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Mortality risk associated with temperature and prolonged temperature extremes in elderly populations in Taiwan ☆

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ABSTRACT

Background: This study investigated mortality risks from all causes, circulatory and respiratory diseases for the elderly associated with prolonged exposure to extreme temperatures in four major cities of Taiwan.

Methods: Daily average temperatures at the high 99th, 97th, and 95th percentiles were defined as extreme heat, and those at the low 10th, 5th, and 1st percentiles were defined as extreme cold for each city in 1994–2007. Distributed lag non-linear model was used to estimate the relative risk (RR) of mortality associated with 30-day lag temperature, and heat and cold extremes lasting for 3–5, 6–8, and >8 days. The random-effects meta-analysis summarized the risks of temperature and extreme temperatures events.

Results: The lowest overall mortality among the elderly was when the temperature was 26 °C on average. Low temperatures caused greater adverse effects than high temperatures, particularly for mortality from circulatory diseases. After accounting for the cumulative 30-day temperature effects, meta-analysis showed that mortality risk slightly increased with strengthened and prolonged heat extremes ($\geq$99th and >3 days; $\geq$97th and >8 days; and $\geq$ 95th and >8 days) that RRs ranged from 1.04–1.05, 1.01–1.05, and 1.05–1.13 for mortality from all causes and from circulatory and respiratory diseases, respectively. The corresponding RRs ranged from 0.98–1.01, 0.92–1.06, and 0.97–1.03, respectively, for shorter duration of heat extremes. This study did not identify significant effect for stronger or prolonged cold extremes.

Conclusions: Extreme temperatures and their duration cause varied mortality associations in the elderly. Short-term extremely low temperatures exhibit the greatest effect on mortality, and intensified and longer periods of heat extremes also exert a slightly increased effect on mortality.

1. Introduction

Previous studies have associated human mortality with temperature variations in U-, V-, and J-shapes (Curriero et al., 2002; Huynen et al., 2001). The elderly populations with cardio-respiratory diseases are particularly vulnerable to exposure to extreme heat and cold (Alberdi et al., 1998; Braga et al., 2002; Keatinge and Donaldson, 1995; Pirard et al., 2005). The temperature considered comfortable and associated with the lowest mortality varies geographically (Baccini et al., 2008; Braga et al., 2002; Curriero et al., 2002; McMichael et al., 2008). This temperature is generally below 20°C in the temperate areas (Hajat et al., 2002; Huynen et al., 2001) but may approach 30°C for populations living in subtropical climates (McMichael et al., 2008; Pan et al., 1995). Compared with people living in temperate climates, people living in warm climates are generally more vulnerable to the effect associated with cold weather (Curriero et al., 2002; Yan, 2000).

Considering the increasing periods of extreme temperatures, understanding the effects of prolonged hot and cold temperature extremes is of importance to health (Anderson and Bell, 2009; D'Ippoliti et al., 2010; Gasparrini and Armstrong, 2011; Hajat et al., 2006; Huynen et al., 2001). Studies generally define temperatures at the 99.5th, 99th, 97th, 95th, and 90th percentiles as extreme heat, whereas those at the 10th, 5th, and 1st percentiles

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Abbreviations: DLNM, Distributed Lag Non-linear Model; PM_{10}, Particulate matter less than 10 μm in aerodynamic diameter; RR, Relative risk; CI, Confidence interval

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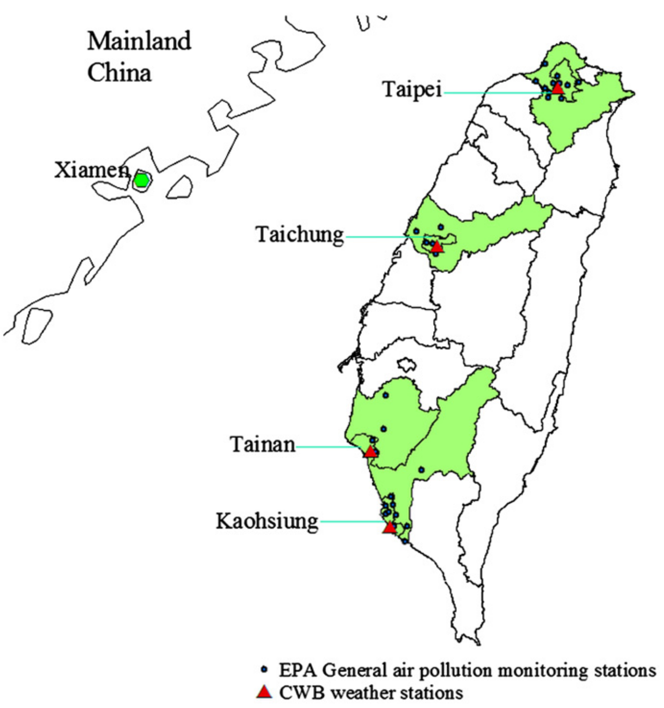

Fig. 1. Locations of the studied cities.

are defined as extreme cold (Anderson and Bell, 2009; Braga et al., 2002; D'Ippoliti et al., 2010; Diaz et al., 2002; Hajat et al., 2006; Hajat et al., 2002; Pattenden et al., 2003). Studies have investigated the effects of prolonged temperature extremes lasting for 2, 4, and more than 3 days. However, only a few studies have observed the effects of temperature extremes lasting 8 days and longer (Hemon et al., 2003). Moreover, most temperature–mortality studies were performed in European and North American cities. The patterns for subtropical populations are rarely reported (Chau et al., 2009; McMichael et al., 2008; Tan et al., 2007).

Taiwan, located in the west of the Pacific Ocean, is a small mountainous island of 394 km (245 mi) long and 144 km (89.5 mi) wide at its broadest point. With the Tropic of Cancer crossing between the middle and south, the temperature varies from north to south with an average annual temperature of 24 °C and an average daily temperature range of 8–33 °C in urban areas. Studies on the health effects of subtropical weather are limited. With intensifying heat waves expected in the future (Meehl and Tebaldi, 2004), evaluating the health risks associated with hot and humid climates, such as that in Taiwan, is worthwhile. The present study investigated the risk of mortality from all causes and from circulatory and respiratory diseases associated with temperature extremes. The assessment emphasizes the effects associated with prolonged temperature extremes on elderly populations in four major Taiwanese cities, namely, Taipei, Taichung, Tainan, and Kaohsiung (Fig. 1).

2. Materials and methods

2.1. Data source

Mortality rates for the four cities were calculated using vital statistics and census data from 1994 to 2007 provided by the Executive Yuan Department of Health and The Ministry of Interior. The four cities comprised approximately 13.6 million inhabitants. The present study focused on the 1.2 million elderly population. Information used included age, gender, underlying cause of death, residential area, and date of death for those aged 65 years and above. Data for deaths from all causes, circulatory diseases (ICD9 390–459), and respiratory diseases (ICD9 460–519), as defined by the *9th Revision* of the *International Classification of Diseases* (ICD9), were compiled for further analysis.

The Central Weather Bureau provided 24-hour weather, data including average, maximum, and minimum temperatures as well as relative humidity (RH) and barometric pressure, collected from 25 real-time weather monitoring stations in Taiwan (Central Weather Bureau, 2011a). The present study used daily weather measurements from the weather stations with the most representative exposure to ambient temperatures for the local population in each target city (i.e., Taipei, Taichung, Tainan and Kaohsiung stations) for years from 1994 to 2007 (Central Weather Bureau, 2011b). Fig. 1 shows the locations of these weather stations.

The Taiwan Air Quality Monitoring Network, established by the Taiwan Environmental Protection Administration in 1993, had 74 stationary monitoring stations distributed throughout the island in 2008 (Taiwan Environmental Protection Administration, 2011; Taiwan Governmental Information Office, 2008). Concentrations of ambient air pollutants, i.e., particulate matter less than 10 μm in aerodynamic diameter (PM_{10}), nitrogen oxides (NO*x*), and ozone (O_3), were measured using beta-ray absorption, chemiluminescence, and ultraviolet absorption, respectively, continuously and hourly at each station. Information on weather status, analytical instruments, and site-specific hourly data for each monitoring site are available online at http://taqm.epa.gov.tw/taqm/en/. The present study analyzed daily average data for PM_{10}, O_3, and NOx monitored at 13, 5, 4, and 10 general ambient stations in Taipei, Taichung, Tainan, and Kaohsiung, respectively, from 1994 to 2007 (Fig. 1).

2.2. Definition of temperature extremes

Previous studies have used various temperature metrics, including minimum and maximum temperatures as well as daily average, to evaluate mortality risk (Anderson and Bell, 2009; Hajat et al., 2006). These studies indicate that the average temperature can be a representative temperature indicator in temperature–mortality association studies. Therefore, only daily average temperatures were used for the subsequent analyses.

The daily average temperatures during the study period were classified into normal, extreme heat, and extreme cold according to the temperature distributions measured in each specific city. Extremely hot and extremely cold days were defined as average temperatures higher than the 95th, 97th, and 99th percentiles and lower than the 10th, 5th, and 1st percentiles, respectively, using the following equation:

$$Extreme_t^c(t) = \sum_{d=1}^{d} I\left(= 1 \text{ if } T_t^c \begin{array}{l} \geq 95^{\text{th}} \text{ or } 97^{\text{th}} \text{ or } 99^{\text{th}} \\ \leq 10^{\text{th}} \text{ or } 5^{\text{th}} \text{ or } 1^{\text{st}} \end{array} \right)$$

where *I* equals 1 if either the city-specific average temperature on day *t* (T_t^c) is greater than or equal to the city-specific 95th, 97th, and 99th percentiles of temperature or if T_t^c is less than or equal to city-specific 10th, 5th, and 1st percentiles of temperature. For days on which the temperature is non-extreme, *I* is equal to 0. Each consecutive extreme temperature (*d*) was further categorized by the number of consecutive days as 3–5, 6–8, and >8 days. Events in which the average temperature was higher than the 99th or lower than the 1st percentiles longer than 6 days were rare. Therefore, prolonged effects of 2–3 days and >3 days were evaluated for these two extreme temperature definitions. The final analysis considered 16 temperature extremes (definitions of 95th, 97th, 10th and 5th percentiles last for 3–5, 6–8, and >8 days, and definitions of 99th and 1st percentiles for 2–3 days and >3 days duration) for evaluation. Paired temperature extremes (10th and 95th, 5th and 97th, and 1st and 99th) were used as indicator variables in the models because of the overlapping definitions for extreme temperature days (e.g., days of 10th percentile included days of 5th and 1st percentiles). The additive effects of temperature extremes listed above were estimated from the exponential of coefficient.

2.3. City-specific relative risk estimate

For each city, the associations between daily average temperatures and daily deaths from all causes and from circulatory and respiratory diseases were evaluated using the distributed lag non-linear model (DLNM) with Poisson distribution (Gasparrini and Armstrong, 2010; Gasparrini et al., 2010). To enable the DLNM to model the non-linear and delayed temperature–mortality association, lag-stratified natural cubic spline (NS) models were adopted. Natural cubic splines with 5 degrees of freedom (*df*) was applied in the daily average temperature (approximately 4 °C for 1 *df*). The knots of average temperatures were placed at equally spaced quantiles of the predictor. Lag stratification was defined as 4 *df* for the average temperature. The knots of lag were set at equally spaced values on the log scale of lags. The mortality risks associated with temperature were measured for a maximum lag of 30 days in the present study. Cumulative mortality risk associated with daily temperature was then estimated using the cross-basis variable as the covariate in the Poisson regression model (Armstrong, 2006; Gasparrini et al., 2010).

The natural cubic spline function of temperature in the DLNM models is incapable of computing the relative risk (RR) of mortality per 1 °C temperature change. Therefore, cumulative 30-day mortality risks and 95% confidence intervals (CI) at 18 °C (approximately 5th–20th percentiles of the average temperature across cities) and 30 °C (approximately 95th–97th percentiles of the average temperature across cities) were estimated by comparing with the average temperature of city-cause-specific lowest mortality (the centered value of the temperature basis variables).

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The previously defined consecutive extreme temperature events were categorized as covariates and compared with the nonconsecutive days of extreme temperature as well as days of normal temperature.

We also examined the linear relationships between mortality and air pollutants for PM_{10}, O_3, and NO*x* with zero thresholds and a 5-day lag maximum. Natural cubic splines with 7 and 4 *df* were applied in time and RH, respectively. Gender of studied population, holiday and day of the week were included in the models as categorical variables. In addition, studies have linked respiratory infection as a noticeable cause leading to the elevated mortality from cardiopulmonary diseases. Because complete information on circulating respiratory viruses was unavailable, the daily mortality rate from pneumonia and influenza was used as a representative factor for respiratory viral activity (Braga et al., 2000). Therefore, this study calculated the city-sex-specific daily mortality rate from pneumonia and influenza (ICD9 480–487) and included it in the models.

The model for the expected cause-sex-specific death count on day (t) in each city (c) is

$$LogE[Y_t^c] = \beta_0 + \sum_{t=0}^{5} X_{i,t}^c + \sum_{t=0}^{30} NS(T_t^c,\ 5;\ lag,4) + Extremes_t^c$$

$$+ \sum_{t=0}^{7} NS(RH_t^c,4) + NS(Time,\ 7/year) + [Confounders]$$

where Y_t^c is the expected cause-sex-specific death for city c on day t, β_0 is the model intercept, $X_{i,t}^c$is the linear effects of air pollutants ($i=1–3$ for PM_{10}, O_3, and NOx) for city c, and $NS(T_t^c,\ 5;lag,\ 4)$ is the natural cubic spline of the daily average temperature. The temperatures for city c with 5 *df* and their effects were totaled for 30 days under 4 *df* lag stratification. $Extremes_t^c$ are categorical variables representing temperature extremes for city c on day t, and $NS(Time,\ 1/year)=$ natural cubic spline of time with 7 *df* per year.

Sensitivity analysis was used to evaluate the *df*, which ranged from 3–6 for temperature–mortality curves and coefficient-lag curves. Time smoothing with various *df* (NS, $df = 4, 7$, and 14 per year) was also performed. The Akaike information criterion (AIC) (Akaike, 1973) was used to choose *df* of smooth function and to identify the specific covariates. Lower AIC values indicate a better fitting model.

2.4. *Random-effect meta-analysis*

City-specific risk estimates of mortality associated with temperatures (18 and 30°C compared with the centered temperature) and its events were further evaluated for combined effects using meta-analysis (Viechtbauer, 2010).

For a set of $c = 1–4$ city-specific studies corresponding to Taipei, Taichung, Kaohsiung, and Tainan, let β_c denotes the city-specific mortality relative risk associated with temperature (or RR of its event). Let θ_c denotes the corresponding (unknown) true effect in the cth study, such that

$$\beta_c | \theta_c \sim N(\theta_c,\ \upsilon_c)$$

The observed effects are assumed unbiased normally distributed estimates of the corresponding true effects with sampling variances equal to ν_c.

For further random-effects modeling, the true effects across the studied cities were assumed normal distributions, with μ denoting the average effect and τ^2 denoting the between-city variance of true effects:

$$\theta_c | \mu,\ \tau^2 \sim N(\mu,\ \tau^2)$$

The random-effects model was fitted with observed effect (β_c) and corresponding sampling variances (υ_c) using restricted maximum-likelihood estimator to estimate the amount of (residual) heterogeneity in this study (Viechtbauer, 2010).

Data manipulation and all statistical analyses were performed using SAS version 9.1 (SAS Institute Inc., Cary, NC, USA) and statistical environment R 2.12.

3. Results

3.1. *Cause-specific mortality and characteristics*

Table 1 describes the latitude, population, detailed distributions of temperature and air pollutant levels, and cause-specific mortality

Table 1
Average daily measures of temperature, air pollutants, mortality, and selected characteristics of the studied cities, 1994–2007, Taiwan.

	Taipei	Taichung	Tainan	Kaohsiung
Latitude, °N[a]	25.0	24.2	23.1	23.0
Population in millions[a]	6.41	2.60	1.87	2.76
Population aged 65+ years, %[a]	9.74	8.13	10.8	9.56
Atmospheric environment				
Average temperature				
Mean	23.2	23.7	24.6	25.3
Minimum	8.1	8.1	9.2	10.5
25th	19.1	20.0	21.0	22.5
50th	23.9	24.8	25.8	26.3
75th	27.7	27.6	28.4	28.3
Maximum	33.0	32.0	31.7	32.0
PM_{10}, $\mu g/m^3$				
Minimum	12.3	10.9	12.3	18.3
25th	32.7	38.6	40.4	43.9
50th	44.4	56.2	66.6	77.7
75th	61.3	80.2	94.8	109
Maximum	222	255	299	225
NOx, ppb				
Minimum	4.65	3.15	1.76	6.11
25th	25.0	22.0	15.7	20.8
50th	32.8	28.7	21.9	29.3
75th	43.4	39.2	30.4	42.2
Maximum	145	108	73.7	86.7
O_3 of 24hr, ppb				
Minimum	3.35	2.26	2.23	2.17
25th	17.4	16.5	18.4	17.0
50th	23.0	22.2	25.3	25.9
75th	29.2	28.7	33.1	35.1
Maximum	64.9	75.0	76.5	75.2
65+ Annual mortality rate, per 100,000				
All-cause mortality (SD)	3,673 (91.8)	4,167 (136)	4,468 (204)	4,340 (125)
Circulatory mortality (SD)	1,019 (102)	1,089 (145)	1,157 (198)	1,033 (154)
Respiratory mortality (SD)	405 (32.3)	457 (39.3)	522 (41.4)	518 (63.2)

[a] Source: Minister of Interior, 2007; Directorate-General of Budget, Accounting and Statistics, Executive Yuan, R.O.C., 2007; SD: standard deviation.

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rates for the four cities. Among these four cities, Taipei is hotter during summer but colder during winter. Kaohsiung, a major heavy-industry city in the south, has higher air pollution levels. Tainan, which is near Kaohsiung, exhibits the highest all-cause mortality.

Table S1 shows that the daily average mortality rates from all causes and from circulatory and respiratory diseases are higher during the cold season (November–December and January–April) than during the hot season (May–October). In general, the excess mortality rates occurred in days with extreme temperatures (> 95th or < 5th percentiles).

3.2. *Adverse temperature effects*

The total mortality risk associated with city-specific average temperature and consecutive temperature extremes was estimated using DLNM after controlling for the daily city-specific average PM_{10}, NO*x*, O_3, and RH, daily mortality from pneumonia and influenza, holiday effects, day of the week, and smooth long-term trend. The temperature associated with the lowest mortality risk varied among cities and generally ranged from 25–27 °C with an average of 26 °C (Table S2).

Fig. 2 shows the V-shaped associations between the cause-specific mortality and temperature at the centered temperature of 26 °C. The adverse effects are greater at low temperatures than at high temperatures.

Figs. S1–S2 show the 30 consecutive daily lag effects on mortality from all causes and from circulatory and respiratory diseases associated with 18 and 30 °C. Compared with the mortality at 26 °C, the RR associated with the low temperature of 18 °C ranged between 0.94 and 0.98 on the lag 0 day and increased daily to a peak RR of above 1.01 generally in 7–10 days. Cold effects lasted less than 30 days. The RR associated with respiratory mortality was weaker. On the other hand, the peak RRs that ranged 1.01–1.06 mostly appeared on lag 0 day at 30 °C. The lag effect did not last longer than 5 days.

Figs. S3 and S4 show the cumulative RRs associated with temperatures of 18 and 30 °C compared with 26 °C, respectively, across 30-day lags. Most cumulative RRs of mortality from all causes and from circulatory diseases exhibit increasing trend at 18 °C. The cumulative RRs show a plateau after 5 days at 30 °C on 0 day.

Fig. 3 summarizes the cumulative 30-day RRs for the elderly exposed to 18 and 30 °C compared with 26 °C by temperature, area, and causes of death. The highest pooled RR for deaths from circulatory diseases was 1.20 (95% CI: 1.11–1.31) at 18 °C or 1.08 (95% CI: 1.02–1.15) at 30 °C. For the all-cause mortality,

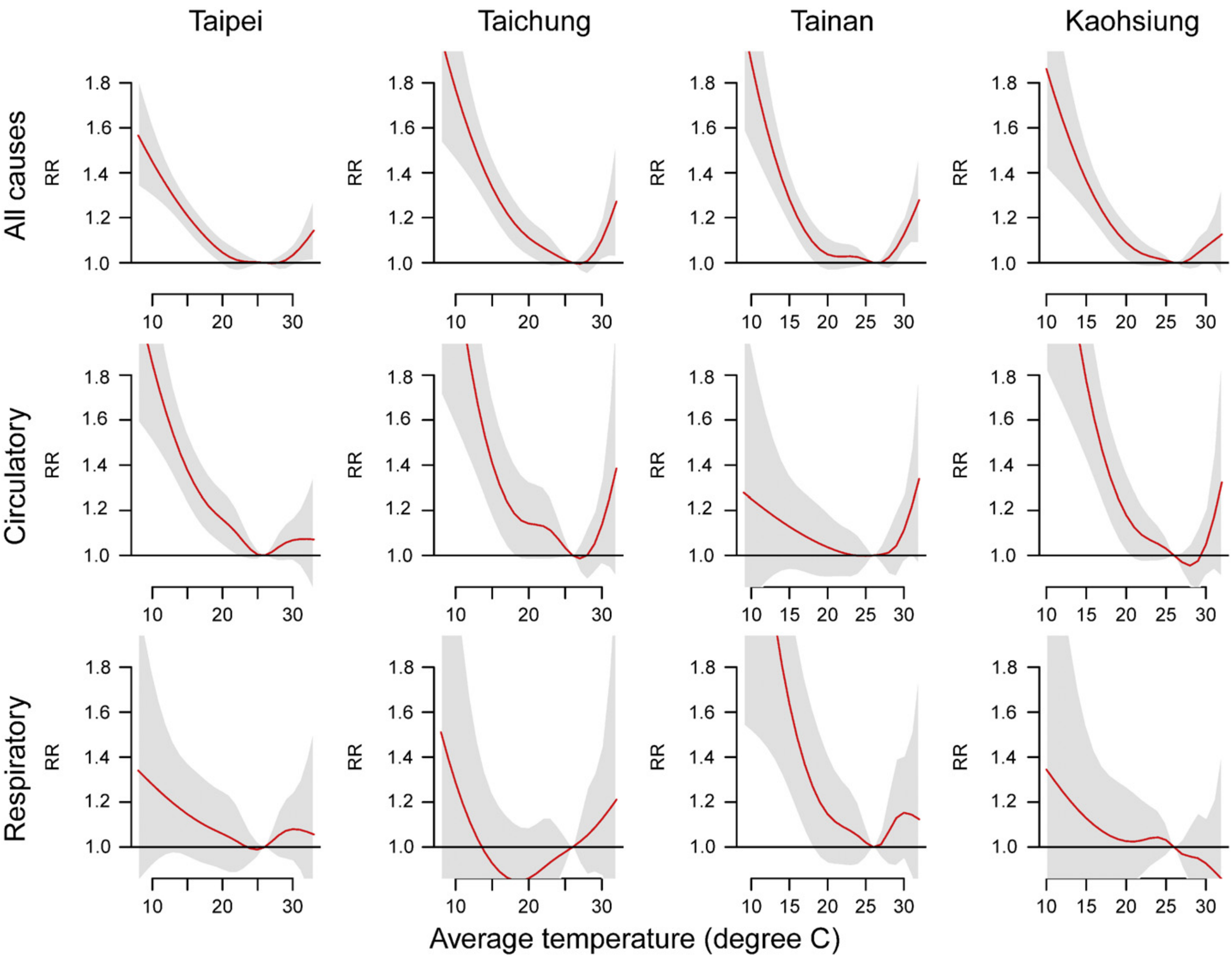

Fig. 2. Associations between cause-specific mortality and daily average temperature in the studied cities using a DLNM to estimate the RRs controlling the consecutive temperature extremes, daily city-specific averages of PM_{10}, NO*x*, O_3, and RH, daily mortality from pneumonia and influenza, gender, holiday effects, day of the week, and long-term trends.

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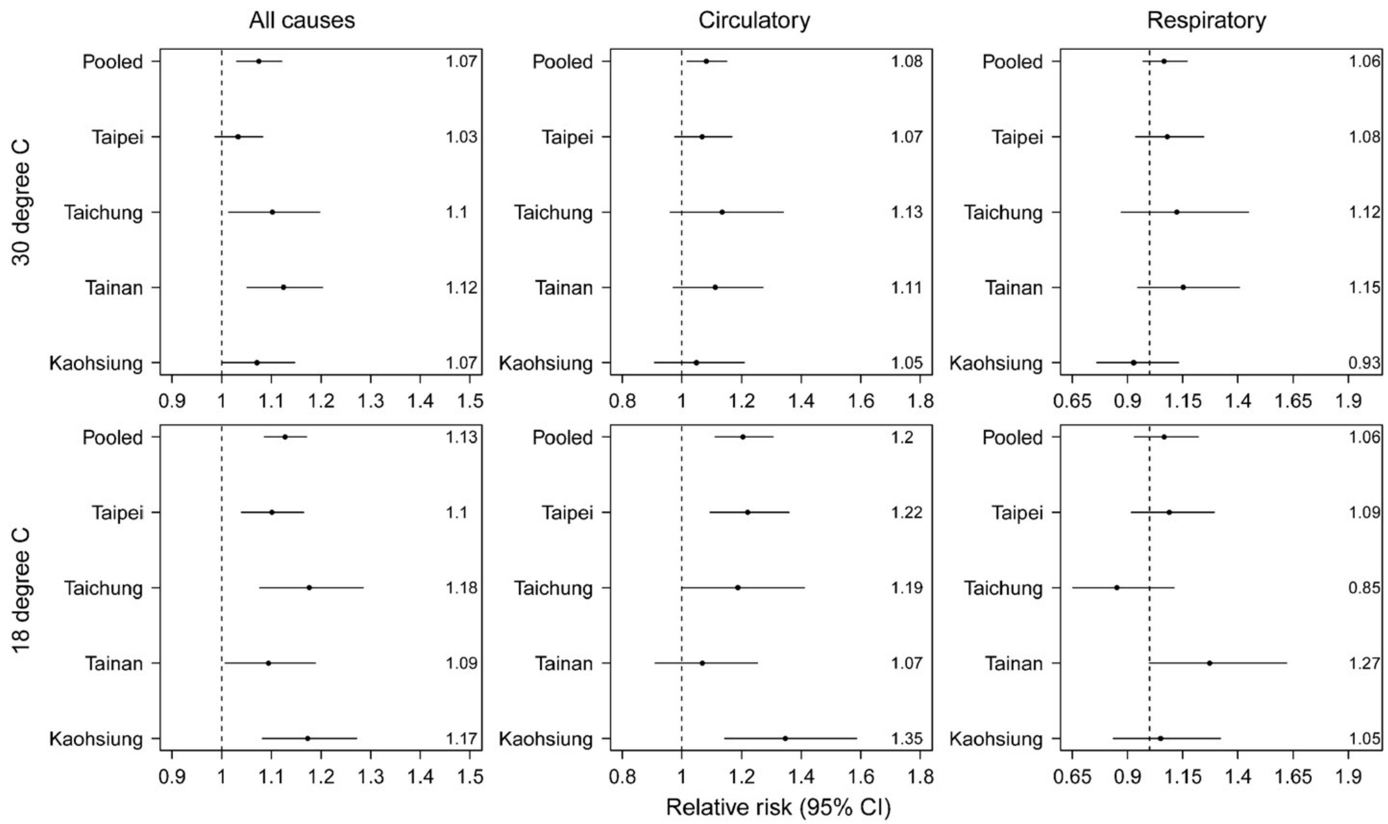

Fig. 3. City-specific and four-city pooled relative risk estimates for the cumulative 30 days at 18 and 30 °C compared with 26 °C using DLNM controlling for the consecutive days of temperature extremes, daily city-specific averages of PM_{10}, NOx, O_3, and RH, daily mortality from pneumonia and influenza, gender, holiday effects, day of the week, and long-term trends. Pooled risk estimates were obtained by random-effect meta-analysis.

the cumulative 30-day RR associated with 18 °C was highest in Taichung and Kaohsiung, followed by Taipei and Tainan. The all-cause mortality risk associated with 30 °C was significant in Tainan (RR= 1.12, 95% CI: 1.05–1.20), Taichung (RR= 1.10, 95% CI: 1.01–1.20), and in the pooled four cities (RR= 1.07, 95% CI: 1.03–1.12).

3.3. *Adverse effects from consecutive days of extreme temperatures*

Additional health effects from consecutive days of extreme temperatures varied by city, cause of death, and extreme temperature (Fig. 4). Parts of prolonged temperature extremes reveal significant associations with city-cause-specific mortality.

Pooled analysis shows that risk estimates increased with the duration of heat extremes under the same definition of extreme temperature (Fig. 5). In contrast, there was no observed significant effect from the cold extreme. In the pooled analysis of all-cause mortality, the RRs for the elderly were approximately similar at the high temperature extremes. RR was 1.05 (95% CI: 0.97–1.13) at the 99th percentile temperatures lasting longer than 3 days, 1.05 (95% CI: 1.00–1.10) at the 97th percentile temperatures lasting longer than 8 days, or 1.04 (95% CI: 1.00–1.08) at the 95th percentile temperatures lasting longer than 8 days. We observed no significant positive associations between mortality from circulatory and respiratory diseases and heat extremes. Although for heat extremes of 97th percentile temperature lasting longer than 8 days, the RR for mortality from respiratory diseases increased to 1.13 (95% CI: 0.98–1.29), but the risk estimate was not significant.

Sensitivity analyses show that the added effects of consecutive temperature extremes were robust to alternative models (data not shown). Table S2 shows the numerical results are useful for further meta-analysis.

4. Discussion

Previous studies on the health effects of extreme temperatures have rarely emphasized the importance of prolonged (i.e., several consecutive days) exposure to temperature extremes. Most studies have focused on mortality from heat waves in Western developed countries (Anderson and Bell, 2009; D'Ippoliti et al., 2010; Hajat et al., 2006; Huynen et al., 2001; Tan et al., 2007). Only a few studies have determined the effects of prolonged temperature extremes in Southeast Asian populations. The present study is the first to investigate the mortality risk associated with prolonged heat and cold temperature extremes in Taiwan.

The results show that the mortality risk in the elderly is higher when the elderly exposed to cold temperatures than to hot temperatures. The Taiwanese population is more vulnerable to death from circulatory diseases than from respiratory diseases. After accounting for the consecutive 30-day cumulative effects of temperature, the present study only found a slightly higher mortality risk is associated with intensified long-duration heat extremes. No significant adverse effect was observed for various defined extreme low temperature events.

In the US, the impact of cold weather on mortality risk is more significant than that of hot weather in southern cities, whereas the effect of hot weather is dominant in northern cities (Anderson and Bell, 2009; Curriero et al., 2002). In Europe, cold weather has a greater effect in warmer cities (Analitis et al., 2008). The threshold temperature for populations in Mediterranean cities is

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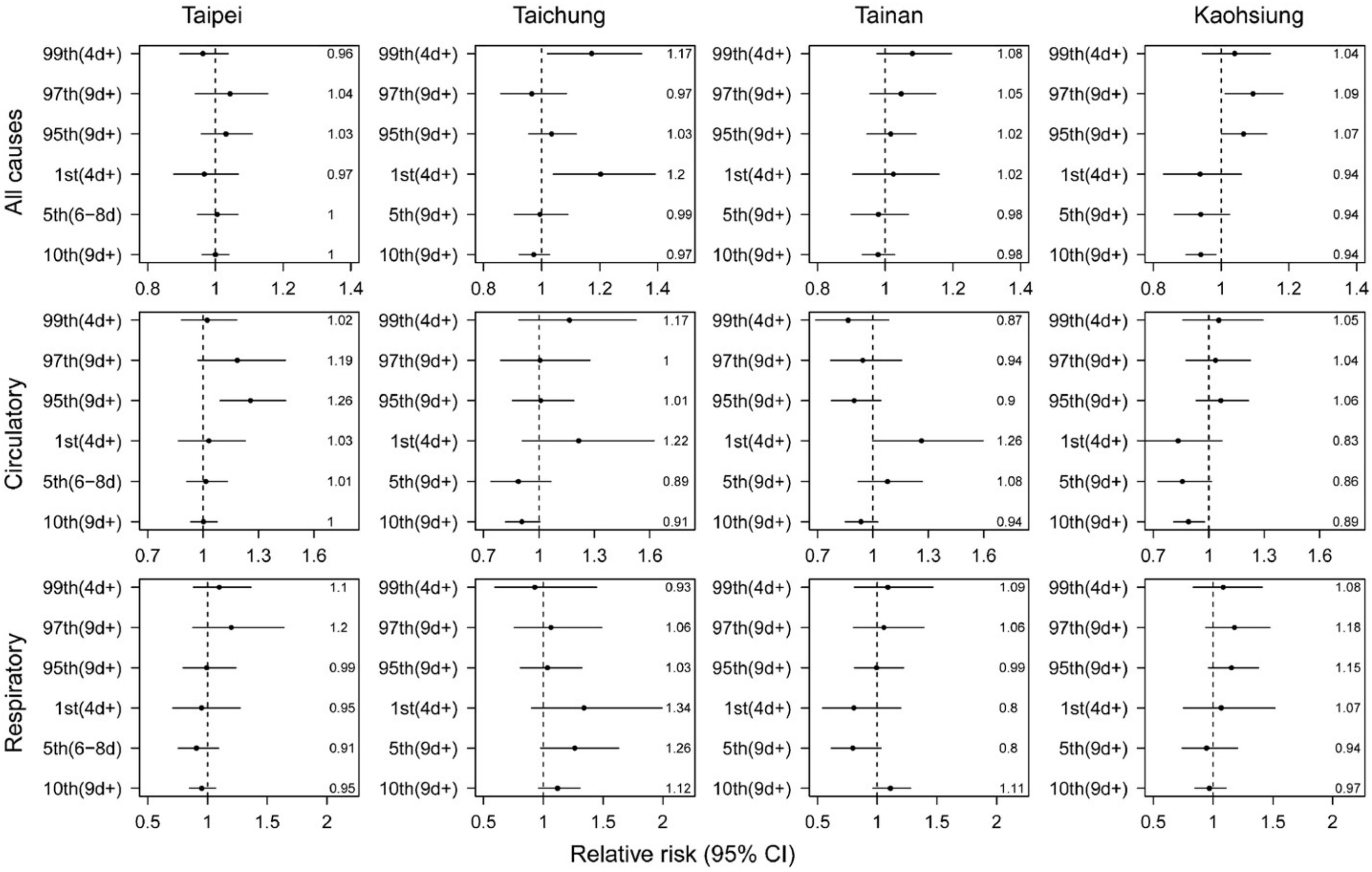

Fig. 4. City-specific relative risks of mortality from all causes and from circulatory and respiratory diseases associated with extreme temperatures consecutive for more than 3 days (4+), 6–8 days, and more than 8 days (9+). The cross-basis of the average temperature, daily city-specific averages of PM_{10}, NO*x*, O_3, and RH, daily mortality from pneumonia and influenza, gender, holiday effects, and day of the week were included in the DLNM model.

higher than that in north-continental cities (29.4 vs. 23.3 °C) (Baccini et al., 2008). The present study reveals a similar pattern that mortality risk of lower temperature is higher in low-latitude cities, such as Tainan and Kaohsiung, than in high-latitude cities.

In an international study, McMichael et al. (2008) evaluated the threshold temperatures associated with increased mortality risk in several Southeast Asian cities. The study identified threshold temperatures ranging from 19–28 °C in Chiang Mai, Thailand, 29 °C in Bangkok, Thailand, and 19–29 °C in Delhi, India. In the present study, the threshold temperature was estimated using Poisson generalized linear regression with 5 *df* for the daily average temperature, 7 *df*/year for time, and potential confounders initially set from 20–30 °C by a gradient of 0.1 °C increase. Threshold temperatures ranged from 20–28 °C.

Intensity, duration, and timing of extreme temperature events are key factors for evaluating the effect on mortality. Hajat et al. (2006) reported the mortality risk increase as the definition of extreme heat increase for heat waves. Anderson and Bell (2009) applied the same definition of extreme temperature to estimate the threshold temperature for the US population. They found a two-fold greater RR at the temperatures of $\geq$99.5th percentile than at the temperatures $\geq$98th percentile. A recent across-Europe study also reported that high-intensity (maximum apparent temperature equal to or above the monthly 95th percentile) and long-duration heat waves are significantly associated with increased mortality risk in Athens, Barcelona, Milan, Paris, and Rome (D'Ippoliti et al., 2010).

Among the few studies that evaluated the effects of temperature extremes in Asian populations, the Hong Kong study reported no correlation between mortality and temperatures exceeding 28 °C (Chau et al., 2009). Another study in South Korea found no correlation between mortality and temperatures lower than -2 °C longer than 2 days (Kim et al., 2008).

Gasparrini and Armstrong (2011) used DLNM to evaluate the main effect of daily temperature and the added effect of consecutive days of extreme high temperature. They found that temperature explains most excess risk of mortality, and heat extremes have only small-added effects sustained for more than 4 days. Their findings are consistent with the results of our present study (Figs. 3 and 5). Temperature causes greater mortality risk than prolonged periods with consecutive days of temperature extremes. Moreover, the magnitude of the mortality risk associated with heat extremes is determined mostly by duration. However, because there are relatively fewer days with temperature extremes at the 99th percentile observed in the four subtropical cities analyzed in the present study, we suggest that the correlation should be investigated further.

Hajat et al. (2006) reported that the mortality risks associated with heat waves are reduced when multi-lag nonlinear models are used to account for the effects of temperature for several days. This study found that, for consecutive days of temperature extremes, the risk estimate obtained by the DLNM lag 0 day model is slightly higher than that obtained by the DLNM lag 30 day model. The RR for all-cause mortality associated with temperature extremes at the 99th percentile longer than 3 days in Taichung varies little from 1.19 (95% CI: 1.04–1.36) in the lag 0 day model to 1.17 (95% CI: 1.02–1.34) in the lag 30 day model. The risk changes from 1.25 (1.09–1.45) derived from lag 0 day model to 1.20 (95% CI: 1.04–1.39) derived from lag 30 day model for extreme temperatures below the 1st percentile longer

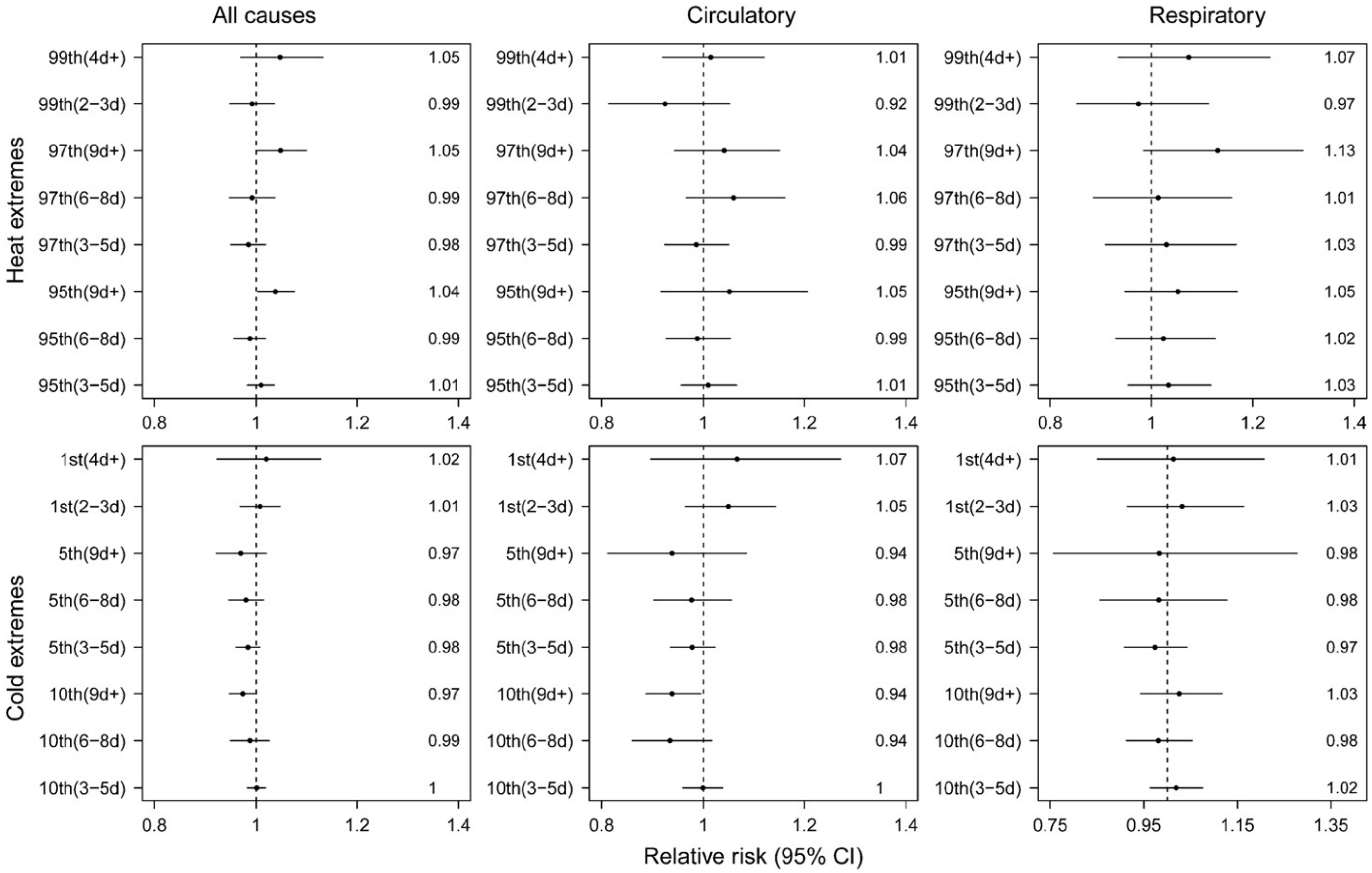

Fig. 5. Four-city pooled relative risks of mortality from all causes and from circulatory and respiratory diseases associated with extreme temperatures consecutive for more than 3 days (4+), 6–8 days, and more than 8 days (9+) by random-effects meta-analysis.

than 3 days. This study also found that the Poisson generalized additive models at lag 0 day and the DLNM of double threshold (20–28 °C) with 30-day temperature lags might obtain similar risk estimates for extreme temperature event to present study.

Ozone and PM_{10} have been associated with mortality from cardiovascular and respiratory diseases during heat waves (Anderson and Bell, 2009; Hajat et al., 2006; Medina-Ramon and Schwartz, 2007). These air pollutants are associated with slightly increased mortality risk from circulatory diseases in our study, but not statistically significant.

Adaptation may reduce the temperature-associated mortality (Anderson and Bell, 2009; Healy, 2003; O'Neill et al., 2005). In our present study, moderator variables were also included in the random-effects models to explore the effects of latitude, socioeconomic conditions, population density, air conditioning prevalence, and city- and disease-specific elderly mortality rate. However, none of these factors consistently and significantly explained the heterogeneity (data not shown) possibly because only a few cities were studied. We recommend future large-scale studies to address this issue.

The adverse effects of temperature and prolonged temperature extremes vary by city and causes of death. Competing causes of death may affect the estimated mortality risk for circulatory and respiratory diseases, which is a limitation common to all studies on secondary data. The lethal mechanisms, whether they are related to temperature alone or to the effects of exposure to consecutive days of temperature extremes, deserve further study in vulnerable populations such as those with chronic cardio-respiratory diseases.

5. Conclusion

Our findings indicate that both short-term temperature and consecutive days of extreme temperatures may increase mortality risk in elderly populations in developed and acclimatized subtropical metropolises. Notably, the short-term effect is greater at low temperatures than at high temperatures. The mortality risk associated with temperatures is higher from circulatory diseases than from respiratory diseases. Additionally, long periods of consecutive days of high temperature extremes may increase all-cause mortality in contrast to long periods of cold temperature extremes do not. The temperature-associated mortality risk depends on the evaluated city, the cause of death, and the definitions of temperature extremes. The present study demonstrates the complex effects of temperature on health in four cities of a small subtropical island.

Conflict of interest statement

All the authors declare that this study has no conflict of interest.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envres.2011.06.008.

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