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Relationship between heat index and mortality of 6 major cities in Taiwan ☆

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HIGHLIGHTS

► Daily mean heat indices are associated with the increased mortality at low latitudes in the northern hemisphere.
► The increased risk ratios of daily mortality are evident when heat indices are extremely high.
► Heat index is a potential predictor of heat-related mortality.
► Vulnerable groups, those 65 and older, need precautionary measures and specific policy attention.

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ABSTRACT

Increased mortality, linked to events of extreme high temperatures, is recognized as one critical challenge to the public health sector. Therefore, this ecological study was conducted to assess whether this association is also significant in Taiwan and the characteristics of the relationship. Daily mean heat indices, from 1994 through 2008, were used as the predictor for the risk of increased mortality in populations from 6 major Taiwanese cities. Daily mortality data from 1994 through 2008 were retrieved from the Taiwan Death Registry, Department of Health, Taiwan, and meteorological data were acquired from the Central Weather Bureau. Poisson regression analyses using generalized linear models were applied to estimate the temperature–mortality relationship. Daily mean heat indices were calculated and used as the temperature metric. Overall, increased risk ratios in mortality were associated with increased daily mean heat indices. Significantly increased risk ratios of daily mortality were evident when daily mean heat indices were at and above the 95th percentile, when compared to the lowest percentile, in all cities. These risks tended to increase similarly among those aged 65 years and older; a phenomenon seen in the cities of Keelung, Taipei, Taichung, Tainan, and Kaohsiung, but not Chiayi. Being more vulnerable to heat stress is likely restricted to a short-term effect, as suggested by lag models which showed that there was dominantly an association during the period of 0 to 3 days. In Taiwan, predicting city-specific daily mean heat indices may provide a useful early warning system for increased mortality risk, especially for the elderly. Regional differences in health vulnerabilities should be further examined in relation to the differential social–ecological systems that affect them.

1. Introduction

High temperatures can cause clinical syndromes such as heat rash, heat cramping, heat exhaustion, heat syncope and heat stroke. One of the most important direct health consequences of periodic extreme high temperatures, such as during heat waves, is the increased mortality incidence which has been reported worldwide in Canada (Pengelly et al., 2007), China (Tan et al., 2004; Tan et al., 2007), France (Rey et al., 2007; Vandentorren et al., 2004), Germany (Hertel et al., 2009), Italy (Conti et al., 2007; Conti et al., 2005; Foroni et al., 2007; Schifano et al., 2009), Japan (Nakai et al., 1999), Korea (Kim et al., 2006; Kim et al., 2004), Sweden (Rocklov and Forsberg, 2007), and the United States (Anderson and Bell, 2009; Hoshiko et al., 2010; Kaiser et al., 2007; Ostro et al., 2009; Semenza et al., 1996). High ambient summer temperatures were also found to increase daily mortalities in cities across Europe (Baccini et al., 2011).

Apparent temperature such as a combination of temperature and wind (wind chill) or temperature and humidity (heat index) was used for the measure of perceived temperature which was also recommended by the U.S. National Digital Forecast Database (NDFD). The ability to properly adapt to heat stress is influenced by more than just dry bulb temperature. Both in humans (Havenith,

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2001) and animal models (Dikmen and Hansen, 2009) humidity, solar radiation, and wind speed, have also been shown to affect thermoregulation. The human body uses evaporative cooling as the primary mechanism to regulate temperature in maintaining physiological homeostasis (Lim et al., 2008). However, effective thermoregulation is reduced in hot and humid environments where the atmosphere can be water-saturated. It may be more appropriate to consider the interrelation between high temperature and relative humidity (Kalkstein and Valimont, 1986; Steadman, 1979) in exerting a tremendous influence on a population in tropical and sub-tropical regions when assessing heat-related health effects. Heat index, one of the biometeorological indices used by the US National Weather Service (Steadman, 1979), combines dry bulb temperature and relative humidity to estimate the magnitude of heat burden due to outdoor conditions as shown in Eq. (1). Utilizing both meteorological parameters has been used before in estimating mortality risk during hot weather (Metzger et al., 2010) and combining both (temperature and relative humidity) in the heat index measure seems very appropriate for Taiwan's environment, rather than relying on only one of these meteorological measures.

$$\begin{aligned} \mathrm{HI}\,(^{\circ}\mathrm{F}) = {} & -42.379 + 2.04901523\,\mathrm{T} + 10.14333127\mathrm{R} \\ & -0.22475541\mathrm{TRH} - 6.83783 \times 10^{-3}\,\mathrm{T}^2 \\ & -5.481717 \times 10^{-2}\mathrm{RH}^2 + 1.22874 \times 10^{-3}\,\mathrm{T}^2\mathrm{RH} \\ & +8.5282 \times 10^{-4}\mathrm{TRH}^2 - 1.99 \times 10^{-6}\,\mathrm{T}^2 \times \mathrm{RH}^2 \end{aligned} \tag{1}$$

People age 65 years and older have been widely shown to be highly vulnerable to heat-induced mortality and morbidity (Basu, 2009; Hajat and Kosatsky, 2010; Hajat et al., 2007). There is increased risk of mortality when threshold temperatures are exceeded. The mortality risks vary by climatic regions (Bi et al., 2008) and specific regional differences (Chung et al., 2009). Higher heat thresholds were seen in cities with hotter summers, reflecting selective adaptation of populations (McMichael et al., 2008). The adaptations of populations include physiological responses i.e. thermoregulation to extreme heat; technological responses, such as the use of heat-resistant building walls and dikes; and behavioral responses by people tending to stay indoors to avoid excessive heat exposure. However the literature on premature heat-related morbidity and mortality, particularly in sub-tropical and tropical areas, is limited.

This study aimed to determine the value of using daily mean heat index (a combined meteorological factor) as an independent predictor of natural-cause daily mortality within the general population, and specifically for the elderly portion of the population in 6 major cities of Taiwan. In addition, the patterns of the relationship between heat index and mortality risk were assessed by determining the temperature thresholds of when the relationship is significantly noticeable as well as if there is any protracted temporal effect of temperature on mortality.

2. Materials and methods

2.1. Study regions

This study investigated the association between daily mean heat index and daily mortality on residents of all ages and specifically the elderly in 6 major cities (Keelung, Taipei, Taichung, Chiayi, Tainan, and Kaohsiung) of Taiwan from 1994 through 2008. The locations of the 6 major cities studied in Taiwan are shown in Fig. 1.

2.2. Mortality data

The daily mortality registration data from 1994 through 2008 were retrieved from the Department of Health, Taiwan. Vital statistics contained underlying causes of death, age, sex, place of death and registered place of residence. The complete age range covers from 0 year (newborn) to 65 years and older (elderly). Analysis of the general-population (all ages from newborn to 65 years and older) was performed along with analysis in which only the elderly population (65+ years old) was examined.

To classify the causes of death, the International Classification of Disease (ICD), 10th edition version (WHO, 2007) was used for 2008 data and the ICD-9 (WHO, 2009) was used for the years 1994 through 2007. Only data from members of the resident population who died of natural-cause mortality were included (ICD-10 codes, A00-R99; ICD-9 codes, 001–799). Data from the deaths in the study regions of those individuals who died from external causes (e.g. accidents/injuries) were excluded.

2.3. Meteorological data

Meteorological data, including hourly measurements of ambient dry bulb temperature and relative humidity, were provided by the Central Weather Bureau (CWB, 1994–2008) from six stations in 6 major cities, Taiwan. We used the daily mean heat index (originally derived from work carried out by Steadman, 1979) utilized by the US National Weather Service (NWS, 2010) and is shown in Eq. (1). Eq. (2) was used to convert Fahrenheit to Celsius. For the equations HI is the heat index (°F), T is the air temperature (°F), RH is the relative humidity (%), F stands for Fahrenheit, and C stands for Celsius

$$^{\circ}\mathrm{C} = (^{\circ}\mathrm{F}-32) \times 5/9. \tag{2}$$

2.4. Data analysis

Analyses were performed across residents of all ages for the populations of the selected 6 major Taiwanese cities; each city's analysis was calculated separately. We used Poisson regression with generalized linear models (GLMs) and also incorporated distributed lag models to estimate the heat–mortality relationship, distinguish a threshold level for each city (if a relationship existed), and determine if the relationship was dependent on time. The initial analyses were performed in which daily mean heat index values were categorized into six groups: 0–4th percentile (the reference group), 5–24th percentile, 25–49th percentile, 50–74th percentile, 75–94th percentile and 95–100th percentile. The five categories of daily mean heat index that include the indices ≥ 5th percentile were compared with the reference group to quantify a predictor effect on natural-cause mortality. This was done for the entire population (all ages) and separate analyses for a selected portion of the population, where only elderly residents (≥65 years old) were included. This was done to better observe and quantify any lag effects as well as to increase the power for the analyses on the selected population. The lowest daily mean heat index value was arbitrarily assigned as the reference value. Results are expressed as risk ratios (with 95% confidence interval [CI]) of daily mortality for daily mean heat index groups among the 6 major cities. Variability based on calendar month was taken into account and controlled as a confounding variable for data in all analyses. All analyses were conducted using SAS version 9.2 (SAS Institute Inc., Cary, NC).

3. Results

In the 15-year study period, the age-specific mortality differed and increased with aging among the 6 major cities (Table 1). The overall daily mean heat index (a measure incorporating daily ambient temperatures and relative humidity) average was between 26.4 °C (79.5 °F) and 28.6 °C (83.4 °F). Among these 6 major cities, Keelung city, the northernmost, had the lowest daily mean temperature, relative humidity and heat index. Kaohsiung city, the southernmost, had the highest daily mean temperature and heat index.

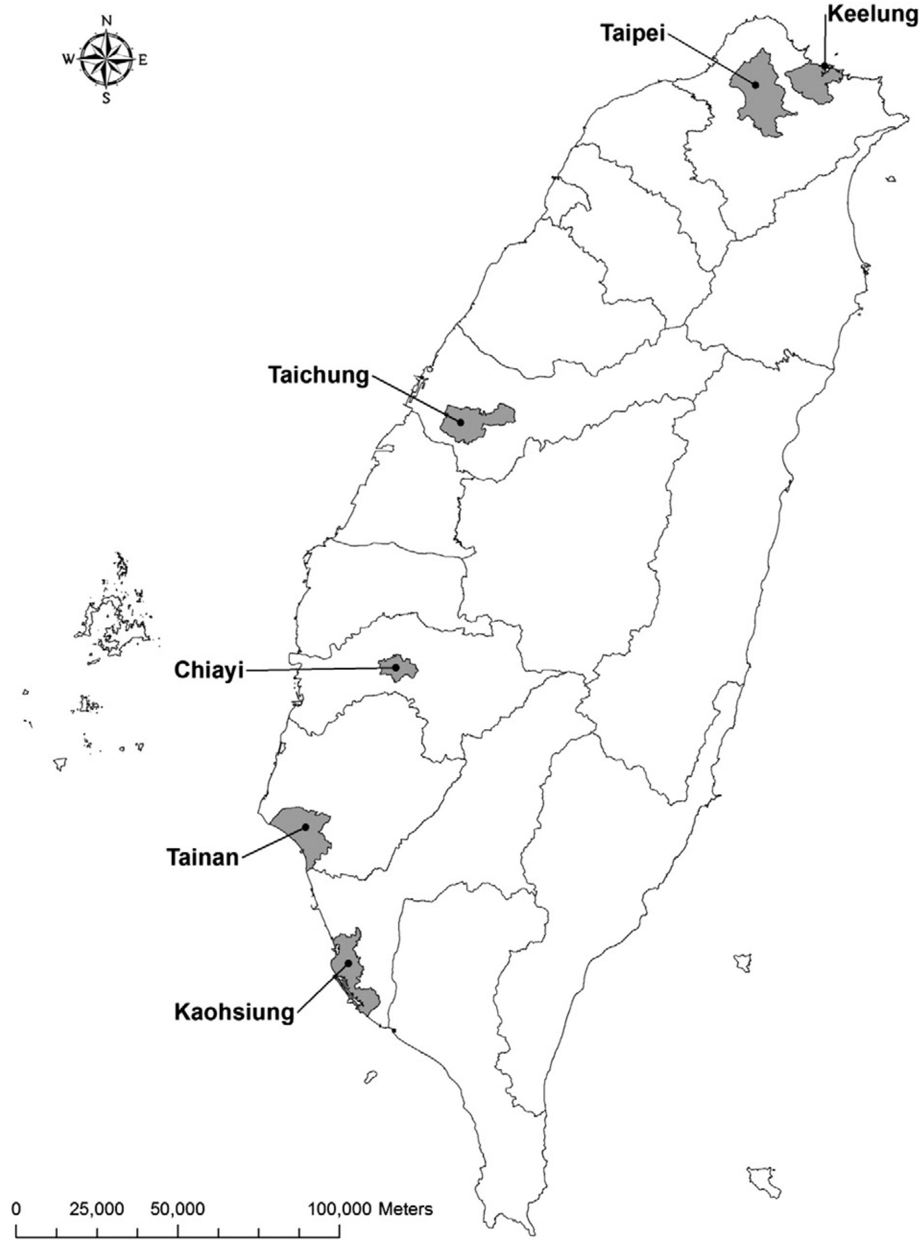

Fig. 1. Map of Taiwan.

Lag structures from 0 to 7 days were tested, but only the short-term effect at a lag of 0 to 4 days showed preponderant statistical significance and so only this data is reported. Poisson regression models with GLMs revealed the increasing mortality risk ratios associated with the highest daily mean heat index group as well as the overall general rising trend with the lag from 0 to 3 days in the 6 major cities (Tables 2 and 3).

Average risk ratios (RRs) of daily mortality, as predicted by daily mean heat index groups, with lags of 0–3 days, were significantly increased to the maximum for the daily mean heat indices of the 95–100th percentile groups (Table 2). The strongest effects of daily mean heat index impacting mortality were found for Chiayi (RR = 1.21 [95% CI = 1.09 to 1.34]) with a lag of 0 days provided; Taipei (RR = 1.15 [95% CI = 1.11 to 1.19]) and Taichung (RR = 1.14 [95% CI = 1.08 to 1.22]) with a lag period of 1 day; Kaohsiung (RR = 1.17 [95% CI = 1.11 to 1.22]) with a lag period of 2 days; Keelung (RR = 1.13 [95% CI = 1.04 to 1.22]) and Tainan (RR = 1.16 [95% CI = 1.08 to 1.23]) with a lag period of 3 days.

When the analysis was restricted to only the elderly, aged 65 or above, average risk ratios for the daily mean heat indices of the 95–100th percentile groups were typically elevated, having significant correlations with daily mortality for 5of the 6 cities previously described (Table 3). RRs of mortality for daily mean heat indices (95–100th percentiles) were significantly increased in 5 of the 6 cities with different lag days, including Keelung, Taipei, Taichung, Tainan, and Kaohsiung. There wasn't a stronger correlation observed in the elderly population for Chiayi, compared to its overall population. The RR for daily mean heat indices of the 95–100th percentile group with a 0-day lag in Chiayi was 1.06 (0.94 to 1.20).

The 3-day lag models provided a better fit (stronger correlation) than the 0-day, 1-day or 2-day lag models for Keelung and Tainan. There was an elevation of daily mortality associated with daily mean heat indices of the 95–100th percentile group with a lag of 3 days. RRs of all ages and for only the elderly were 1.13 (1.04 to

Table 1
Descriptive characteristics of 6 major cities in Taiwan, 1994–2008.

	Keelung	Taipei	Taichung	Chiayi	Tainan	Kaohsiung
Avg population, no.	385,330	2,629,355	975,061	267,405	739,144	1,486,459
Total deaths, no.	35,417	195,712	62,091	22,836	58,588	113,077
Gender (%)[a]						
Male	62.3	60.9	61.0	59.8	61.0	62.3
Female	37.7	39.1	39.1	40.2	39.0	37.7
Age (%)[a]						
≥65	65.5	70.5	62.1	65.9	64.1	60.3
40–64	25.4	22.4	27.3	26.1	27.6	30.0
15–39	7.2	5.4	7.9	6.0	6.6	7.8
0–14	1.8	1.8	2.7	2.0	1.7	1.9
Weather station						
Latitude (N)	25°13′	25°04′	24°15′	23°50′	22°99′	22°57′
Longitude (E)	121°74′	121°51′	120°68′	120°43′	120°20′	120°32′
Altitude (meter)	36	6	84	27	14	2
Temperature (°C)						
Mean ± SD	22.8 ± 5.1	23.2 ± 5.3	23.6 ± 4.7	23.4 ± 4.7	24.6 ± 4.6	25.2 ± 3.8
Relative humidity (%)						
Mean ± SD	75.9 ± 9.1	76.0 ± 9.1	74.8 ± 7.7	79.0 ± 6.0	76.6 ± 7.0	75.9 ± 7.1
Heat index quantile (°C)						
Mean ± SD	26.4 ± 5.2	26.8 ± 5.4	27.1 ± 4.5	26.7 ± 4.9	28.1 ± 5.3	28.6 ± 4.9
100% max	42.4	42.6	42.4	42.6	41.2	40.4
99%	36.8	37.9	36.0	36.6	38.5	38.1
95%	34.8	35.9	34.5	35.0	36.8	36.5
90%	33.9	34.7	33.4	33.8	35.6	35.4
75%	30.9	31.3	30.8	31.0	32.8	32.7
50% median	25.3	25.6	26.5	26.0	27.6	28.2
25%	22.5	22.6	23.5	22.5	23.5	24.2
10%	19.9	20.2	21.8	20.9	21.6	22.8
5%	18.7	18.9	20.6	19.9	20.6	22.0
1%	17.0	17.0	18.4	18.2	18.5	20.1
0% min	14.2	14.0	14.8	15.9	14.2	16.1

[a] Chi-square test < .0001.

1.22) and 1.11 (1.01 to 1.22) for Keelung, and 1.16 (1.08–1.23) and 1.12 (1.04–1.21) for Tainan, respectively (Tables 2 and 3).

4. Discussion

The daily mean heat index can be used as a putative predictor of natural-cause daily mortality in 6 major cities of Taiwan. Mortality risk generally showed an increased trend with a daily mean heat index within the 95–100th percentile range, so when daily mean heat indices reached the highest 5%, citizens were at a significantly greater risk of dying due to natural causes. The risk for being in the danger zone of daily mean heat indices varied across regions of Taiwan. This finding is true among senior citizens, a particularly vulnerable population to hot conditions, as shown by the relationship being consistent for the elderly.

The mathematical relationship between environmental temperature and relative humidity values is virtually linear, in Taiwan. In this study, the daily mean heat index was chosen as the predictor due to its better predictive capacity of daily mortality as compared to daily mean ambient temperature as a possible predictor (Kim et al., 2006). When assessing the temperature related health effects in the humid zones of sub- and tropical climates, the evaporation rate is reduced therefore heat dissipates from the body at a lower rate. This means that the body will retain more heat than it would in a more arid environment. Subjective descriptions of how hot it feels also demonstrate the importance of considering humidity in any assessment examining temperature effects.

Economic status can also have its own independent association with mortality rates as the low-income groups often have higher risks of mortality compared to the general population, typically 1.3–1.7 fold greater (Kim and Joh, 2006). For the populations in this study, the average proportions of low-income households for Keelung, Taipei, Taichung, Chiayi, Tainan and Kaohsiung are 95, 45, 80, 96, 39, and 44 per 10,000 population respectively, from 1998 through 2008 (DGBAS, 2010). Those of low-income households in Chiayi and Keelung were more than double the proportions of Tainan, Kaohsiung, and Taipei. However the mortality rate in Chiayi was not much higher than other cities which may explain small cities are less susceptible to a heat-island effect. The 2008 statistics of causes of overall death indicated that standardized death rates per 10,000 population based on 2000 WHO standard population for Keelung, Taipei, Taichung, Chiayi, Tainan and Kaohsiung are 508.6, 366.2, 448.3, 469.5, 490.9, and 500.2 (DOH, 2008). A comparison of citizens in inner-city communities with those from other metropolitan and suburban communities in generalized linear models can restrain potential confounding effects of socioeconomic inequalities and demographic differences and will be taken into account in our future studies examining heat effects on mortality and other health outcomes.

Three indicators of vulnerability previously reported and associated with extreme temperature-related mortality in Taiwan, included urbanization and associated medical resources, being either older or very young, and ethnic status (being aboriginal) (Wu et al., 2008). Most of the selected sites in this study are metropolitan cities; only Chiayi was a sub-metropolitan area at the time the data was recorded, but it had a similar degree of urbanization as the other cities. The indicator category of medical resources refers to registered medical institutions and healthcare professionals, including medical equipment, supplies and furniture. Numbers of licensed healthcare professionals per 10,000 population for Keelung, Taipei, Taichung, Chiayi, Taiwan and Kaohsiung were 70, 139, 154, 92, 139, and 103, besides numbers of beds of hospitals and health care per 10,000 population were 64, 88, 133, 71, 83, and 75 from 1998 through 2008 (DGBAS, 2010). This implies that the allocation of medical resources was more limited in Keelung. There were no aboriginal villages in any of the 6 major cities so ethnic status cannot be assessed in our data. The different

Table 2
Risk ratios (RRs) with 95% CIs for daily mortalities from 0 to 4 lag days among all ages and daily mean heat index categories (percentiles) in 6 major cities of Taiwan, 1994–2008.

		Lag 0	Lag 1	Lag 2	Lag 3	Lag 4
		RR[a] (95% CI)	RR[a] (95% CI)	RR[a] (95% CI)	RR[a] (95% CI)	RR[a] (95% CI)
Keelung	≥95th (34.8 °C)	1.01 (0.93–1.09)	1.04 (0.96–1.12)	1.08 (1.00–1.17)	1.13 (1.04–1.22) **	1.06 (0.98–1.15)
	75th (30.9 °C)–94th	0.99 (0.93–1.06)	1.03 (0.96–1.10)	1.02 (0.96–1.09)	1.04 (0.98–1.12)	1.07 (1.01–1.15) *
	50th (25.3 °C)–74th	1.01 (0.95–1.07)	1.03 (0.97–1.09)	1.01 (0.96–1.07)	1.05 (1.00–1.11)	1.04 (0.98–1.10)
	25th (22.5 °C)–49th	1.01 (0.95–1.06)	1.02 (0.97–1.08)	0.98 (0.93–1.04)	1.02 (0.97–1.08)	1.02 (0.96–1.07)
	5th (18.7 °C)–24th	1.00 (0.95–1.06)	1.00 (0.94–1.05)	0.98 (0.93–1.03)	1.02 (0.97–1.08)	1.00 (0.95–1.06)
Taipei	≥95th (36.0 °C)	1.11 (1.07–1.14) ****	1.15 (1.11–1.19) ****	1.14 (1.10–1.18) ****	1.12 (1.09–1.16) ****	1.11 (1.07–1.15) ****
	75th (31.4 °C)–94th	1.04 (1.01–1.07) **	1.08 (1.05–1.11) ****	1.08 (1.05–1.11) ****	1.08 (1.05–1.11) ****	1.05 (1.02–1.08) ***
	50th (25.7 °C)–74th	1.01 (0.99–1.04)	1.05 (1.02–1.07) ****	1.04 (1.02–1.07) ***	1.05 (1.02–1.07) ***	1.03 (1.00–1.05) *
	25th (22.6 °C)–49th	1.01 (0.98–1.03)	1.03 (1.01–1.06) **	1.02 (1.00–1.05) *	1.02 (1.00–1.05) *	1.01 (0.98–1.03)
	5th (18.9 °C)–24th	1.00 (0.98–1.02)	1.01 (0.99–1.04)	1.01 (0.99–1.04)	1.02 (1.00–1.05)	1.00 (0.98–1.03)
Taichung	≥95th (34.5 °C)	1.11 (1.05–1.19) ***	1.14 (1.08–1.22) ****	1.08 (1.02–1.15) *	1.09 (1.02–1.16) **	1.11 (1.07–1.15) ****
	75th (30.8 °C)–94th	1.09 (1.04–1.15) ***	1.09 (1.04–1.15) ***	1.05 (1.00–1.11) *	1.04 (0.99–1.10)	1.05 (1.02–1.08) ***
	50th (26.5 °C)–74th	1.07 (1.02–1.12) **	1.07 (1.02–1.12) **	1.04 (1.00–1.09)	1.02 (0.98–1.07)	1.03 (1.00–1.05) *
	25th (23.5 °C)–49th	1.03 (0.98–1.07)	1.04 (1.00–1.09) *	1.02 (0.98–1.06)	1.00 (0.96–1.04)	1.01 (0.98–1.03)
	5th (20.6 °C)–24th	1.03 (0.99–1.08)	1.01 (0.97–1.05)	0.99 (0.95–1.03)	0.99 (0.95–1.03)	1.00 (0.98–1.03)
Chiayi	≥95th (35.0 °C)	1.21 (1.09–1.34) ***	1.19 (1.07–1.32) ***	1.15 (1.04–1.27) **	1.11 (1.00–1.23) *	1.04 (0.98–1.10)
	75th (31.0 °C)–94th	1.12 (1.03–1.21) **	1.06 (0.97–1.15)	1.03 (0.95–1.12)	1.05 (0.96–1.14)	1.03 (0.98–1.09)
	50th (26.0 °C)–74th	1.09 (1.01–1.17) *	1.07 (0.99–1.15)	1.02 (0.95–1.10)	1.04 (0.97–1.12)	1.01 (0.96–1.05)
	25th (22.5 °C)–49th	1.04 (0.97–1.12)	1.03 (0.96–1.11)	0.96 (0.90–1.03)	1.02 (0.95–1.09)	0.98 (0.94–1.02)
	5th (19.9 °C)–24th	1.05 (0.98–1.12)	1.02 (0.95–1.09)	0.98 (0.92–1.05)	1.00 (0.94–1.07)	0.98 (0.94–1.02)
Tainan	≥95th (36.8 °C)	1.14 (1.07–1.21) ****	1.14 (1.07–1.22) ****	1.12 (1.05–1.20) ***	1.16 (1.08–1.23) ****	1.07 (0.97–1.19)
	75th (32.8 °C)–94th	1.10 (1.04–1.16) ***	1.11 (1.06–1.18) ****	1.06 (1.00–1.12) *	1.07 (1.01–1.12) *	1.02 (0.94–1.10)
	50th (27.6 °C)–74th	1.05 (1.00–1.10)	1.04 (0.99–1.09)	1.03 (0.98–1.08)	1.05 (1.01–1.11) *	1.02 (0.95–1.10)
	25th (23.5 °C)–49th	1.04 (1.00–1.08)	1.04 (0.99–1.08)	1.02 (0.98–1.06)	1.03 (0.99–1.07)	0.97 (0.91–1.04)
	5th (20.6 °C)–24th	1.01 (0.97–1.05)	0.98 (0.94–1.02)	0.99 (0.95–1.04)	1.02 (0.97–1.06)	0.99 (0.93–1.06)
Kaohsiung	≥95th (36.5 °C)	1.14 (1.08–1.20) ****	1.17 (1.11–1.23) ****	1.17 (1.11–1.22) ****	1.12 (1.06–1.17) ****	1.07 (1.00–1.14)
	75th (32.7 °C)–94th	1.10 (1.06–1.15) ****	1.10 (1.06–1.15) ****	1.12 (1.07–1.16) ****	1.08 (1.04–1.13) ***	1.02 (0.96–1.07)
	50th (28.2 °C)–74th	1.08 (1.04–1.12) ****	1.08 (1.04–1.12) ****	1.09 (1.05–1.13) ****	1.07 (1.03–1.11) ***	1.00 (0.96–1.05)
	25th (24.2 °C)–49th	1.03 (1.00–1.07) *	1.05 (1.02–1.08) **	1.06 (1.02–1.09) ***	1.05 (1.02–1.09) **	0.99 (0.95–1.03)
	5th (22.0 °C)–24th	1.01 (0.98–1.04)	1.03 (1.00–1.07) *	1.04 (1.01–1.07) **	1.03 (1.00–1.07) *	0.98 (0.94–1.02)

[a] Analyzed by generalized linear models with Poisson regression. Each risk ratio function was compared with the reference (0–4th percentile) and adjusted for daily accumulated precipitation and calendar month.
* $p<0.05$.
** $p<0.01$.
*** $p<0.001$.
**** $p<0.0001$.

aboriginal groups in Taiwan are a quickly aging population, but still only make up 7–11% of the population age 65 years and older, based on demographic statistics (DGBAS, 2010).

The presence of a lag effect with the heat–mortality relationship is consistent with previous studies (Hajat et al., 2006; Hajat et al., 2002; Huynen et al., 2001; Metzger et al., 2010; Tan et al., 2007). Associations were generally largest at either the 0 or 1 day lag. There were even significant associations with lags greater than 1 day, however most significant correlations had receded by 3 days and beyond. The best-fitting model was measured at a 0-day lag for Chiayi and a 3-day lag for Keelung, and this was true for the overall population data and when only elderly population data was used. In Chiayi, lag 0 can reflect the quick attack due to the heat which may be explained by the geographical heterogeneity and more vulnerable populations i.e. lower income families, less care facilities available and so less able to adapt to the immediate health challenges imposed by extreme temperature to have the lowest-income/less care facilities to have less adaption. However Chiayi has the smallest population (avg population: 267,405) than other metropolitan cities of Keelung (385,330), Taipei (2,629,355), Taichung (975,061), Tainan (739,144), and Kaohsiung (1,486,459) which makes the inference harder to interpret particularly with a smaller aged population. Keelung had the weakest heat-related mortality of all six cities. The effects are not strong and the rate ratios are increased significantly only when the HI≥95th (34.8 °C) for both all ages and specifically the elderly. It did not follow the particular trends. Even though the differences of lag time existed, if the vulnerable population can be identified earlier, they can receive proper medical treatments to prevent the increased mortality following increasing temperature. Regional-specific lag effects are prominent examples of the regional variation in heat effects found in this study and this knowledge can help regional policy makers know the time frame with which any action they develop must operate in if it is to be effective in protecting the health of their local population.

In recent years there has been a heightened awareness of the threats to human health with increased climate change (McMichael and Butler, 2009; McMichael and Wilcox, 2010). The impact of climate change on human health is quite unequal worldwide with certain populations being far more vulnerable than others. Specific evidence-based data are crucial to quantify risks and vulnerabilities on regional scales. The predictions of heat index-related mortality are well described in high-latitude countries e.g. America and Korea, however there is still limited evidence on regions exposed to high temperature associated with tropical/subtropical latitudes (0–23.4° and 23.5–40° N or S latitudes) where at least more than half of world's population (UW, 2009) lives, and potentially these people have very different underlying physiological tolerances to heat. This is also a major strength of our study that we compared the heat–mortality relationship in both subtropical (Keelung, Taipei and Taichung) and tropical (Chiayi, Tainan and Kaohsiung) regions, and discovered that there were significant increases in excess mortalities when daily mean heat indices were at the 95–100th percentile; this was when there was greater vulnerability to heat stress. Further studies will have to be performed, when the data becomes available, to assess if the thresholds of daily mean heat index found in this study are absolute thresholds of increased mortality risk or is it always the highest 5th percentile where increased vulnerability

Table 3
Risk ratios (RRs) with 95% CIs for daily mortality from 0 to 4 lag days among only elderly members of the populations (age 65+) and daily mean heat index categories (percentiles) in 6 major cities of Taiwan, 1994–2008.

		Lag 0	Lag 1	Lag 2	Lag 3	Lag 4
		RR[a] (95% CI)	RR[a] (95% CI)	RR[a] (95% CI)	RR[a] (95% CI)	RR[a] (95% CI)
Keelung	≥95th (34.8 °C)	0.98 (0.89–1.08)	0.99 (0.90–1.09)	1.08 (0.98–1.19)	1.11 (1.01–1.22) *	0.98 (0.89–1.08)
	75th (30.9 °C)–94th	0.99 (0.91–1.07)	1.00 (0.93–1.08)	1.02 (0.94–1.10)	1.05 (0.97–1.13)	1.05 (0.97–1.13)
	50th (25.3 °C)–74th	0.99 (0.93–1.06)	1.02 (0.95–1.08)	1.01 (0.95–1.08)	1.05 (0.98–1.12)	1.00 (0.94–1.07)
	25th (22.5 °C)–49th	0.98 (0.92–1.04)	1.02 (0.95–1.08)	0.98 (0.92–1.04)	1.00 (0.94–1.07)	0.98 (0.92–1.05)
	5th (18.7 °C)–24th	0.99 (0.93–1.05)	0.99 (0.92–1.05)	0.97 (0.91–1.04)	1.01 (0.95–1.08)	0.98 (0.92–1.04)
Taipei	≥95th (36.0 °C)	1.07 (1.03–1.12) ***	1.12 (1.08–1.17) ****	1.13 (1.08–1.17) ***	1.09 (1.05–1.13) ****	1.07 (1.03–1.11) **
	75th (31.4 °C)–94th	1.03 (1.00–1.07) *	1.06 (1.03–1.10) ***	1.09 (1.06–1.13) ****	1.07 (1.03–1.10) ****	1.05 (1.01–1.08) **
	50th (25.7 °C)–74th	1.01 (0.99–1.04)	1.05 (1.02–1.08) ***	1.05 (1.02–1.08) ***	1.04 (1.01–1.07) **	1.02 (0.99–1.05)
	25th (22.6 °C)–49th	1.01 (0.98–1.03)	1.03 (1.00–1.06) *	1.03 (1.00–1.06) *	1.02 (0.99–1.05)	1.00 (0.98–1.03)
	5th (18.9 °C)–24th	1.00 (0.98–1.03)	1.01 (0.98–1.04)	1.02 (0.99–1.04)	1.02 (0.99–1.04)	1.01 (0.98–1.03)
Taichung	≥95th (34.5 °C)	1.12 (1.04–1.21) **	1.16 (1.07–1.24) ***	1.09 (1.01–1.17) *	1.08 (1.00–1.16) *	1.05 (0.97–1.13)
	75th (30.8 °C)–94th	1.08 (1.02–1.14) *	1.10 (1.03–1.17) **	1.05 (0.99–1.12)	1.05 (0.99–1.12)	1.06 (0.99–1.12)
	50th (26.5 °C)–74th	1.07 (1.02–1.13) *	1.07 (1.02–1.13) *	1.04 (0.98–1.09)	1.01 (0.96–1.07)	1.02 (0.96–1.07)
	25th (23.5 °C)–49th	1.00 (0.96–1.06)	1.03 (0.98–1.09)	1.02 (0.97–1.07)	1.00 (0.95–1.05)	0.99 (0.94–1.04)
	5th (20.6 °C)–24th	1.03 (0.98–1.08)	1.01 (0.96–1.06)	0.98 (0.93–1.03)	0.98 (0.94–1.03)	1.00 (0.95–1.05)
Chiayi	≥95th (35.0 °C)	1.06 (0.94–1.20)	1.02 (0.91–1.15)	1.03 (0.91–1.16)	0.97 (0.86–1.09)	0.95 (0.84–1.07)
	75th (31.0 °C)–94th	1.04 (0.94–1.15)	0.98 (0.88–1.08)	0.98 (0.89–1.08)	0.95 (0.86–1.05)	0.96 (0.87–1.06)
	50th (26.0 °C)–74th	1.05 (0.96–1.14)	1.00 (0.91–1.09)	0.98 (0.90–1.07)	0.97 (0.89–1.06)	0.95 (0.88–1.04)
	25th (22.5 °C)–49th	1.02 (0.94–1.10)	0.98 (0.91–1.06)	0.94 (0.87–1.02)	0.97 (0.90–1.05)	0.92 (0.85–0.99)
	5th (19.9 °C)–24th	1.04 (0.96–1.12)	0.98 (0.91–1.07)	0.96 (0.88–1.03)	0.96 (0.88–1.04)	0.95 (0.88–1.03)
Tainan	≥95th (36.8 °C)	1.06 (0.98–1.15)	1.09 (1.00–1.17) *	1.08 (1.00–1.17) *	1.12 (1.04–1.21) **	1.02 (0.94–1.10)
	75th (32.8 °C)–94th	1.06 (1.00–1.14)	1.08 (1.01–1.15) *	1.06 (1.00–1.13)	1.04 (0.98–1.11)	1.00 (0.94–1.06)
	50th (27.6 °C)–74th	1.01 (0.95–1.07)	1.01 (0.96–1.07)	1.02 (0.97–1.09)	1.04 (0.98–1.10)	0.99 (0.94–1.05)
	25th (23.5 °C)–49th	1.02 (0.97–1.07)	1.02 (0.96–1.07)	1.02 (0.97–1.08)	1.01 (0.96–1.06)	0.97 (0.92–1.02)
	5th (20.6 °C)–24th	1.00 (0.95–1.06)	0.98 (0.93–1.03)	1.00 (0.95–1.05)	1.00 (0.95–1.05)	0.97 (0.92–1.01)
Kaohsiung	≥95th (36.5 °C)	1.11 (1.04–1.18) ***	1.13 (1.06–1.20) ***	1.13 (1.06–1.20) ****	1.09 (1.02–1.16) **	1.01 (0.95–1.07)
	75th (32.7 °C)–94th	1.09 (1.04–1.15) ***	1.08 (1.03–1.14) **	1.09 (1.04–1.15) ***	1.07 (1.02–1.12) *	1.02 (0.97–1.08)
	50th (28.2 °C)–74th	1.06 (1.01–1.10) *	1.04 (1.00–1.09)	1.07 (1.02–1.12) **	1.05 (1.00–1.10)	1.01 (0.96–1.05)
	25th (24.2 °C)–49th	1.02 (0.98–1.06)	1.03 (0.99–1.07)	1.04 (1.00–1.08)	1.05 (1.01–1.09) *	1.01 (0.97–1.05)
	5th (22.0 °C)–24th	1.00 (0.96–1.04)	1.02 (0.98–1.06)	1.04 (1.00–1.08)	1.03 (0.99–1.07)	1.01 (0.97–1.05)

[a] Analyzed by generalized linear models with Poisson regression. Each risk ratio function was compared with the reference (0–4th percentile) and adjusted for daily accumulated precipitation and calendar month.
* $p<0.05$.
** $p<0.01$.
*** $p<0.001$.
**** $p<0.0001$.

of death to heat stress occurs. However, we cannot wait for this study, adoption of relevant adaptations and precautions are most urgently needed to deal with extreme future temperatures.

There are two limitations of the study that need to be acknowledged and addressed. Our use of year-end population as denominator instead of daily population ignored daily variations in the population growth rate. Uncontrolled environmental pollutants may introduce non-differential misclassification and bias toward the null hypothesis of no differential heat-related health effects (Wacholder et al., 1995). It should be mentioned that the findings of this study are based on populations and the ecological inferences for the relationship between daily mean heat index and mortality, should not be applied to an individual to assess their personal risk.

5. Conclusion

In conclusion, this study has shown that daily mean heat index predicts mortality risk in 6 major cities of Taiwan. It can be a very useful tool in several areas. It points out the environmental conditions that can harm our vulnerable populations, especially those 65 and older. Future studies assessing heat-related effects should now adjust for regional climate scenarios when determining relative vulnerabilities.

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