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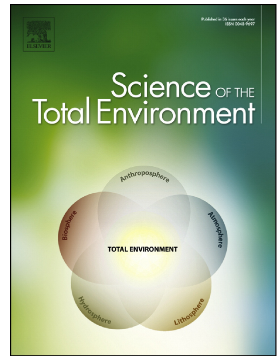

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Projection of future temperature extremes, related mortality, and adaptation due to climate and population changes in Taiwan

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ABSTRACT

Background: Extreme temperature events have been observed to appear more frequently and with greater intensity in Taiwan in recent decades due to climate change, following the global trend. Projections of temperature extremes across different climate zones and their impacts on related mortality and adaptation have not been well studied.

Methods: We projected site-specific future temperature extremes by statistical downscaling of 8 global climate models followed by Bayesian model averaging from 2021-2060 across Taiwan under the representative concentration pathway (RCP) scenarios RCP2.6, RCP4.5, and RCP8.5. We then calculated the attributable mortality (AM) in 6 municipalities and in the eastern area by multiplying the city/county- and degree-specific relative risk of mortality according to the future population projections. We estimated the degree of adaptation to heat by slope reduction of the projected AM to be comparable with that in 2018.

Results: The annual number of hot days with mean temperatures over 30℃ was predicted to have a substantial 2- to 5-fold increase throughout the residential areas of Taiwan by the end of 2060 under RCP8.5, whereas the decrease in cold days was less substantial. The decrease in cold-related mortality below 15℃ was projected to outweigh heat-related mortality for the next two decades, and then heat-related mortality was predicted to drastically increase and cross over cold-related mortality, surpassing it from 2045-2055. Adjusting for future population size, the percentage increase in heat-related deaths per 100,000 people could increase by more than 10-fold under the worst scenario (RCP8.5), especially for those over 65 years old. The heat-related impacts will be most severe in southern Taiwan, which has a tropical climate. There is a very high demand for heat-adaptation prior to 2050 under all RCP scenarios.

Conclusions: Spatiotemporal variations in AM in cities in different climate zones are projected in Taiwan and are expected to have a net negative effect in the near future before shifting to a net positive effect from 2045-2055. However, there is an overall positive and increasing trend of net effect for elderly individuals under all the emission scenarios. Active adaptation plans need to be well developed to face future challenges due to climate change, especially for the elderly population in central and southern Taiwan.

Keywords: Bayesian model average, Climate zone, Crossover, Representative concentration pathway, Statistical downscaling

1 Introduction

Global warming due to climate change over the past few decades has raised serious public health concerns, especially regarding heat-related mortality (Nitschke et al., 2011; Vandentorren et al., 2006; Zuo et al., 2015). According to the recent assessment of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2013), the average ambient temperature is projected to continue to increase globally based on the state-of-the art Coupled Model Intercomparison Project phase 5 (CMIP5) model ensemble. It is very likely that the frequency, duration, and intensity of heat waves will continue to increase; whereas the frequency, duration, and intensity of cold waves will decrease (IPCC 2013; Melillo et al. 2014, Wang et al. 2016). As a result, for certain cities in the U.S., Europe, and China, increases in heat-related deaths are projected to outweigh decreases in cold-related deaths by the end of the century (Weinberger et al., 2017; Zhang et al., 2018). However, the projected temperature-related mortality will be largely dependent on geographical differences. A null or marginally negative net effect due to decreased excess cold-related mortality has been projected in northern Europe, East Asia, and Australia (Gasparrini et al., 2017; Hajat et al., 2014; Vardoulakis et al., 2014). In contrast, an increase in heat-related mortality has been projected in central and southern parts of America and Europe, and an especially sharp increase will occur in tropical countries and Southeast Asia (Gasparrini et al., 2017; Lee et al., 2019a).

Studies have shown that exposure to temperature extremes increases mortality, with a well-established U-shaped association (Gasparrini et al, 2015; Guo et al., 2014; Lee and Kim, 2016; Lin et al., 2019; Weinberger et al., 2017; Zhang et al., 2018). However, the relative risks (RRs) of cold- and heat-related mortality may vary depending on the study area or region. For example, people living in high latitude cities, such as Toronto, Stockholm, and Shenyang, are relatively insensitive to extremely cold temperatures but are vulnerable to high temperatures (Gasparrini et al., 2015; Ma et al., 2014). In contrast, people living in cities with subtropical climates, such as Guangzhou, Hong Kong, and Taipei, are more adapted to heat but are vulnerable to cold temperatures (Gasparrini et al, 2015; Lin et al., 2019; Ma et al., 2014). Therefore, different adaptation strategies to temperature extremes may need to be adopted according to the characteristics of the local climate.

In these previous studies, downscaled temperature predictions from global climate models (GCMs) under different greenhouse gas emission scenarios were obtained from other sources to relate to epidemiological estimates of future heat- and cold-related mortality projections. The lack of information on the future distributions of local temperature extremes hinders efforts to develop effective adaptation strategies to assess their possible health impacts. Furthermore, study outcomes based on aggregate data might not provide suitable guidance for countries with heterogeneous climate regions. In this study, we projected site-specific temperature extremes from 2021-2060 in Taiwan using statistical downscaling of 8 CMIP5 climate models under three representative concentration pathway (RCP) scenarios: RCP2.6, RCP4.5, and RCP8.5. The predicted annual number of days with temperature extremes was then multiplied by the city/county-specific RR of mortality per degree Celsius (Lin et al., 2019) and the future population estimates of 6 municipalities in different climate regions and eastern areas to project the attributable mortality (AM). In addition, for elderly individuals who are more vulnerable to cold- and heat-stresses (Bunker et al., 2016; Gamble et al., 2013), we calculated the projected AMs based on the RRs from an earlier epidemiological study in Taiwan (Lin et al., 2011). The degree of adaptation that needs to be developed under different RCP scenarios was estimated for each city/area based on the study outcomes in comparison with the heat-related AM in 2018.

2 Methods

2.1. Overview of the study area

Located in central East Asia off the coast of mainland China, the main island of Taiwan has an area of 35,960 km^2, spans 385 km from north to south, and has a width at the widest point from east to west of 143 km. The Central Mountain Range, which is located in the middle of the island, has an altitude of up to 3,952 meters and stretches from north to south, dividing the residential area into western and eastern sections. The area to the north of the Tropic of Cancer, which intersects mid-southern Taiwan, has a subtropical monsoon climate; the area to the south has a tropical monsoon climate. In the north, summers (June-September) are normally hot and humid, with a daily mean temperature of approximately 28℃, and winters (December-February) have a temperature of approximately 16℃; whereas winters in the south are relatively warmer, with a mean temperature of approximately 19℃. The year-round relative humidity is approximately 76%. Among the total population of

23.6 million people in Taiwan, approximately 70% reside in the 6 municipalities along the western coastal plains; listed from north to south, the municipalities are as follows: Taipei, New Taipei, Taoyuan, Taichung, Tainan, and Kaohsiung. Except for Tainan and Kaohsiung, which have tropical climates, the other 4 cities have subtropical climates. Fig. 1 shows the locations of the 6 municipalities and their geographic characteristics, such as the elevation of Taiwan.

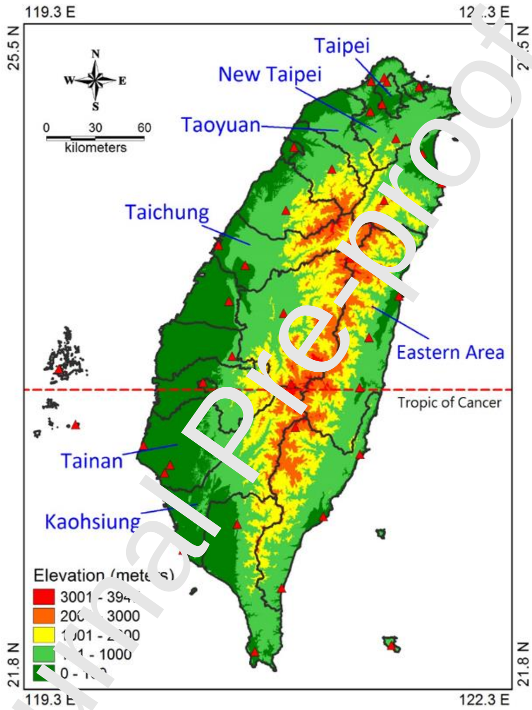

Fig. 1. Map of the main island of Taiwan, locations of the 6 municipalities, and distributions of 42 meteorological stations (red triangles).

2.2. Data collection

Historical hourly temperature records of 42 meteorological stations were obtained from the Data Bank for Atmospheric and Hydrologic Research of the Taiwan Typhoon and Flood Research Institute for the 1951-2018 period. We used 8 CMIP5 climate models from the IPCC that are suitable for making future projections at the latitude/longitude of Taiwan: bcc-csm1-1 m, CCSM4, CESM1-BGC, CESM1-CAM5, CMCC-CM, EC-EARTH, MRI-CGCM3, and MRI-ESM1. We also obtained downscaled projections with a resolution of 5 km × 5 km for these 8 CMIP5 models during the time period of 2021-2060 from the Taiwan Climate Change Projection Information and Adaptation Information Platform (TCCIP, 2020). We obtained the population projection for Taiwan up to 2060 from the National Development Council (NDC) (NDC, 2020). Additionally, for demographic data, we obtained city/county-specific population size and mortality data at the end of 2018 from the Ministry of the Interior of Taiwan. The city/county-specific RRs for all-cause (nonaccidental) mortality per degree Celsius of the suboptimal daily mean temperature from 1995-2008 (Lin et al., 2019) and the RRs of the elderly individuals (≥65 years old) from 1994-2007 (Lin et al., 2011) were based on the outcomes of previous epidemiological studies in Taiwan. Both studies used a distributed-lag nonlinear model (DLNM) to account for the cumulative lag effects (a maximum lag of 30 days in Lin et al., 2011; and 26 days in Lin et al., 2019) of ambient temperature on mortality. Therefore, for future projections, the same lag effects of temperature extremes on mortality were applied for the general population (26 days) and the elderly population (30 days).

2.3. Future temperature projection

In total, 18 available emission scenarios under RCP2.6 (bcc-csm1-1m, CCSM4, CESM1-CAM5, MRI-CGCM3), RCP4.5 (bcc-csm1-1m, CCSM4, CESM1-CAM5, MRI-CGCM3,CESM1-BGC, CMCC-CM), and RCP8.5 (bcc-csm1-1m, CCSM4, CESM1-CAM5, MRI-CGCM3, CESM1-BGC, CMCC-CM, EC-EARTH, and MRI-ESM1) of the Fifth Assessment Report (AR5) were considered.

2.3.1. Statistic downscaling of climate models

For each RCP scenario of the 8 climate models, we applied the probabilistic downscaling method (CDF-t) by Michelangeli et al. (2009) for future temperature projections. Specifically, the established functional form of the cumulative distribution function (CDF) of temperature at a local station and that of the historical run of CMIP5 models during the period from 1961-2005 were used to project the future CDF of the temperature at that station. Because only the minimum and maximum daily mean temperatures from historical observations were available, temperature extremes below or exceeding the limits of observed historical data were projected using model fitting of a generalized Pareto distribution based on extreme value theory (XCDF-t) (Kallache et al., 2011). The projections obtained by using the CDF-t method (Michelangeli et al., 2009) were then concatenated with those of the XCDF-t method (Kallache et al., 2011) for temperatures below or exceeding the observed limits. Please see the Supplementary Materials (SM) for the detailed methodology. The 5th and 95th temperature percentiles were approximately 15℃ and 30℃, respectively, from 1995 to 2011 in Taiwan (Lin et al., 2019). Here, we set the temperature thresholds for cold and heat as 15℃ and 30℃, respectively, so that the overall tail percentages would be less than 10% across different cities/areas. Using the downscaled outcomes, the annual number of days with a daily mean temperature

≤15℃ in winter months (December-February) and ≥30℃ in summer months (June-September) per degree were projected for each RCP scenario of the 8 CMIP5 models during the 2021-2030, 2031-2040, 2041-2050, and 2051-2060 periods. The projected number of days for stations within the same city/county were averaged for city/county-specific predictions. For cities/counties without any stations, the averaged projections of the nearest stations were used as estimates for each city/county.

2.3.2. Bayesian model averaging for future projection

To assess the performance of the GCMs, we performed statistical downscaling based on the historical run data of each of the 8 CMIP5 models from 2006-2017 under different RCP scenarios and compared the CDF with that of the historical observations during that period. A Bayesian model averaging (BMA) method was then employed for the statistical downscaling results of the model ensemble. Specifically, given the historical observations D and the historical run data of the climate model M_i between 2006 and 2017, the corresponding weight of M_i is proportional to the reciprocal of the integrated difference between the CDF of the model and that of the observation data; this relationship can be described as follows:

$$\mathrm{P}(T > t|D) = \sum_{M_i} P(M_i|D)P(T > t|D, M_i) \tag{1}$$

where T is the mean temperature as a random variable, t is the observed mean temperature, and $\mathrm{P}(M_i|D)$ can be described as follows:

$$\mathrm{P}(M_i|D) = \frac{P(D|M_i)P(M_i)}{\sum_{l=1}^{K} P(D|M_l)P(M_l)}, \tag{2}$$

$$\mathrm{P}(D|M_i) \propto \frac{1}{\int \left|F_Y(t) - F_{M_i}(t)\right| f_{M_i}(t)dt}, \tag{3}$$

$$M_i \in \mathcal{M} = \{M_l, l = 1, \cdots, K\},$$

where $F_Y(t)$ and $F_{M_i}(t)$ are the CDFs of the observation and climate models M_i, respectively, and K is the number of candidate models.

2.4. Projection of future temperature-related mortality

We calculated the AM according to the following equation:

$$\mathrm{AM} = \mathrm{Pop} \times \mathrm{Mortality} \times \mathrm{PAF} \tag{4}$$

where Pop is the population size, Mortality is the mortality rate, and PAF is the population attributable fraction (PAF). The PAFs attributed to heat (PAF_H) and cold (PAF_C) were estimated by using the following equations:

$$PAF_H = \frac{\sum_{30}^{M} P(x)(RR(x)-1)}{1+\sum_{30}^{M} P(x)(RR(x)-1)} \tag{5}$$

and

$$PAF_C = \frac{\sum_{m}^{15} P(x)(RR(x)-1)}{1+\sum_{m}^{15} P(x)(RR(x)-1)} \tag{6}$$

where $RR(x)$ is the RR of mortality at temperature *x*, $P(x)$ is the projected probability of temperature *x* for the future year, and m and M are minimum and maximum temperatures below and above the daily mean temperature of 15℃ and 30℃, respectively. The RRs of attributable mortality ≥30℃ and ≤15℃ per degree Celsius for the general and elderly populations are given in Table S1, SM (Lin et al., 2011; 2019). We assumed that the city/county-specific mortality rates remained the same as those in 2018. Additionally, the RRs of exceeding the maximum temperature and being below the minimum temperature available for the city/county during the study period from 1995-2008 for the general population (Lin et al., 2019) and from 1994-2007 for the elderly population (Lin et al., 2011) were assumed to be the same for future projections of mortality. The RRs for the elderly population in Taoyuan and the eastern area were unavailable from the Lin et al. (2011) study. To avoid underestimation, RRs of less than 1 were omitted in calculating the PAF (Table S1, SM).

3 Results

3.1. Calibrations of statistical downscaling

To assess the performance of the statistical downscaling of the 8 chosen CMIP5 models, Fig. S1 (SM) compares the CDF of the historical run data of the ensembled outcomes of the 8 CMIP5 models and that of the observation data from 2006-2017 under the RCP2.6, RCP4.5, and RCP8.5 scenarios using BMA. The results showed that, under any of the RCP scenarios, the CDF curves of the historical run data and the observations were all closely matched for each of the cities and areas studied. Therefore, it was expected that the future projections based on BMA of the 8 CMIP5 models would have reasonably good performance.

3.2. Predictions of future temperature extremes from 2021-2060

Fig. 2 shows the predictions of the annual number of days with mean temperature ≥30℃ and ≤15℃ from 2021-2030, 2031-2040, 2041-2050, and 2051-2060 across Taiwan under the RCP8.5 scenario based on the downscaled data from TCCIP with weights obtained from BMA of the 8 CMIP5 models. The results show that the number of hot days with mean temperatures ≥ 30℃ from 2021-2030 will increase from 20-30 days in sporadic areas to more than 50-60 days over most of the residential areas from 2050-2060, especially in southern Taiwan. In contrast, the number of cold days with daily mean temperatures ≤15℃ was predicted to decrease from north to south over the next few decades. However, the trend was not as apparent compared to that of increasing hot days. The corresponding downscaled predictions under RCP2.6 and RCP4.5 are shown in Fig. S2 (SM). The predicted outcomes under these two RCP scenarios were similar but with less noteworthy patterns in changes.

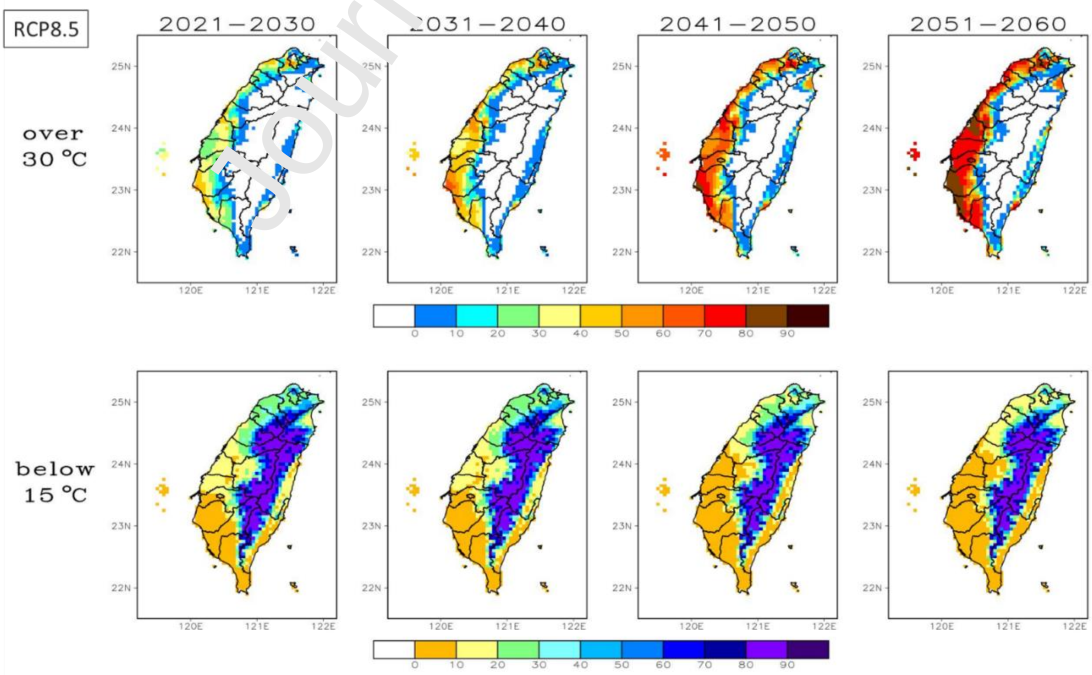

Fig. 2. Predictions of the mean number of days ≥30℃ from June-September (upper row) and ≤15℃ from December-February (lower row) from 2021-2030, 2031-2040, 2041-2050, and 2051-2060 across Taiwan under the RCP8.5 emission scenario.

Table 1 lists the percentages of the annual number of days ≥30℃ and ≤15℃ from 2021-2030, 2031-2040, 2041-2050, and 2051-2060 in the 6 municipalities and the eastern area of Taiwan (Yilan and Hualien). Because of the low population density in mountainous areas, the temperature projections for each city were obtained by averaging the projections of the stations with altitudes lower than 1,000 meters within each city. Similar to the pattern shown in Fig. 2, there were clear increasing trends in the annual percentages of hot days for all cities/areas over the next four decades. Compared to those in 2018, the percentages of hot days in New Taipei and Taichung gradually increased from less than 5% to over 10% from 2051-2060 under RCP8.5. The predictions for Taipei and Taoyuan had similar increasing patterns but to a lesser extent. For Tainan and Kaohsiung, which have tropical climates, the increase in the number of hot days was even higher over the next four decades. It should be noted that there was a five-fold increase in Taichung and Tainan from 2051-2060 under RCP8.5. For residential areas in the east, a dramatic increase from 1.0% in 2018 to 12.1% from 2051-2060 was predicted under RCP8.5. In general, the predicted increases were most significant under RCP8.5, followed by those under RCP4.5 and RCP2.6, as expected. The ranges of the predicted percentages (numbers in parentheses in Table 1) showed that there could be up to a 7-fold difference in the predictions of the 8 GCMs. However, the overall increasing trends under different RCP scenarios from 2021 to 2060 were all consistent.

Table 1

Predicted percentages of days ≤15℃ and ≥30℃ in the 6 municipalities and the eastern portion of Taiwan from 2021-2030, 2031-2040, 2041-2050, and 2051-2060 under the RCP2.6, RCP4.5, and RCP8.5 emission scenarios.

		2018	2021-2030			2031-2040			2041-2050			2051-2060		
City/Area			RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Taipei	Hot	14.8	8.8 (6.3-11.5)	9.0 (6.3-11.0)	9.3 (6.8-13.2)	10.4 (7.4-12.6)	9.3 (5.5-11.8)	10.7 (6.6-14.0)	10.7 (8.2-14.8)	12.[illegible] (9.6-15.[illegible])	15.3 (13.4-21.1)	11.0 (4.9-17.3)	14.2 (11.8-17.3)	18.6 (15.6-22.7)
	Cold	6.3	8.5 (7.7-9.9)	8.5 (7.9-10.1)	8.2 (6.8-9.6)	8.2 (4.4-9.9)	7.9 (6.0-9.9)	7.7 (6.8-9.0)	7.7 (6.3-8.5)	6.8 (6.3-7.7)	6.0 (2.2-10.1)	6.8 (3.6-8.2)	5.5 (3.0-7.4)	4.7 (1.1-10.7)
New Taipei	Hot	4.6	5.5 (3.6-7.5)	5.8 (3.6-7.5)	5.8 (4.2-9.2)	6.8 (4.5-8.9)	5.8 (3.2-7.7)	7.0 (4.0-9.3)	7.1 (5.0-10.0)	8.3 (6.2-10.6)	10.3 (8.8-15.1)	7.7 (4.3-11.8)	9.6 (7.7-11.8)	12.9 (10.6-16.3)
	Cold	9.5	11.1 (9.5-12.7)	11.2 (10.5-13.2)	10.5 (8.6-12.3)	10.9 (7.1-12.7)	10.3 (7.7-12.7)	10.1 (8.6-11.9)	10.[illegible] (7.8-11.2)	8.5 (7.4-10.1)	7.9 (5.5-10.8)	9.1 (6.2-10.8)	7.7 (6.0-9.8)	6.4 (3.4-11.3)
Taoyuan	Hot	10.1	8.2 (5.8-11.8)	9.0 (6.0-11.8)	9.0 (6.6-14.0)	10.4 (7.1-13.7)	9.3 (6.0-11.5)	10.7 (6.6-13.7)	10.7 (7.7-14.5)	12.1 (9.9-15.1)	15.1 (13.2-21.1)	11.2 (5.5-16.7)	13.7 (11.5-16.2)	18.4 (15.1-25.2)
	Cold	7.4	8.8 (7.7-9.9)	8.8 (7.9-10.1)	8.2 (7.1-9.6)	8.2 (4.7-9.9)	7.7 (5.2-9.9)	7.7 (6.8-9.[illegible])	7.7 (5.5-8.8)	6.3 (4.9-7.7)	5.5 (3-7.9)	6.8 (3.3-8.2)	5.5 (3.8-7.4)	4.1 (1.4-8.2)
Taichung	Hot	2.7	6.0 (2.7-8.8)	5.5 (2.5-9.3)	7.1 (5.5-11.2)	7.1 (4.9-9.3)	6.3 (3.6-10.4)	9.6 (4.1-19.7)	7.1 (4.9-9.3)	9.9 (4.4-17.0)	11.5 (7.7-22.5)	8.8 (4.1-14.8)	12.1 (5.8-25.8)	17.0 (7.4-22.5)
	Cold	6.3	6.0 (4.4-7.1)	6.6 (5.5-8.2)	5.2 (3.0-7.4)	6.3 (3.3-8.2)	4.7 (2.7-[illegible].4)	4.9 (2.7-6.8)	4.4 (3.8-6.0)	3.8 (2.7-6.0)	3.6 (1.1-6.6)	3.8 (2.5-6.0)	3.3 (1.6-6.0)	2.7 (0.5-5.5)
Tainan	Hot	4.1	9.9 (4.7-18.9)	8.2 (6.0-9.9)	10.7 (5.2-18.9)	11.0 (6.8-18.9)	11.0 (5.[illegible]-19.5)	13.7 (8.2-21.6)	9.0 (7.1-10.4)	12.9 (6.8-22.7)	18.4 (14.5-31.0)	13.4 (8.2-18.9)	15.6 (9.3-21.6)	22.2 (17.8-31.0)
	Cold	3.0	2.5 (2.2-2.7)	3.3 (2.7-3.8)	2.5 (1.9-3.0)	2.7 (1.6-3.3)	2.[illegible] (2.2-3.3)	2.7 (1.9-3.6)	2.5 (1.9-2.7)	2.2 (1.6-2.7)	1.9 (1.4-2.7)	1.9 (1.4-2.7)	1.9 (1.6-2.7)	1.6 (1.1-2.5)
Kaohsiung	Hot	9.0	9.6 (4.1-21.6)	5.5 (3.6-6.6)	8.2 (4.4-21.6)	10.[illegible] (4.9-21.6)	9.3 (4.1-21.6)	11.8 (5.8-21.6)	6.3 (4.1-8.8)	11.5 (5.8-23.0)	17.8 (12.3-32.6)	12.3 (4.9-21.6)	14.5 (8.8-21.6)	21.4 (14.8-32.6)
	Cold	1.4	0.8 (0.8-1.1)	1.4 (0.8-1.6)	0.8 (0.5-0.8)	1.1 (0.8-1.4)	0.8 (0.5-1.4)	1.1 (0.5-1.6)	0.8 (0.5-1.1)	0.8 (0.3-1.1)	0.5 (0.3-0.8)	0.8 (0.5-1.1)	0.8 (0.5-1.1)	0.5 (0.3-0.8)
Eastern Area	Hot	1.0	2.1 (1.2-3.0)	3.3 (1.1-5.2)	3.7 (1.2-6.6)	3.3 (2.1-5.8)	4.0 (1.9-6.8)	5.3 (1.5-10.7)	3.7 (1.4-6.0)	6.0 (2.5-10.5)	8.8 (3.8-14.4)	4.7 (1.8-8.2)	7.1 (1.9-14.4)	12.1 (8.1-24.1)
	Cold	4.7	4.1 (2.9-5.8)	4.7 (4.1-6.0)	3.7 (2.6-5.8)	4.2 (1.6-5.8)	3.7 (1.9-6.0)	3.6 (1.8-5.6)	3.6 (2.3-5.1)	2.7 (1.9-4.9)	2.3 (0.7-5.3)	2.7 (1.1-5.2)	2.3 (1.0-4.9)	1.8 (0.3-5.8)

In contrast to the predictions for hot days, the percentages of cold days ≤15℃ from 2021-2060 only slightly decreased. For example, the projected percentage of cold days in New Taipei decreased from 9.5% in 2018 to 6.4% from 2051-2060 under RCP8.5. The percentages of cold days in Tainan, Kaohsiung, and the eastern area were predicted to be essentially less than 2%. This predicted pattern is also shown in Fig. 2, which indicates that there was not much change projected in the number of cold days across Taiwan from 2021-2060. Similar to the predictions for hot days, there was large variation (up to 10-fold) in the predictions for cold days among the 8 CMIP5 models.

3.3. Projections of attributable mortality due to temperature extremes from 2021-2060

Fig. 3 (a) displays the projected AM due to temperature extremes (≤15℃ and ≥30℃) from 2021-2060. The point estimates (per 5 years) of the curves were obtained by taking the moving average of the projections with a window width of 10 years (5 years prior to and after the estimated year). The shades of the curves were obtained based on the high and low estimates of projected population size (NDC, 2020). Except for Kaohsiung, which is in the utmost south, the total projected cold-related deaths substantially decreased by 2- to 3-fold from 2021 to 2060 in all areas and under all the considered RCP scenarios. Among these, the projected mortality in Taipei and New Taipei decreased from over 1,000 in 2021 to less than 500 in 2060. The projected deaths of Taichung and Tainan also decreased from over 500 to approximately 200, whereas mortality in Kaohsiung only slightly decreased. In contrast, the projected deaths due to hot days (≥30℃) increased drastically in New

Taipei, Tainan, and Kaohsiung from 100-200 in 2021 to 500-800 in 2060 under RCP8.5. There was also a 3-fold increase of projected deaths from 50 to 150 in the eastern area. However, the projected deaths due to heat for Taipei and Taoyuan remained approximately the same. It should be noted that, starting in 2045, the number of deaths in Tainan due to heat was projected to surpass those from cold under RCP8.5. Similarly, there was a crossover in New Taipei, Taichung, and the eastern area in 2055. The crossover was most significant under the RCP8.5 scenario, followed by RCP4.5.

Because of the aging population and low fertility rate, the population size in Taiwan is projected to decrease from 23.5 million in 2021 to 18.1 million in 2060 (NDC, 2020). In contrast, the elderly population is projected to increase from approximately 4 million to 7.3 million during the same period (NDC, 2020). The dramatic changes in both total and elderly populations will greatly impact future mortality projections. Fig. 3 (b) shows the mortality projections in 5 municipalities for elderly individuals who are more vulnerable to cold- and heat-stresses. In general, the projected patterns for the elderly population were similar to those for the general population. However, there were increases of up to 10-fold in heat-related deaths, which were much larger than those for the general population, especially for Taichung, Tainan, and Kaohsiung in central and southern Taiwan. The decreases in cold-related deaths were relatively small compared to those for the general population. Notably, there was even a slight increase in cold-related deaths from 2020 to 2040 in Taipei, New Taipei, and Taichung under RCP2.6 mainly due to the projected increase in the elderly population for the next few decades, which is underestimated in Fig. 3 (a). Starting in 2030, there is a crossover of heat- and cold-related deaths for elderly individuals in Tainan and Kaohsiung, with heat-related AM monotonically increasing under all the RCP emission scenarios.

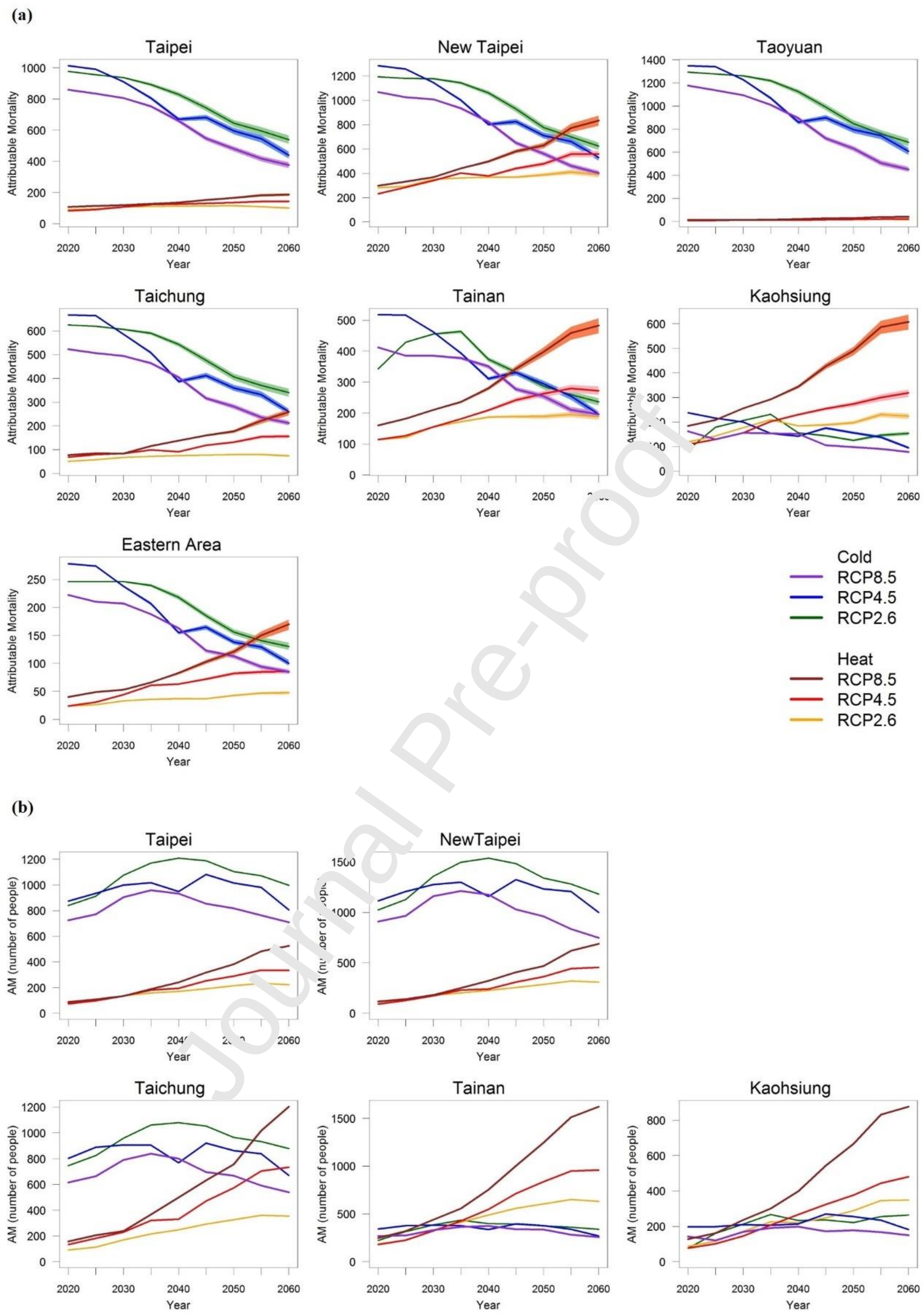

Fig. 3. Five-year moving averages of the projected mean attributable number of deaths due to temperature extremes (≥30℃ from June-September and ≤15℃ from December-February) in 6 municipalities and the eastern area of Taiwan from 2021-2060 across Taiwan under the RCP8.5, RCP4.5, and RCP2.6 scenarios for: (a) the general population, and (b) the elderly population.

Because of the opposite projection trends in declining total population size and increasing elderly population, the population composition and thus the size of population at risk (vulnerable population) changes over time. To be able to compare the AMs between the cities/areas, we standardized the projected AMs per 100,000 people. Table 2 (a) lists the projected numbers of deaths due to temperature extremes per 100,000 people for the general population. Considering the projected decrease in population size of more than 20% from 2018 to 2060, the projected number of deaths per 100,000 people attributable to temperature extremes was even more severe than that shown in Fig. 3. The attributable mortality per 100,000 people due to heat (daily mean temperature ≥ 30℃) was projected to have a more than 10-fold increase in the central (Taichung), southern (Tainan and Kaohsiung), and eastern areas from 1-6 in 2018 to 11-30 from 2051-2060 under RCP8.5. The projection for New Taipei in the north showed a slightly more-than-4-fold increase, whereas the numbers of deaths in Taipei and Taoyuan remained approximately the same. The projected decrease in cold-related mortality per 100,000 people across the cities/areas was 3- to 4-fold, causing a reduction from 10-44 in 2018 to 2-18 from 2051-2060 under RCP8.5.

Table 2 (b) lists the projected AMs per 100,000 people for the elderly population (≥65 years old). The projected heat-related deaths increased from 2-4 in 2018 to 21-23 from 2051-2060 per 100,000 people in the north (Taipei/New Taipei) under RCP8.5. The projected increase during the same period was even more drastic in central (Taichung) and southern Taiwan (Tainan, Kaohsiung), increasing from 1-4 to 38-99 under RCP8.5. In contrast, cold-related deaths remained at approximately the same level, with the projected AMs highest under RCP2.6 in general, followed by RCP4.5, and the lowest values projected under RCP8.5.

Table 2

Projected number of deaths per 100,000 people attributable to temperature extremes (≤15℃ and ≥30℃) of different municipalities (areas) across Taiwan from 2021-2030, 2031-2040, 2041-2050, and 2051-2060 under the RCP2.6, RCP4.5, and RCP8.5 scenarios for: (a) the general population, and (b) the elderly population.

(a)

City/Area (population $\times 10^5$)		2018	2021-2030			2031-2040			2041-2050			2051-2060		
			RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Taipei (26.7)	Hot	6	3 (3-5)	4 (3-5)	4 (3-6)	5 (3-6)	4 (2-5)	5 (3-7)	5 (3-6)	6 (4-8)	7 (5-10)	5 (2-8)	7 (5-8)	9 (6-11)
	Cold	37	35 (26-48)	37 (30-49)	30 (20-47)	34 (16-49)	30 (17-48)	31 (20-50)	31 (23-50)	26 (20-52)	22 (7-49)	26 (13-49)	22 (10-50)	18 (3-49)
New Taipei (40.0)	Hot	6	7 (4-12)	8 (4-13)	9 (4-17)	10 (6-19)	8 (4-13)	11 (5-23)	8 (5-12)	14 (6-25)	17 (8-33)	11 (4-25)	17 (8-27)	26 (10-44)
	Cold	38	30 (22-39)	32 (25-42)	25 (16-38)	28 (12-40)	25 (13-39)	25 (16-41)	26 (16-40)	21 (14-45)	17 (5-39)	21 (9-40)	18 (8-41)	13 (2-34)
Taoyuan (22.2)	Hot	0*	1 (0-1)	1 (0-1)	1 (0-1)	1 (1-1)	1 (0-1)	1 (0-2)	1 (0-1)	1 (0-2)	1 (1-3)	1 (0-2)	1 (1-2)	2 (1-5)
	Cold	67	57 (42-74)	60 (49-79)	49 (34-72)	54 (26-77)	48 (29-74)	50 (32-77)	51 (34-75)	40 (31-84)	35 (16-75)	40 (19-75)	36 (20-76)	24 (5-64)
Taichung (28.0)	Hot	1	2 (1-3)	2 (1-4)	2 (2-7)	2 (2-5)	2 (1-6)	4 (1-11)	2 (2-5)	5 (1-11)	6 (2-16)	4 (1-9)	6 (2-18)	11 (3-23)
	Cold	34	21 (14-27)	25 (18-33)	17 (8-29)	22 (10-32)	17 (7-29)	19 (7-33)	18 (14-27)	14 (9-31)	13 (2-32)	14 (7-27)	12 (4-30)	8 (1-23)
Tainan (18.8)	Hot	2	7 (4-13)	7 (4-10)	9 (4-16)	10 (5-16)	11 (5-20)	13 (7-22)	10 (5-17)	14 (5-25)	21 (11-42)	14 (6-24)	18 (8-29)	30 (16-52)
	Cold	36	18 (17-23)	29 (21-49)	18 (10-22)	21 (10-35)	21 (15-38)	23 (10-50)	20 (11-26)	15 (9-23)	15 (8-23)	15 (8-24)	15 (9-28)	10 (7-23)
Kaohsiung (27.7)	Hot	6	7 (3-16)	5 (3-7)	7 (3-19)	8 (4-19)	9 (3-20)	11 (5-20)	6 (3-12)	11 (5-24)	16 (9-33)	10 (4-22)	14 (7-25)	27 (13-55)
	Cold	10	5 (3-6)	7 (5-20)	3 (2-5)	6 (5-13)	5 (2-13)	6 (2-20)	5 (2-6)	5 (1-6)	2 (2-6)	3 (2-6)	5 (2-10)	2 (1-6)
Eastern Area (7.8)	Hot	2	2 (2-4)	5 (2-9)	6 (2-11)	5 (3-8)	6 (2-12)	9 (2-19)	5 (2-8)	11 (4-24)	17 (5-33)	7 (2-17)	16 (3-39)	25 (12-61)
	Cold	44	31 (20-45)	34 (27-51)	24 (14-45)	30 (10-46)	26 (11-51)	27 (11-58)	25 (16-41)	20 (13-61)	18 (4-52)	20 (8-48)	17 (6-43)	13 (1-44)

*The number was rounded to zero due to small calculated attributable mortality.

(b)

City/Area (population × 10^5)		2018	2021-2030			2031-2040			2041-2050			2051-2060		
			RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Taipei (4.6)	Hot	4	3 (2-5)	4 (2-5)	4 (2-8)	6 (4-12)	5 (3-8)	7 (3-14)	7 (3-10)	11 (6-18)	13 (7-25)	10 (4-20)	15 (8-23)	23 (10-37)
	Cold	26	32 (24-46)	36 (28-48)	28 (19-46)	45 (21-66)	39 (21-63)	41 (26-67)	51 (37-81)	40 (32-88)	35 (10-77)	46 (24-90)	41 (18-93)	32 (5-84)
New Taipei (5.4)	Hot	2	3 (2-5)	3 (2-5)	4 (2-7)	6 (4-11)	5 (2-7)	7 (3-13)	6 (4-8)	10 (4-17)	12 (6-22)	8 (3-19)	13 (6-21)	21 (8-34)
	Cold	27	29 (22-37)	31 (24-40)	24 (16-37)	36 (17-52)	33 (18-51)	33 (21-54)	42 (27-63)	34 (23-71)	27 (9-61)	38 (18-70)	32 (16-72)	24 (4-60)
Taichung (3.4)	Hot	1	4 (2-7)	4 (1-10)	6 (4-16)	8 (5-16)	8 (4-18)	12 (4-35)	10 (6-20)	19 (5-45)	23 (10-64)	18 (6-40)	27 (9-80)	49 (14-106)
	Cold	33	28 (19-35)	33 (25-44)	22 (11-38)	40 (19-58)	31 (13-53)	35 (13-59)	39 (31-61)	31 (20-69)	29 (6-71)	36 (19-66)	31 (10-73)	22 (2-57)
Tainan (2.8)	Hot	3	13 (6-23)	14 (7-17)	16 (7-28)	24 (12-38)	26 (11-46)	31 (17-51)	31 (15-46)	40 (17-71)	62 (34-119)	44 (21-74)	59 (27-93)	99 (56-164)
	Cold	18	13 (12-17)	21 (15-33)	13 (8-16)	21 (10-34)	21 (15-35	23 (11-47)	24 (15-30)	19 (11-27)	19 (9-27)	21 (12-32)	21 (14-36)	14 (9-29)
Kaohsiung (4.2)	Hot	4	5 (2-12)	4 (2-5)	5 (2-15)	8 (4-20)	8 (3-21)	12 (5-21)	8 (4-14)	13 (6-30)	21 (13-43)	16 (6-31)	20 (10-35)	38 (20-75)
	Cold	6	5 (3-6)	7 (5-13)	3 (2-5)	8 (6-14)	7 (3-14)	8 (3-17)	9 (4-10)	8 (1-10)	4 (3-9)	6 (4-12)	9 (4-15)	4 (1-10)

To assess the relative changes along the timeline among the cities/areas, we compared the projected AMs with those in 2018. Fig. 4 (a) displays the projected changes in heat- and cold-related AMs and net changes (sum of changes in heat- and cold-related AMs) per 100,000 people compared to those in 2018 for the general population over the next four decades. For convenience, the change bars are placed in the middle year of each decade (2025, 2035, 2045, and 2055). As shown in Fig. 4 (a), except for Kaohsiung, all the other cities and the eastern area were expected to have negative net changes in AM relative to the 2018 levels under RCP8.5 (Fig. 4 (a)). However, the net effect may be null or marginally negative considering variations in future population projections. Similar patterns with less substantial changes in AM were projected under the RCP2.6 and RCP4.5 scenarios (Fig. S3 (a), (c), SM).

Fig. 4 (b) shows the projected changes per 100,000 people for the elderly population. In contrast to the projected null or marginally negative net changes in AMs for the general population, the net changes in AMs were all positive. This is mainly because the changes in cold-related deaths were nearly null, whereas the number of hot days and the elderly population were both projected to increase over the next 4 decades. Tainan, in the south, was projected to have the most severe heat-related deaths and net changes under RCP8.5, followed by Taichung, in central Taiwan. The scale of net changes under RCP2.6 and RCP4.5 were less substantial, although there was still an overall positive net change across the cities (Fig. S3 (b), (d), SM). The tropical climate of Tainan was expected to still have a significant impact of heat-related AM and the net change under the controlled emission scenarios RCP2.6 and RCP4.5, likely mainly due to the growing proportion of the aging population.

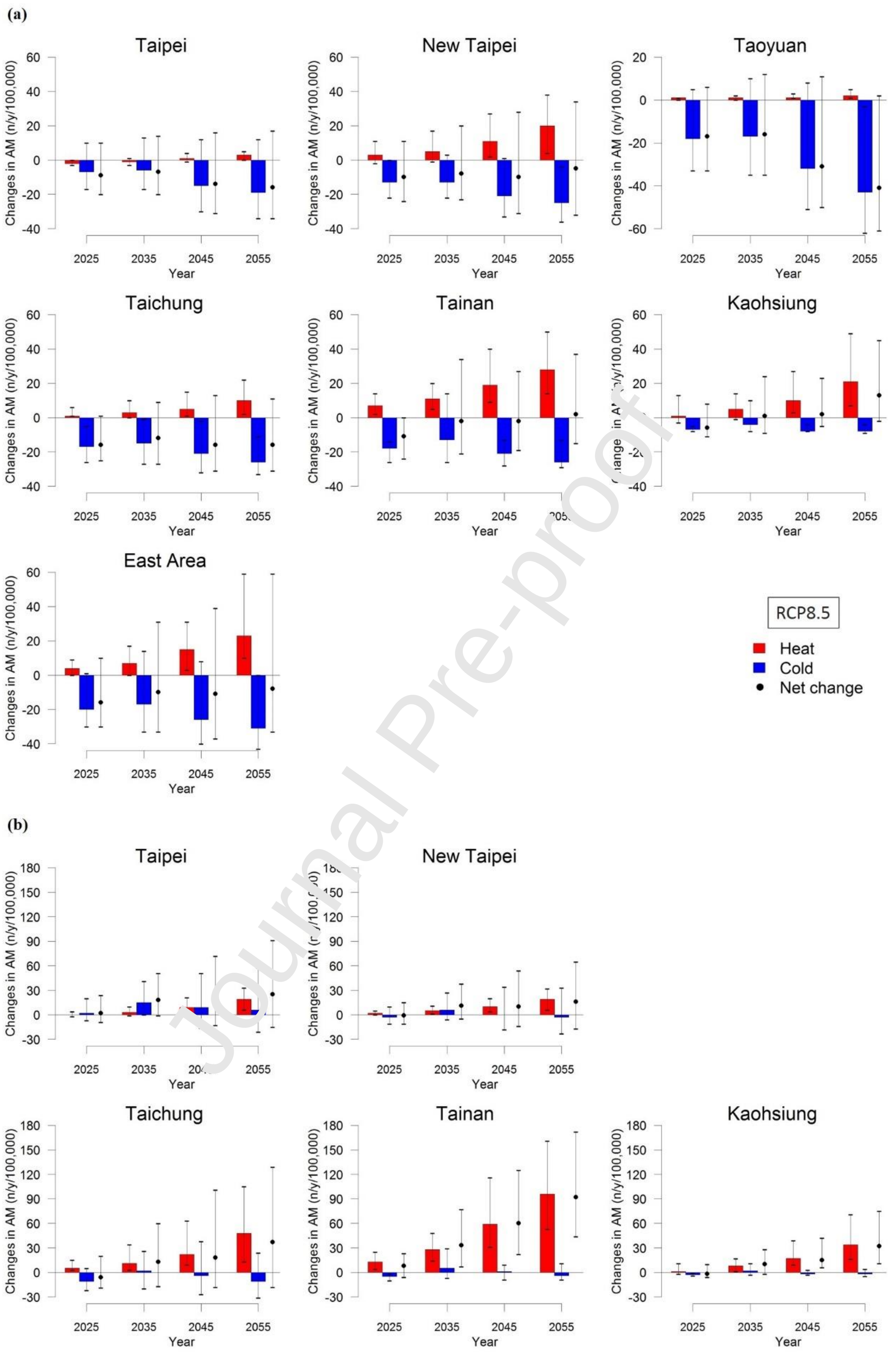

Fig. 4. Projected changes in the heat- and cold-related attributable mortality (AM) and net change (sum of temperature-related AMs) per 100,000 people compared to that in

2018 under the RCP8.5 emission scenario for: (a) the general population, and (b) the elderly population.

3.4. Degree of adaptation needed due to climate and population changes

Based on the projections under different RCP emission scenarios, we estimated the degree of adaptation needed for each city/area so that the future projected AMs would remain at approximately the same level as that in 2018. Because all the projected cold-related AM trends decreased, we assessed mainly heat adaptation. For simplicity, here, we defined an m% adaptation to be a reduction of m% for all the RRs exceeding the temperature threshold 30℃, which is essentially based on the assumption of a slope reduction of the exposure-response function for adaptation (Lee et al., 2019b; Gosling et al., 2017). Specifically, given an RR (>1), a reduction of m% is defined to be:

$$RR_m^* = 1 + \left(\frac{RR-1}{100}\right) \times (1 - m\%). \quad (7)$$

Thus, a degree of m% adaptation was obtained by replacing the modified RR_m^* in equations (4) and (5) with the adapted AM_m^*.

Fig. 5 shows the estimated degree of adaptation needed for each city/area under different RCP scenarios over the next 4 decades based on the AMs per 100,000 people listed in Table 2, allowing the adjusted AM_m^* to be comparable with that in 2018. The results showed that, for the general population (Fig. 5 (a)), Taipei and Taoyuan would observe the lowest impact on mortality due to global warming and thus could serve as role models of adaptation (null to medium 40%) for other cities/areas. The estimated magnitudes of adaptation for New Taipei and Kaohsiung were approximately the same level, with a need for high adaptation (61% to 80%) starting in the mid-century. However, Taichung and the eastern area would need a high degree of adaptation from 2041-2050 and an extremely high demand for adaptation (81% to 100%) from 2051-2060. A well-developed adaptation plan is urgently needed, especially for Tainan in southern Taiwan, which would face the immediate challenge of a high degree of adaptation from 2021-2030.

Accounting for the rapid growth of the aging population, there is a severe demand for extremely high adaptation in all the cities investigated under RCP8.5 from 2051-2060 (Fig. 5 (b)). Immediate adaptation plans and strategies need to be developed for Taichung and Tainan, which already face high adaptation requirements from 2021-2030 under all the emission scenarios. Similar challenges will be faced in Taipei, New Taipei, and Kaohsiung after two more decades from 2041-2050 under RCP4.5 and RCP8.5.

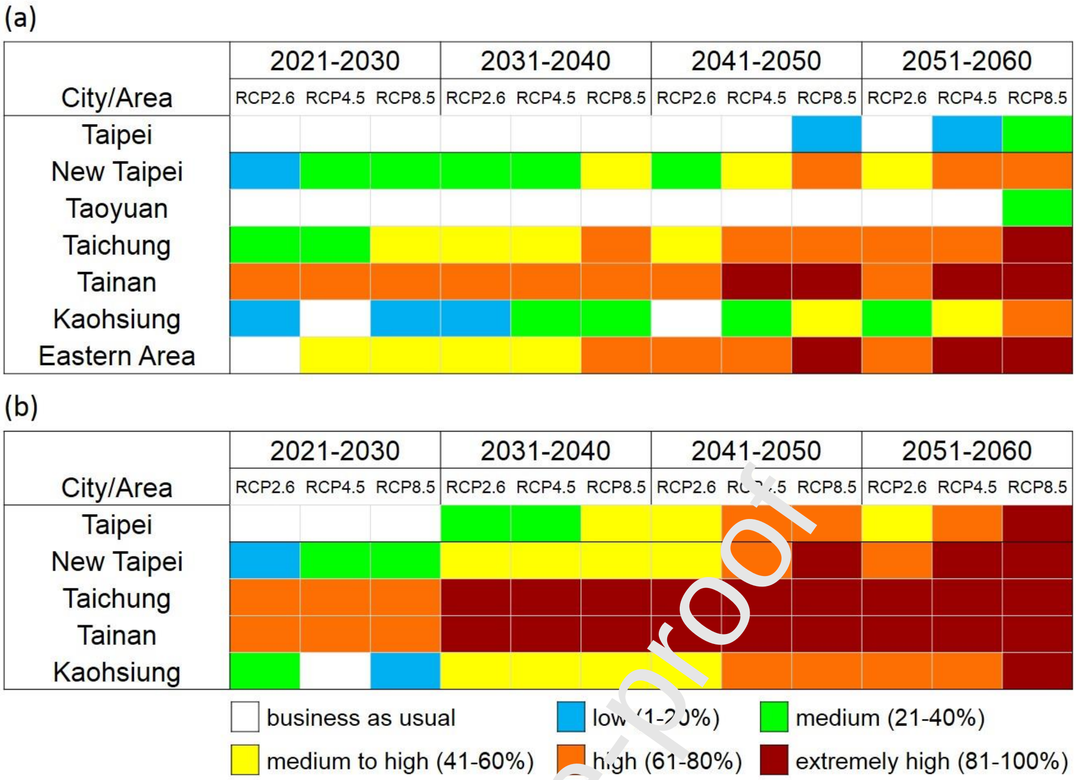

Fig. 5. Degree of adaptation to heat necessary for each city/area to remain at the same level of AM in 2018 under different RCP scenarios for: (a) the general population, and (b) the elderly population.

4. Discussion

In this study, we showed that there are spatiotemporal variations in projected temperature extremes and temperature-related mortality due to climate change in areas with heterogeneous demographic structures and climate zones in Taiwan. As a result, different scales and schedules of adaptation are needed for each city/area under various emission scenarios along the timeline. The annual number of hot days with a mean temperature ≥30°C was predicted to have a substantial 2- to 5-fold increase throughout the residential areas of Taiwan by the end of 2060 under RCP8.5, especially in the south, which has a tropical climate. In contrast with the increase in the number of hot days, the decrease in the number of cold days was less apparent. For attributable mortality, the decrease in cold-related deaths was projected to outweigh that of heat for the next two decades. However, starting from 2045 to 2055, a crossover was expected, with heat-related mortality drastically increasing and surpassing cold-related mortality. Adjusting for the projected decrease in population size, the percentage increase in heat-related deaths per 100,000 people could be more than 10-fold under the worst-case scenario (RCP8.5), except in northern Taiwan.

As indicated in a global study, most temperature-related mortality is attributable to cold (Gasparrini et al., 2015). Because summer in Taiwan is generally hot and humid and is long-lasting, residents of the island have become adapted to such a climate, and the use of air conditioning is very prevalent. In contrast, winter is relatively warm and short, and very few households have installed heating; thus, elderly people and cardiovascular patients are especially vulnerable to cold fronts. As a result, the RRs of cold-related deaths were higher than those due to heat (Table S1, SM), and the net health impacts of AM were projected to be null or marginally negative in the near future until 2045-2055. However, followed by the increase of global warming, heat-related mortality was projected to drastically increase and surpass cold-related mortality around the middle of the century (Fig. 3). The projected increase in the heat-related death rate under a high emission scenario by mid-century was also consistent with other studies (Martinez et al., 2018; Weinberger et al., 2017; Zhang et al., 2018).

We showed that the projections were somewhat different for the cities of Taipei and Kaohsiung, which are in the north and south, respectively (Fig. 3). Because Taipei is the capital and the most urbanized city in Taiwan, summer in the Taipei Basin is hotter than in other cities due to the large urban heat island effect (Table 1) (Bai et al., 2011). However, most citizens of Taipei live in air-conditioned apartments or buildings and have access to the most advanced and effective medical treatments. As a result, the reported RRs were less than 1, even as the daily mean temperatures exceeded 32℃ (Table S1, SM). The projected decrease in cold-related mortality was most significant by the end of 2060, whereas the change in heat-related mortality remained null. In contrast, as a metropolitan area located in the south with a tropical climate, Kaohsiung exhibited an entirely opposite picture; projected heat-related deaths increased by 3-fold by the end of 2060, whereas the level of cold-related deaths remained approximately the same because of the small number of cold days. Interestingly, the distinct patterns of different cities were consistent with the projections for both northern Europe and East Asia, with a large decrease in cold-related excess mortality and Southeast Asia, with a sharp surge in heat-related impacts globally by the end of the century (Gasparrini et al., 2017).

Elderly individuals who are older than 65 years of age are known to be especially vulnerable to climate change because of their generally higher prevalence of chronic health issues, such as cerebrovascular and cardiovascular diseases and diabetes (Gamble et al. 2013, Bunker et al., 2016). Elderly individuals also tend to be socially isolated with difficulty in financial status. All these physiological, psychological, and socioeconomic factors contribute to their vulnerability and sensitivity to extreme heat (Gamble et al., 2013). The elderly population in Taiwan was 14% in 2018, and the percentage is expected to exceed 20% in 2025, making Taiwan a superaged society, and 40% by 2065 (NDC, 2020). We projected the numbers of AMs and AMs per 100,000 people in Fig. 3 (b) and Table 2 (b), and the net changes in Fig. 4 (b). The decreases in cold-related AMs were relatively flat for all cities/areas, whereas the heat-related AMs consistently monotonically increased due to the aging population. As a result, the overall net changes in AMs were positive, with Tainan in southern Taiwan projected to experience the most severe impact.

To be comparable with the heat-related AM level in 2018, we estimated the degree of adaptation needed for each city/area under various emission scenarios by using the slope reduction method, which was supported by an epidemiological study in South Korea (Fig. 4, Lee et al., 2019b). The results showed that there is, in general, a need for moderate adaptation over the next two decades for the general population, and a need for high adaptation in Tainan, southern Taiwan. This picture might be overly optimistic, as it does not account for the aging population. Fig.5 (b) shows that, when considering elderly individuals, there would be a need for extremely high adaptation in all the cities by 2060 under RCP8.5. For Taichung and Tainan, there is already a need for a high degree of adaptation from 2021-2030 and an extremely high degree starting from 2031.

The current study adopted the RR estimates to temperature extremes based on mortality data in 1994-2008 (Lin et al., 2011; 2019), which might have overestimated the AM impacts. Studies on temperature-attributable mortality over long observation periods have shown a decrease in health impacts due to heat over the past decade (Bobb et al., 2014; Gasparrini et al., 2015). Furthermore, Vicedo-Cabrera et al. (2018) found that the decrease in heat-related mortality was well beyond that expected from pure adaptation. A previous study also showed that there was a 43% slope reduction when comparing the curve of RRs over 30℃ from 2006-2015 with that from 1991-2000 (Lee et al., 2019). It is possible that individuals might be gradually becoming more adapted to heat, and public health policies might further help to mitigate heat-related impacts due to climate change.

Our study outcomes suggest that there are still approximately 10-20 years remaining before crossover to escalating heat-related mortality in major municipalities in Taiwan (Fig. 3). However, some cities will already face the challenge of high adaptation starting in 2021, accounting for the aging population, especially Taichung and Tainan in central and southern Taiwan (Fig. 5). To accomplish the magnitude of adaptation, individuals may adapt spontaneously, such as via physiological acclimatization or wearing appropriate clothing, during hot days (Arbuthnott et al., 2016; Gosling, et al., 2017). Planned adaptation may also be developed at the government or city level, such as the introduction of heat-health warning systems, the introduction of government subsidies to increase air conditioning installations, improved building design such as ACROS with vertical greening and green roofs to be more heat resilient, and urban greening to avoid heat exposure (Arbuthnott et al., 2016; Gosling, et al., 2017; Mabon et al., 2019). Strategies such as interventions to reduce medical vulnerability, improve the treatment of heat-related morbidity, and provide shelter or arrange home visits to vulnerable populations may also be developed (Gosling et al., 2017; Paz et al., 2016). In a case study in California, general principles such as mainstreaming and a population perspective were suggested as guidance to help public health policymakers mitigate the health impacts of climate change (Ganesh and Smith, 2018). Other mitigation and adaptation strategies may include heat response plans (Weinberger et al., 2017), early action through urban land use planning (Xu et al., 2019), and establishment of mangrove blue carbon stocks through vegetated coastal ecosystems at the national scale (Taillardat et al., 2018).

In this study, AMs were projected until 2060 rather than until the end of the century, as in many other studies. However, even within a relatively short 4-decade timespan, the study outcomes show significant changes and health impacts and indicate an urgent need for well-planned adaptation in some cities (Figs. 2-5). Additionally, the current reliable population projections by the Taiwan Development Council cover the period until 2065 (TDC, 2020). There is great uncertainty surrounding long-term demographic changes. After adjusting for future population projections and the elderly population, the changes in cold- and heat-related mortality per 100,000 people and net changes were even more significant, especially in central and southern Taiwan (Table 2 and Fig. 4). Considering the rapid growth of the elderly population, adaptation planning at both the government and city levels should be actively developed.

We adopted fixed temperature thresholds of 15℃ and 30℃ for each city/area instead of relative thresholds. The rationales behind these thresholds are as follows: i) the island of Taiwan is relatively small compared to mainland continents, such as Mainland China and North America. Thus, fixed temperature thresholds should be sufficient; ii) there is not much difference in health effects across different cities/areas in Taiwan (Table S1, SM and Fig. 3 of Lin et al., 2019); and iii) it is more straightforward to present and discuss the study outcomes with fixed temperature thresholds rather than relative thresholds for each city/area. We performed future temperature projections for each city/area based on the downscaling outcomes of the station(s) located at population-dense locations in the city/area. The resulting resolution is thus approximately from 10× 10 to 20×20 square kilometers. Because temperature variations within such a small area could be negligible, uncertainties might not be a serious issue for the present study.

This study had several novel strengths. We downscaled 8 CMIP5 climate models for each of the 42 meteorological stations followed by BMA of the model ensemble. Fig. S1 shows that the CDFs of the observed data and those based on the historical run of the ensembled climate model were very close to each other for the cities investigated under different RCP scenarios. The variations in the 8 CMIP5 models were also fully represented, as shown in Table 1. Previous studies have used downscaled temperature projections from other sources without related information on specific regional changes in temperature extremes. Thus, it may be difficult to develop public health strategies to mitigate the possible impacts on attributable mortality. Second, city/county-specific RRs per degree Celsius (Lin et al., 2011; 2019) were used to calculate the future projections of mortality attributable to temperature extremes, which allowed us to completely capture the heterogeneity in local climate adaptations and in the demographic structures of different cities. Third, the study outcomes showed distinct patterns of projected mortality due to temperature extremes in the main metropolitan areas in different climate zones in Taiwan. Furthermore, the time schedule for the crossover to predominantly heat-related mortality from predominantly cold-related mortality varied by city. Finally, we estimated to what extent adaptation to heat is needed for each city/area under various emission scenarios up to 2060. These detailed, informative study outcomes can be used to provide local governments with information to develop effective adaptation strategies according to the projected time schedule.

Some limitations must be acknowledged in this study. First, the RRs we adopted were based on mortality data for all ages from 1994-2008 (Lin et al., 2011; 2019). We assumed that the RRs for temperatures exceeding (or below) the temperature extremes of the current observed epidemiological study outcomes of the city/area would remain at the same level (Table S1, SM). The health impacts beyond the observed temperature extremes are unknown at this point. Alternatively, the projected AMs might be overestimated due to adaptations or public health strategies that could mitigate the health impacts. As shown in some epidemiological studies (Lee et al., 2019; Vicedo-Cabrera et al. 2018), there has been a decrease in the impacts of heat mortality over recent decades in different populations. The heat-related mortality rates might be lower than the projections obtained in the current study. Second, we considered AMs below the 15℃ and over the 30℃ temperature thresholds only. It is well-known that AMs are also associated with temperatures over 15℃ and below 30℃. Furthermore, days with sub-optimal mean temperatures occur much more often compared to days with temperature extremes. Thus, the projected temperature-related mortalities were underestimated, especially for days with chilly temperatures but over 15℃. Because of the major concern of global warming and less-significant health effects below 30℃ (Lin et al., 2011; 2019), this might not be of serious concern.

5. Conclusions

Located in the middle of East Asia with areas consisting of both subtropical and tropical climates, the future distributions of temperature extremes and AM were projected to be spatial- and time-dependent across cities of different climate zones in Taiwan during 2020-2060. The annual number of hot days was projected to have a substantial 2- to 5-fold increase under the RCP8.5 emission scenario. Compared to the extreme temperature-attributable mortality in Taiwan in 2018, the AM projected appeared to have a negative net effect due to climate change in the near future before switching to a net positive effect from 2045-2055. However, there was an overall positive effect and a consistent increasing trend for elderly individuals under all the emission scenarios. Southern Taiwan (Tainan in particular, which has a tropical climate) may suffer the most heat-related mortality. Before the surge in heat-related mortality, there are still approximately 10 to 20 years to develop public health policies, such as increasing greenness with more plants for urban land use planning, to mitigate potential health impacts due to climate change. Local governments in different climate zones may need to adopt adaptation strategies according to their projected time schedules.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contributions

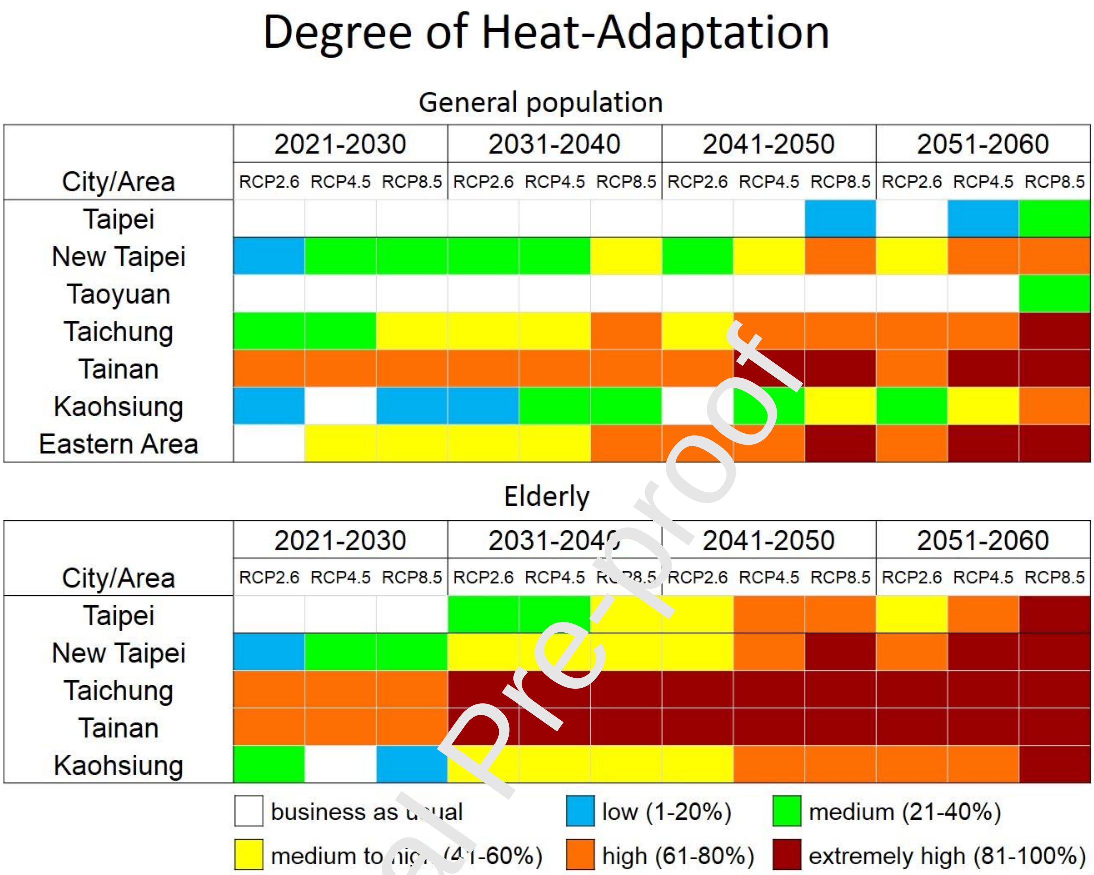
Chu-Chih Chen: Conceptualization, Methodology, Visualization, Writing, Review & Editing. **Yin Ru Wang**: Data curation, Software, Validation. **Yu-Chun Wang:** Data curation, Investigation. Shiou-Li Lin: Software. **Cheng-Ta Chen**: Software, Validation. **Mong-Ming Lu**: Review. **Yue-Liang L. Guo**: Project administration, Supervision, Review.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical abstract



Highlights

- Spatiotemporal differences across areas of sub-tropical and tropical climate zones
- A substantial 2- to 5-fold increase in hot days over 30℃ under RCP8.5 by 2060
- Cold-related mortality outweigh that of heat prior to 2045
- A crossover of heat-related mortality surpasses that of cold in 2045-2055
- Southern Taiwan of tropic climate has the most severe health impacts in mortality