneity of heatwave effects.

geographical scale of heatwave-vulnerable region spread to Midwestern Thailand when heatwave intensity increased to HW_{high}, indicating that heatwave prevention sources may need to be more allocated to Western or Midwestern Thailand. Nevertheless, the acute effect of heatwaves on total mortality in some provinces (e.g., Prachuap Khiri Khan, and Yala) decreased when heatwave intensity increased to HW_{high}, and the geographical distribution of heatwave vulnerability varied by cause of death, highlighting that province-specific heatwave early warning might be optimal for Thailand. In terms of the drivers behind the spatial heterogeneity in heatwave vulnerability, we found that higher proportion of elderly population was associated with greater heatwave vulnerability. The greater heat/heatwave sensitivity in elderly population has been extensively reported (Arbuthnott and Hajat, 2017; Ma et al., 2015), which may be largely due to their compromised thermoregulatory function because of their insufficient increase in cardiac output and less redistribution of blood flow from renal and splanchnic circulations etc. (Basu, 2009). Our finding suggests that heatwave prevention strategies in Thailand focusing on elderly people protection may largely relieve heatwave-related mortality burden and improve public health. In this study, we've also noticed that a better education attainment was associated with a lower heatwave vulnerability, which is consistent with a study conducted in Guangdong, China (Liu et al., 2013), but inconsistent with another study conducted in 66 communities in China (Ma et al., 2015). We speculate that better education attainment may raise the awareness of heatwave threat or conception of proper prevention measures. Also, education attainment might be a proxy of socioeconomic status as people living in poverty may not have enough access to good education in under-developed countries, although in this study we cannot testify this hypothesis because of the lack of GPPPC data in year 2000. It has also been observed that low relative humidity contributed to greater heatwave vulnerability in this study. The popular scientific opinion is that high relative humidity during heatwaves may make people suffer more as people cannot sweat properly when relative humidity is too high, although the exact role relative humidity plays in the relationship between ambient temperature/heatwave and human health remains largely unclear so far (Zeng et al., 2017).

This study has several strengths. First, for the first time, 30 heatwave definitions covering all widely used heatwave intensities and durations were grouped into three heatwave categories, allowing us to comprehensively understand how low intensity heatwaves, middle intensity heatwaves and high intensity heatwaves affected mortality. Second, GCV was used to identify the optimal lags for each province/cause-specific mortality, which made it possible to not just assess the acute effect of heatwaves on mortality, but also accurately and adequately quantify the mortality burden attributable to different heatwaves. Third, this is, to the best of our knowledge, the most comprehensive study examining how heatwaves affected total and cause-specific mortality using the data from most provinces of Thailand.

Several limitations of this study also need to be acknowledged. First, due to data availability issue, no air pollutants were controlled for in the model, although research in the US found temperature effects on mortality may be robust to air pollutants (Anderson and Bell, 2009). Second, the data that we used were from year 1999 to year 2008, and heatwave sensitivity in Thailand population may change from 2009 until now, although this is the best data set so far. Third, data on GPPPC during the study period were not available and we used GPPPC in year 2013 as a proxy, restricting us to better examine whether economic factor modified the effect of heatwaves on mortality in Thailand.

5. Conclusion

Mild heatwaves were associated with greater cumulative effects on total and cause-specific mortality in Thailand than extreme heatwaves. Heatwave-related mortality burden from neoplasms and infectious diseases may continue to increase in the future as climate change proceeds, and province-specific and tailored heatwave prevention strategies focusing on elderly population may relieve heatwave-related health burden in Thailand. This study calls for more in-depth investigations which quantify health effects of different intensity heatwaves incorporating evidence-based lag structure in other countries/regions.

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Competing interest

The authors declare no competing interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2018.08.058.

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