ORIGINAL ARTICLE

Temperature Related Mortality in A Tropical Climate Country: A Time Series Analysis

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ABSTRAK

Suhu ekstrem tinggi dan rendah memberi kesan negatif kepada kesihatan manusia seterusnya meningkatkan kadar kematian. Kami telah menganalisis hubungan antara suhu dan kematian di kawasan iklim tropika di dua negeri di utara Semenanjung Malaysia. Kajian ekologi ini dijalankan menggunakan data harian kematian dan meteorologi dari tahun 2005-2019 di Negeri Kedah dan Kelantan. Model Linear Umum dan Model Lag Teragih Tidak Linear digunakan untuk menganalisis hubungan antara suhu dan kematian. Kesan kumulatif suhu tinggi (persentil 90^{th}-99^{th}) dan suhu rendah (persentil 1^{st}-10^{th}) terhadap kematian (semua sebab) distratifikasi mengikut umur (0-14, 15-64 dan 65 tahun), jantina dan sebab kematian (kardiovaskular dan respiratori). Model terbaik dipilih menggunakan Kriteria Maklumat Quasi-Akaike. Lag pendek menunjukkan hubungan signifikan terhadap kematian berkaitan suhu tinggi, manakala kematian berkaitan suhu rendah lebih ketara dilihat pada lag panjang. Suhu ekstrem tinggi dan rendah meningkatkan risiko kematian, terutama dalam kalangan kumpulan rentan seperti warga emas, wanita dan pesakit dengan penyakit respiratori atau kardiovaskular. Dapatan kajian ini boleh dijadikan asas untuk merangka dasar dan

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langkah intervensi yang berkesan untuk mengurangkan kesan suhu terhadap kesihatan di peringkat tempatan dan serantau.
Kata kunci: *Kajian ekologi; kesihatan awam; kumpulan rentan; Malaysia; mortaliti; suhu*

ABSTRACT

Extreme high and low temperatures negatively affect human health, thereby increasing mortality rates. We analysed the relationship between temperature and mortality in the tropical climate areas of two northern Peninsular Malaysia states. This ecological study was conducted using daily mortality and meteorological data from 2005-2019 in the states of Kedah and Kelantan. A generalised linear model with a distributed lag non-linear model was used to analyse the relationship between temperature and mortality. The cumulative effects of high temperature (90-99th percentile) and low temperature (1-10th percentile) on mortality (all-cause) were stratified by age (0-14, 15-64, and 65 years), sex and cause of death (cardiovascular and respiratory). The best model was selected using the Quasi-Akaike Information Criterion. Short lags were more significantly linked to high temperature-related deaths, while long lags were more strongly linked to low temperature-related deaths. Mortality related to high temperatures showed a stronger association with short lags, while mortality related to low temperatures showed a stronger association with longer lags. Extreme high and low temperatures were associated with a significantly increased mortality risk, especially among vulnerable groups such as the elderly, females and patients with respiratory or cardiovascular diseases. These findings can serve as a basis for formulating effective policies and intervention measures to mitigate the impact of temperature on health at the local and regional levels.
Keywords: Ecological study; Malaysia; mortality; public health; temperature; vulnerable groups

INTRODUCTION

Climate change is a significant and growing threat to public health in many countries and is directly linked to the rise in mortality rates when humans are exposed to temperature variations over a short-term duration (Smith et al. 2015). Global warming and the projected higher climate scenarios will continue to increase population exposure to high temperatures and lead to greater health risks, where the effect of high temperatures on human health is typically greater than that of low temperatures (Intergovernmental Panel on Climate Change 2022; Lee et al. 2023).

The temperature-mortality relationship is U-, V-, or J-shaped and is mainly detected in temperate and cold climate regions (Anderson & Bell 2009; Breitner et al. 2014; Ma et al. 2014). The U and V shapes, for example, indicate the peaks of mortality that occur at extremely high and extremely low temperatures. Furthermore, a new pattern, i.e. the L-shaped temperature-mortality relationship, was identified (Gasparrini et al. 2015). The L-shaped pattern shows that effects at low temperatures have a steeper slope than effects at high temperatures, which are almost flat (Gasparrini et al. 2015). Interestingly, the L-shaped pattern is mainly detected in tropical or subtropical regions (Dang et al. 2016; Guo et al. 2012) and how it occurs remains unclear. In addition, studies carried out in tropical and subtropical locations indicated that both low and high temperatures were associated with an increase in mortality (Guo et al. 2012; Hashizume et al. 2009). High temperature impacts on mortality are often immediate or have a shorter delay than low temperature effects, which might take many days to weeks (Dang et al. 2016; Gasparrini et al. 2015; Scovronick et al. 2018).

Most studies on temperature effects on health were performed in developed countries with temperate and continental climates. Nevertheless, developing country populations are more susceptible to the adverse effects of extreme temperatures than their developed counterparts due to their heightened sensitivity and limited capacity for adaptation (Costello et al. 2009; Mcmichael et al. 2008). The groups that are vulnerable to the increasing temperatures are the elderly, children, and those with pre-existing conditions, such as cardiovascular and respiratory diseases (Alahmad et al. 2020; Baccini et al. 2008; Basu & Samet 2002). Both cardiovascular and respiratory mortality were associated with low and high temperatures (Scovronick et al. 2018; Yang et al. 2018). However, a few studies reported that at extremely low temperatures, respiratory mortality was higher than cardiovascular mortality (Dadbakhsh et al. 2017; Guo et al. 2022).

Although numerous researchers have examined the association between temperature and mortality on a global scale, there is limited number of studies undertaken specifically in tropical climate zones. Generally, tropical climate countries receive intense sunlight with constant average temperatures of 25-28°C throughout the year. However, it is possible for these countries, specifically those in Southeast Asia, to experience high or low temperature variations due to meteorological phenomena such as the El Niño-Southern Oscillation (ENSO) and cold surges during the winter monsoon (Thirumalai et al. 2017). Malaysia recorded a series of heatwaves following strong ENSO in the past few years, with maximum temperatures of up to 39.3°C and 37.7°C in 2016 and 2019, respectively (Jabatan Meteorologi Malaysia 2020). Cold surge events lead to rapid temperature decreases in tropical climate countries, which was also observed in the Peninsular Malaysia northeast coast (Abdillah et al. 2021; Shariff et al. 2015).

In order to develop local and regional intervention measures against the impacts of temperature on health, it is essential to have a better understanding of the association between temperature and mortality in nations with tropical climates, particularly in Southeast Asian countries. To date, studies on the temperature-mortality relationship in Malaysia have been limited to local characteristics, urban populations (i.e. Klang Valley) (Yatim et al. 2021), and age-specificity (i.e. children) (Phung et al. 2023). Thus, extreme temperature exposure in the climate-affected areas of Peninsular Malaysia northern states has not been studied recently. Therefore, the objective of this study was to examine the relationship between extreme (high and low) temperatures and mortality in two northern states of Peninsular Malaysia.

MATERIALS AND METHODS

Study Design and Setting: Kedah and Kelantan

This is an ecological study based on a 15-year time series model (2005-2019). The study was conducted in the northern Peninsular Malaysian states of Kedah and Kelantan.

Kedah, located in the northwest, is known for its flat terrain and extensive paddy fields. It has a tropical climate with consistent temperatures averaging 26-28°C and significant rainfall during monsoon seasons. Health facilities in Kedah range from urban hospitals to rural clinics, with common health issues including non-communicable diseases (NCDs) like diabetes and hypertension, as well as infectious diseases such as dengue fever.

Kelantan, situated in the northeast, features a mix of coastal plains and forested highlands. The state experiences similar climatic conditions to Kedah, with temperatures averaging 25-27°C and heavy monsoon rains. Health infrastructure is less developed compared to Kedah, particularly in rural areas. Kelantan deals with health problems similar to those in Kedah. Agriculture is essential to the economy of Kelantan.

Both states recorded one of the highest number of extreme heat or heatwave events in Peninsular Malaysia in 2001-2019 (Jabatan Meteorologi Malaysia 2020).

Data

The mortality statistics for each day throughout the study period from 2005 to 2019 were obtained from the Department of Statistics Malaysia (DOSM), using data that was regularly gathered. Individual-level data was utilised for the analysis. We developed a database based on the Tenth Revision of the International Classification of Disease (ICD-10) format and subdivided it into age, sex and cause of death. We reported all-cause mortality, age-specific mortality [0-14 (children), 15-64, 65 years (elderly)], sex-specific mortality, and cause-specific mortality (cardiovascular (I00-I99) and respiratory (J00-J99) diseases).

Inclusion criteria for the mortality data included all deaths registered in Kedah and Kelantan from 2005 to 2019 with complete demographic and ICD-10 classification information. Records with incomplete demographic details (e.g., missing age, sex, or cause of death), deaths outside the study period, or duplicate/inconsistent records were excluded.

The meteorological data on temperature (minimum, maximum, and mean) and relative humidity for Kedah and Kelantan were obtained from the Malaysian Meteorological Department (18 stations) for the period of 2005-2019. All recordings from all monitoring stations were used to generate the daily averages of the meteorological variables (Alahmad et al. 2020; Yatim et al. 2021).

The inclusion criteria for the meteorological data involved using daily recordings from stations that consistently provided reliable observations throughout the study period. Missing data were addressed through the application of imputation techniques to fill in the gaps and ensure a complete dataset. Outlier values identified as incorrect, based on validation with historical trends and station metadata, were excluded from the analysis.

Operational Definitions

The following operational definitions outlined the key variables used in this study, distinguishing between dependent and independent variables that are critical to understanding the relationship between temperature and daily mortality. Dependent variable included (i) all-cause mortality: Total daily deaths from all causes; (ii) cause-specific mortality: Daily deaths due to cardiovascular diseases (ICD-10 codes I00-I99) and respiratory diseases (ICD-10 codes J00-J99); (iii) age-specific mortality: Daily deaths categorised into three age groups: Children (0-14 years); Adults (15-64 years), Elderly (≥65 years); and (iv) sex-specific mortality: Daily deaths disaggregated by sex (male or female). Independent variable included (i) daily mean temperature: The daily average of minimum and maximum temperatures, calculated across 18 meteorological stations in Kedah and Kelantan; (ii) temperature extremes (high): Defined as the 90th and 99th percentiles of the daily mean temperature distribution; (iii) temperature extremes (low): Defined as the 1st and 10th percentiles of the daily mean temperature distribution; (iv) daily relative humidity: The daily average of relative humidity, also calculated across the 18 meteorological stations in Kedah and Kelantan; and (v) minimum mortality temperature (MMT): The temperature associated with the lowest mortality risk, used as the reference point for assessing the impact of temperature variations on mortality.

Statistical Methods

Overdispersion of the daily death distribution was modelled using a quasi-Poisson generalised linear model (GLM) with distributed lag non-linear model (DLNM) analysis (Gasparrini 2011; Wei et al. 2021). The GLM covariates were: (i) a natural cubic spline (NCS) function of calendar time with 5 degrees of freedom (df) per year to control for seasonality and long-term trends in daily mortality; (ii) NCS function of relative humidity (df = 3); and (iii) indicator variables for day of the week (DOW) (Supplementary files). Since the mean temperature had the lowest Quasi-Akaike Information Criterion (QAIC) values, it was utilised as the main mortality predictor (Seposo et al. 2016). Furthermore, the mean temperature is a more precise predictor of heat-related mortality, according to several studies. (Anderson & Bell 2009; Gao et al. 2015; Guo et al. 2017). The lowest QAIC value was used as the criterion to select the df in the model (Seposo et al. 2016).

The MMT threshold was identified with GLM analysis (Yatim et al. 2021). The MMT was defined as the mean daily temperature at which the lowest mortality occurred (Folkerts et al. 2020). The selected best model measured the relative risk (RR) from the association between temperatures above/below the threshold and mortality controlling for covariates per 1 unit temperature increase/decrease.

The potential lagged and non-linear effects of temperature on mortality were measured with the DLNM model using the cross-basis function (Dang et al. 2016; Kim et al. 2020; Li et al. 2019). In order to accommodate lag effects at shorter delays and ensure adequate flexibility at the extremes of temperature distribution, the log scale was modified to include temperature and lag spline knots at equal intervals and spaces, respectively. Based on the QAIC value, the non-linear association between temperature and mortality was modelled with a NCS with df = 3 while the lag effect of temperature was modelled with a NCS with df = 4. The assessment of temperature impacts and necessary changes for harvesting was conducted with time lags of up to 28 days. The general model was as follows:

$$\text{Log}E\,(Yt) = \alpha + \beta T_{t,\,l} + \text{ns (time, df=i/year)} + \text{ns}\,(rh_t, \text{df} = 3) + DOW_t$$

where t was the observation day, Yt was the number of daily deaths on day t, α was the intercept, β was the regression coefficient vector for the cross-basis function where (Tt, l) was a matrix obtained by applying the t temperatures, l was the lag days, DOWt was a DOW on day t represented as categorical variables, and ns was the smoothing parameter set to the NCS. Time was used to control long-term trends and seasonality with i df per year, and rht was the daily relative humidity. To examine the high and low temperature effects on cause-specific mortality, we calculated the RR for mortality associated with extreme low temperature (1st and 10th temperature percentiles) and extreme high temperature (90th and 99th temperature percentiles) relative to the MMT and lag periods (0-3, 0-7, 0-14, 0-21, 0-28 days), respectively (Anderson & Bell 2009). These lag periods allow us to uncover how past events influence current outcomes, helping to explain seasonal variation and identify recurring patterns over time.

To elucidate the relationship between temperature (independent variable) and mortality (dependent variable) over time, we examined various shapes (L, V, U, and J) that represented different patterns of this relationship. L-Shaped pattern illustrated an initial rapid decrease in cold-related deaths as temperatures rise. Beyond a certain temperature threshold, mortality rates plateau, indicating that further increases in temperature had minimal additional impact on mortality. Meanwhile, U- or V-shaped representing the peaks of deaths occurring at very high and low temperatures; the U-shaped curve had a more pronounced decrease and increase in mortality with a rise in temperature than the V-shaped curve. In J-shaped relationship, mortality rates remained stable or even decreased slightly at low to moderate temperatures. However, as temperatures continued to rise and cross a higher threshold, mortality rates increased sharply.

All analyses were performed with R 4.2.0 (R Foundation for Statistical Computing, Vienna, Austria) using the dlnm package (version 2.4.7) (Gasparrini 2011). The sensitivity analysis involved altering the df of the covariate and the maximum lags in the DLNM. Statistical significance was determined by $p<0.05$. The R code necessary to reproduce the results of this study is available upon request from the first author.

RESULTS

Descriptive Statistics

Table 1 presented the distribution of all-cause mortality according to sex and age for the 2005-2019 study period. Within the 15-year study period, Kedah and Kelantan recorded total of 186,479 and 152,616 mortalities, respectively. The proportion of mortalities was as follows: children (≤14 years old), 3.38% (Kedah) and 5.05% (Kelantan); people aged 15-64 years, 39.70% (Kedah) and 39.41% (Kelantan); and the elderly (65 years old), 56.92% (Kedah) and 55.54% (Kelantan). Mortalities among the elderly accounted for the majority of total mortalities in both states.

TABLE 1: Descriptive analysis of mortality data (total count from 2015-2019)

Variables	Kedah (n=186479)		Kelantan (n=152616)	
	n	%	n	%
Sex				
Male	105723	56.69	86244	56.51
Female	80756	43.31	66372	43.49
Age (years)				
0-14	6273	3.38	7705	5.05
15-64	74029	39.70	60147	39.41
≥ 65	106176	56.92	84761	55.54
Cause of death				
Cardiovascular	27155	14.56	20362	13.34
Respiratory	17561	9.42	10522	6.89
Others	141763	76.02	121732	79.77

The summary statistics for meteorological variables (average) throughout the study period indicated that the daily mean ± SD temperature was 29.15 ± 1.09°C in Kedah and 27.29 ± 1.17°C in Kelantan (Table 2 & 3). The average daily minimum ± SD temperature was 24.44 ± 0.98°C in Kedah and 22.74 ± 1.19°C in Kelantan. The average daily maximum ± SD temperature for Kedah was 33.86 ± 1.79 C and was 33.24 ± 2.29°C in Kelantan. The mean ± SD daily relative humidity in Kedah was 63.18 ± 10.76% and 64.28 ± 10.69% in Kelantan.

Temperature-Mortality Relationship - Kedah

The GLM analysis using the daily mean temperature determined that the Kedah MMT was 28.9°C. Figure 1 presented the cumulative overall temperature effects on all-cause mortality at different lag periods for Kedah states. The supplementary file listed the cumulative overall temperature effects on all-cause mortality at different lag periods (0-28). In lags 0-3 and 0-7, the temperature–mortality relationship was J-shaped, where only high temperatures increased the mortality risk. In lags 0-14, the relationship was U-shaped wherein both high and low temperatures increased mortality risk. For lags 0-21 and 0-28, the pattern was L-shaped, wherein low temperature significantly increased the mortality risk. These findings indicated a greater association between high temperature-

TABLE 2: Summary statistics of daily mortality and daily meteorological data in Kedah, 2005-2019 (average)

	Mortality	Maximum Temperature	Mean Temperature	Minimum Temperature	Relative Humidity
Mean	34.04	33.86	29.15	24.44	63.18
±SD	7.17	1.79	1.09	0.98	10.76
Minimum	13.00	25.70	24.70	19.00	34.00
Maximum	64.00	40.00	33.00	27.60	100.00
Percentile					
25th	29.00	32.80	28.45	23.80	56.00
50th	34.00	33.80	29.10	24.40	61.75
75th	39.00	34.90	29.80	25.10	68.25
90th	44.00	36.10	30.55	25.70	77.84

Notes: SD: standard deviation; mortality was given in number of deaths per day

TABLE 3: Summary statistics of daily mortality and daily meteorological data in Kelantan, 2005-2019 (average)

	Mortality	Maximum Temperature	Mean Temperature	Minimum Temperature	Relative Humidity
Mean	27.86	33.24	27.29	22.74	64.28
±SD	6.08	2.29	1.17	1.19	10.69
Minimum	7.00	24.40	22.80	15.70	37.00
Maximum	56.00	40.00	30.70	26.70	100.00
Percentile					
25th	24.00	32.00	26.60	22.20	57.00
50th	28.00	33.68	27.30	22.80	62.29
75th	32.00	34.90	28.10	23.40	69.50
90th	36.00	35.92	28.70	24.10	79.71

Notes: SD: standard deviation; mortality was given in number of deaths per day

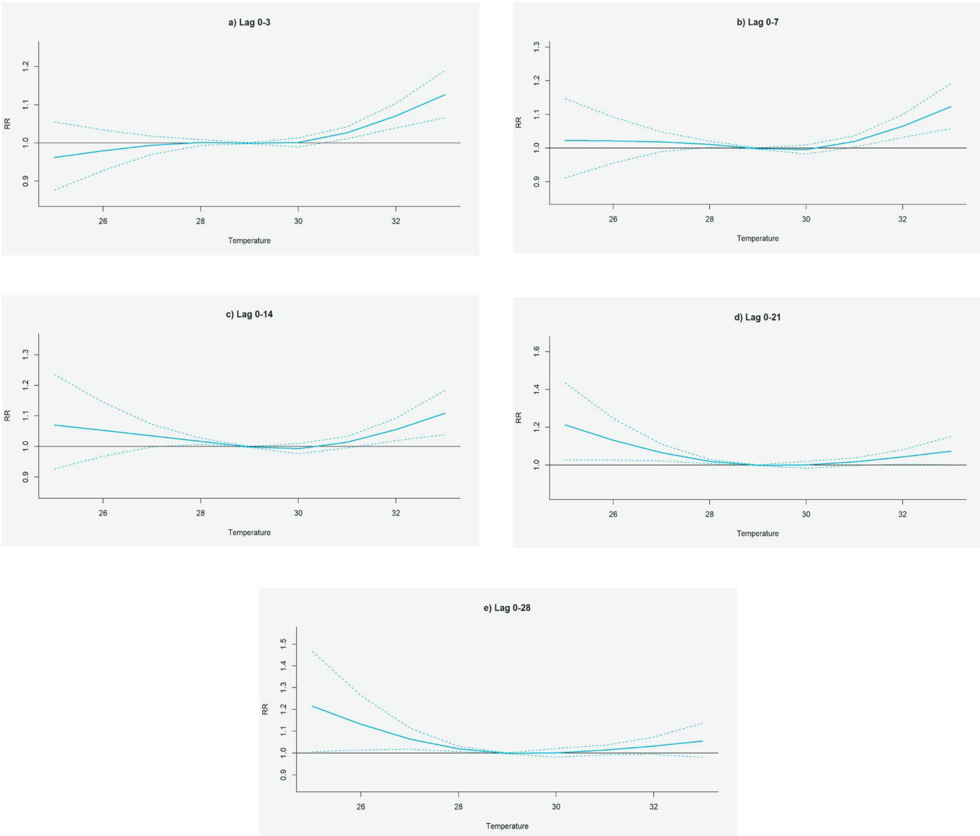

FIGURE 1: Cumulative overall temperature effects on all-cause mortality at different lag periods for Kedah states. The DLNM cross basis functions with 3 df for the temperature and 4 df for the lag dimension. The reference was at the minimum mortality temperature (MMT). Blue lines were the cumulative RR, and the dotted lines are 95% confidence interval. (a) Lag 0-3 (a) and (b) 0-7: J-shaped pattern; (c) lag 0-14: U-shaped pattern; (d) lag 0-21 and (e) 0-28: L-shaped pattern

related mortality and short lags and between low temperature-related mortality and longer lags.

- Kelantan

The GLM analysis using the daily mean temperature determined that the Kelantan MMT was 27.3°C. Figure 2 depicted the cumulative overall temperature effects on all-cause mortality at the different lag periods. In all lags, the temperature-mortality relationship was L-shaped wherein low temperature effects were more prominent than high temperature effects.

Vulnerable Groups
- Kedah

Females and the elderly were particularly vulnerable to high temperatures across multiple lag periods, showing increased mortality at the higher percentile levels. Respiratory disease patients demonstrated increased vulnerability

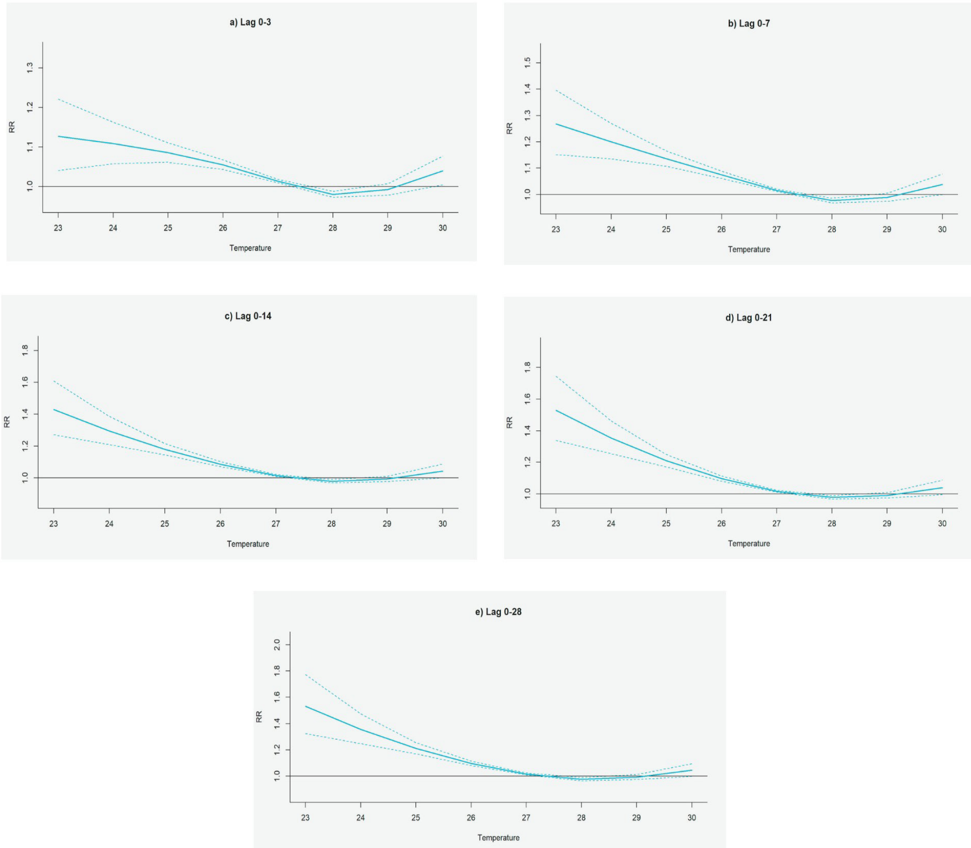

FIGURE 2: Cumulative overall temperature effects on all-cause mortality at different lag periods for Kelantan states. The DLNM cross basis functions with 3 df for the temperature and 4 df for the lag dimension. The reference was at the minimum mortality temperature (MMT). Blue lines were the cumulative RR, and the dotted lines were 95% confidence interval. (a) Lag 0-3, (b) 0-7, (c) 0-14, (d) 0-21 and (e) 0-28 showed L-shaped pattern

mainly at slightly lower percentile levels. The increase in mortality ranges from 4-10% for females, 4-9% for the elderly, and around 7% for patients with respiratory diseases, depending on the lag period.

Males consistently showed vulnerability across various lag periods, particularly at the 1st percentile of low temperature exposure with mortality risk ranges from 1% to 21%. People aged 15-64 years, female and the elderly were susceptible to low temperatures, especially at the 1st and 10th percentiles, over longer lag periods.

- **Kelantan**

High temperatures affected various groups differently over time. Females and the elderly were consistently vulnerable, especially at the highest percentile with mortality risk ranges from 8-9%. They showed vulnerability across lag periods of 0-3, 0-7, and 0-14 days. Only the elderly displayed increased vulnerability over longer periods of 0-21 and 0-28 days.

Similarly, different demographic groups were vulnerable to low temperatures over different time frames. Males, females, individuals aged 15-64 years, and the elderly consistently showed vulnerability, particularly at the coldest temperatures. They exhibited vulnerability across lag periods of 0-3, 0-7, 0-14, 0-21 and 0-28 days. The elderly showed the most vulnerability across all periods, followed by females and males with mortality risk ranges 2-64%.

Table 4 and Table 5 depicted the summary of the cumulative effects of high and low temperature on age-, sex- and cause-specific mortality according to the lag days and temperature percentiles for both states.

DISCUSSION

This long-term ecological study examined the temperature-mortality relationship in Kedah and Kelantan based on the maximum and minimum temperatures both states experienced during 2005-2019. Kedah experienced a higher MMT (28.9°C) compared to Kelantan (27.3°C), which was in line with a previous local study (Yatim et al. 2021). Other studies in tropical countries reported MMT values of 26.0-27.0°C (Dang et al. 2016; Seposo et al. 2015). Thus, our findings could be useful for similar climate zones. Nevertheless, local and geographical characteristics will determine the effects of temperature on certain populations.

We determined that the temperature-mortality cumulative overall curves varied across various lag periods. Both Kedah and Kelantan exhibited similar trends for high temperature effects, with shorter lags presenting higher mortality risk compared to longer lags. During shorter lags, only the effects of high temperature were notable, forming a J-shaped pattern. Conversely, during longer lags, only the effects of low temperature were notable, forming an L-shaped pattern.

Kedah demonstrated rapid changes from the J-shaped to L-shaped pattern, likely attributable to the narrow temperature range in the region. Kelantan did not exhibit the J-shaped pattern but exhibited the L-shaped pattern throughout the shorter and longer lags. This finding can be explained by the relatively lower mean temperature in Kelantan, where the low temperature effect (L-shape) would be more prominent. However, both states exhibited prominent L-shaped patterns for all lag days. Studies in tropical climate regions, such as Thailand and Vietnam, reported similar findings (Dang et al. 2016; Guo et al. 2012; Hashizume et al. 2009). Yet, a few studies conducted between temperate and low temperate areas in Vietnam that reported on the MMT observed J-shaped patterns (Graczyk et al. 2022; Zhang et al. 2018), which could be related to the restrictive lag model used in those studies. Typically, previous studies focused on short lags, which might have missed the delayed effect (Tong et al. 2015; Zhang et al. 2018). These findings also demonstrated that the temperature–mortality relationship was inherently non-linear.

Despite both high and low temperature effects demonstrating significant temperature-mortality relationships, we determined that the mortality RR for high temperature effects were much lower than that of the low temperature effects, which was similar to previous findings (Dang et al. 2016; Gasparrini et al. 2015; Kyselý et al. 2011; Liu et al. 2020; Wu et al. 2013). Furthermore, some studies reported that mortality in a subtropical climate area was lower during summer than in winter (Chau & Woo 2015; Ou et al. 2013). This revealed tropical people are unaccustomed to low temperatures. However, a previous study in the Klang Valley, Malaysia, reported opposite findings, with the RR indicating a greater

TABLE 4: The summary of cumulative effects (RR) of high temperature on age, sex, and cause-specific mortalities

	Lag	Age			Gender		Cause-specific mortalities	
		0-14	15-64	≥ 65	Male	Female	Cardiovascular	Respiratory
Kedah	0-3		1.05 (1.00, 1.10)[a]	1.09 (1.04, 1.13)[a]	1.05 (1.01, 1.09)[a]	1.04 (1.01, 1.07)[a]		1.07 (1.02, 1.12)[a]
				1.04 (1.02, 1.06)[b]		1.10 (1.05, 1.15)[b]		
	0-7			1.08 (1.04, 1.13)[a]		1.10 (1.05, 1.15)[a]		1.07 (1.01, 1.12)[b]
				1.03 (1.01, 1.05)[b]		1.04 (1.01, 1.06)[b]		
	0-14			1.07 (1.03, 1.12)[a]		1.09 (1.04, 1.15)[a]		1.09 (1.02, 1.15)[b]
	0-21			1.05 (1.00, 1.10)[a]		1.07 (1.01, 1.13)[a]		1.10 (1.03, 1.18)[b]
	0-28							1.10 (1.03, 1.18)[b]
Kelantan	0-3			1.09 (1.04, 1.14)[a]		1.09 (1.03, 1.14)[a]		
	0-7			1.08 (1.03, 1.14)[a]		1.08 (1.02, 1.14)[a]		
	0-14			1.08 (1.02, 1.14)[a]		1.07 (1.01, 1.14)[a]		
	0-21			1.08 (1.02, 1.14)[a]				
	0-28			1.08 (1.02, 1.15)[a]				

Notes: 90th/99th: high temperature; a: 99th percentile; b: 90th percentile; only statistically significant data ($p<0.05$) included with corresponding 95% confidence intervals were included

mortality effect from high temperatures compared to low temperatures (Yatim et al. 2021). This could be attributed to the difference in study geographical characteristics/location, urbanisation characteristics, shorter study period (5 years) and age-specificity (<5 years). Furthermore, the Klang Valley experiences more constant high temperatures throughout the year and has a higher population density compared to Kedah and Kelantan.

Regarding the vulnerable populations, age-, sex- and cause-specific mortality were significantly related. Both low and high temperatures exerted greater effects on mortality among the elderly (age ≥65 years) compared to younger age groups (i.e. age 0-14 and 15-64 years). Numerous studies reported that the elderly was the group most vulnerable to low and high temperature effects on mortality (Cheng et al. 2018; Huang et al. 2018; Kollanus et al. 2021; Zhang et al. 2018). The ageing-induced reduction in thermoregulatory function most likely contributes to this finding (Vansomeren 2000). However, children (age 0-14 years) should not be overlooked, as this group is also vulnerable to temperature effects on mortality. Children, especially those aged <5 years, are vulnerable to increasing temperatures (Fouillet et al. 2006; Hutter et al. 2007; Xu et al. 2012). However, we did not obtain significant findings on low and high temperatures effects on mortality among children. One of the possible reasons for the non-significant results in our study is the lower mortality count within this age group.

According to sex-specific analysis, females were more affected by both high and low temperatures than men, which is consistent with some earlier results. (Davídkovová et al. 2014; Liu et al. 2020). A systematic review demonstrated that sex could modify the temperature effect on mortality based on location and population (Son et al. 2019).

TABLE 5: The summary of cumulative effects (RR) of low temperature on age, sex, and cause-specific mortalities

	Lag	Age			Gender		Cause-specific mortalities	
		0-14	15-64	≥ 65	Male	Female	Cardiovascular	Respiratory
Kedah	0-3							
	0-7				1.01 (1.00, 1.02)[c]			
	0-14			1.02 (1.01, 1.03)[c]	1.02 (1.01, 1.03)[c]			
	0-21		1.18 (1.02, 1.37)[d]	1.02 (1.01, 1.04)[c]	1.02 (1.01, 1.04)[c] 1.21 (1.07, 1.38)[d]			
	0-28			1.03 (1.01, 1.04)[c] 1.16 (1.00, 1.34)[d]	1.02 (1.00, 1.04)[c] 1.17 (1.02, 1.36)[d]	1.02 (1.00, 1.04)[c]		
Kelantan	0-3		1.03 (1.02, 1.05)[c] 1.09 (1.01, 1.17)[d]	1.07 (1.05, 1.09)[c] 1.14 (1.07, 1.21)[d]	1.06 (1.04, 1.08)[c] 1.12 (1.05, 1.19)[d]	1.05 (1.03, 1.07)[c] 1.10 (1.02, 1.18)[d]	1.07 (1.04, 1.11)[c]	
	0-7		1.04 (1.02, 1.06)[c] 1.10 (1.01, 1.20)[d]	1.10 (1.08, 1.12)[c] 1.29 (1.19, 1.38)[d]	1.08 (1.06, 1.10)[c] 1.20 (1.11, 1.30)[d]	1.07 (1.05, 1.10)[c] 1.20 (1.11, 1.31)[d]	1.09 (1.05, 1.13)[c] 1.24 (1.07, 1.45)[d]	
	0-14		1.05 (1.03, 1.07)[c] 1.13 (1.02, 1.26)[d]	1.12 (1.10, 1.14)[c] 1.46 (1.34, 1.59)[d]	1.09 (1.07, 1.11)[c] 1.32 (1.21, 1.44)[d]	1.08 (1.06, 1.11)[c] 1.29 (1.17, 1.43)[d]	1.10 (1.06, 1.14)[c] 1.36 (1.13, 1.64)[d]	1.06 (1.00, 1.11)[c] 1.48 (1.15, 1.90)[d]
	0-21		1.06 (1.03, 1.08)[c]	1.13 (1.11, 1.15)[c] 1.57 (1.42, 1.73)[d]	1.10 (1.08, 1.25)[c] 1.33 (1.21, 1.48)[d]	1.09 (1.07, 1.11)[c] 1.38 (1.23, 1.55)[d]	1.10 (1.05, 1.14)[c] 1.37 (1.11, 1.69)[d]	1.07 (1.02, 1.14)[c] 1.63 (1.23, 2.16)[d]
	0-28		1.06 (1.03, 1.08)[c]	1.14 (1.11, 1.16)[c] 1.64 (1.47, 1.83)[d]	1.11 (1.08, 1.13)[c] 1.32 (1.18, 1.47)[d]	1.10 (1.07, 1.12)[c] 1.44 (1.28, 1.63)[d]	1.11 (1.06, 1.16)[c] 1.33 (1.06, 1.68)[d]	

Notes: 1st/10th: low temperature; c: 10th percentile; d: 1st percentile; only statistically significant data ($p<0.05$) included with corresponding 95% confidence intervals were included

Females may be at greater risk as female had a higher risk due to a high surface-to-mass ratio and greater subcutaneous fat thickness than male (Seidell et al. 1988).

In this study, both high and low temperatures were significant for the temperature-mortality relationship among respiratory disease patients. This finding was similar to those of studies conducted in Iran (Farajzadeh & Darand 2008) and Brazil (Gouveia et al. 2003). Exposure of the respiratory system to high temperatures leads to thermal hypercapnia and pulmonary alkalosis secondary to hyperventilation (Beker et al. 2018), while low temperatures might lead to hypoventilation and pulmonary acidosis (Beker et al. 2018). We identified a significant relationship between low temperatures and cardiovascular mortality, which was similar to that of studies conducted in Japan (Atsumi et al. 2013) and the Czech Republic (Urban et al. 2014). This can be explained by the low temperature effect that leads to peripheral vasoconstriction, with blood shifting to the central circulation (Beker et al. 2018). A study conducted in the United States demonstrated that high temperature effects were associated with higher cardiovascular mortality rates (Khatana et al. 2022). This finding implied that cardiorespiratory disease patients should be closely monitored during both temperature regimes.

In our study, the DLNM analysis presented an objective approach to analyse the temperature–mortality relationship. Using several lags enabled the capture of the immediate and delayed effects of temperature on mortality (Guo et al. 2011). We also demonstrated that despite being located in the same country, different regions yielded different findings. Thus, prevention strategies by local stakeholders must consider all factors, such as the local geography factors, local climate conditions, and the population characteristics, i.e. baseline health, demography and socioeconomic status (Wu et al. 2013).

In our study, the DLNM analysis presented an objective approach to analyse the temperature–mortality relationship. Using several lags enabled the capture of the immediate and delayed effects of temperature on mortality (Guo et al. 2011). We also demonstrated that despite being located in the same country, different regions yielded differing findings. For Kedah, the results underscore the importance of implementing heatwave early warning systems to address the immediate effects of extreme high temperatures within 1-3 days, particularly for vulnerable groups such as the elderly, children, and individuals with pre-existing cardiovascular or respiratory conditions. These systems could also assist healthcare providers in preparing resources, such as human capital, and enhancing their capacity to diagnose and manage heat-related illnesses during critical periods.

In Kelantan, the analysis highlighted the significance of addressing the longer lag effects associated with extreme low temperatures. Strengthening public health measures and healthcare preparedness for cold-related risks is crucial, particularly for populations with limited access to adequate heating or medical facilities. Thus, prevention strategies by local stakeholders must consider all factors, such as the local geography factors, local climate conditions, and the population characteristics, i.e. baseline health, demography and socioeconomic status (Wu et al. 2013).

One of the limitations of the study is the lack of control for air pollution data for this time series analysis. Previous studies reported no dramatic changes to the temperature-mortality relationship effects before and after adjustment for air pollutants (Pinheiro Sde et al. 2014; Yatim et al. 2021). However, some studies reported that air pollutants significantly affected the temperature-mortality relationship (Breitner et al. 2014; Park et al. 2011; Scortichini et al. 2018). Thus, future local studies could consider including air pollutants as a confounding factor that should be controlled. Furthermore, the restricted number of deaths in certain variables (such as age 0-14 years and cause of death) may have hindered our capacity to identify subtle changes in the relationships between temperature and cause-specific mortality. However, this limitation would not have significantly impacted the primary findings.

CONCLUSION

Both high and low temperatures significantly affected mortality. Both high and low temperatures had immediate impacts, but the effects of low temperatures lasted longer than those of high temperatures. The elderly, females and cardiorespiratory disease patients were more vulnerable to the temperature effects. Furthermore, we ascertained a differential impact of temperature on daily mortality according to states in Malaysia. These findings have the potential to set the groundwork for formulating effective policies to tackle the impact of temperature on health, particularly in Malaysia, and may also be applicable to other nations with comparable tropical climates.

Supplementary materials: Supplementaty tables can be found via this link https://doi.org/10.6084/m9.figshare.29348480.

Ethical statement: This study received ethical approval from the Universiti Kebangsaan Malaysia (UKM) Research Ethics Committee (UKM PPI/111/8/JEP-2021-091) and the Medical Research & Ethics Committee of the Ministry of Health Malaysia (NMRR-20-3111-57500) and was registered with National Medical Research Register (NMRR).

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