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Net impact of air conditioning on heat-related mortality in Japanese cities

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ABSTRACT

Background: Air conditioning (AC) presents a viable means of tackling the ill-effects of heat on human health. However, AC releases additional anthropogenic heat outdoors, and this could be detrimental to human health, especially in urban communities. This study determined the excess heat-related mortality attributable to anthropogenic heat from AC use under various projected global warming scenarios in seven Japanese cities. The overall protection from AC use was also measured.
Methods: Daily average 2-meter temperatures in the hottest month of August from 2000 to 2010 were modeled using the Weather Research and Forecasting (WRF) model with BEP+BEM (building effect parameterization and building energy model). Risk functions for heat–mortality associations were generated with and without AC use from a two-stage time series analysis. We coupled simulated August temperatures and heat–mortality risk functions to estimate averted deaths and unavoidable deaths from AC use.
Results: Anthropogenic heat from AC use slightly augmented the daily urban temperatures by 0.046 °C in Augusts of 2000–2010 and up to 0.181 °C in a future with 3 °C urban warming. This temperature rise was attributable to 3.1–3.5 % of heat-related deaths in Augusts of 2000–2010 under various urban warming scenarios. About 36–47 % of heat-related deaths could be averted by air conditioning use under various urban warming scenarios.
Discussion: AC has a valuable protective effect from heat despite some unavoidable mortality from anthropogenic heat release. Overall, the use of AC as a major adaptive strategy requires careful consideration.

1. Introduction

High levels of ambient heat adversely affect human health, especially amongst vulnerable populations. For example, hot temperatures may exceed the physical limits of individuals with pre-existing medical conditions (e.g., cardiovascular and respiratory ailments), leading to severe ailments or death (Beker et al., 2018). In the very young and old, age-related thermoregulation limitations prevent sufficient adaptation to extreme heat. Physical and mental impairment can also reduce a person's capacity to respond and adapt to very high temperatures (Ebi et al., 2021). For people who spend extensive periods of time outdoors, such as workers in certain industries and athletes, extreme heat can overwhelm their body's thermoregulatory capacity, potentially leading to internal overheating and heat stroke (Ramphal-Naley, 2012).

Several global-scale epidemiological studies have determined the heightened risk of mortality from extreme temperatures, heat waves, and summertime heat (Gasparrini et al., 2016; Gasparrini et al., 2015; Guo et al., 2017). Given this serious risk, the expected future rise in temperatures as a result of climate change could lead to significant numbers of additional heat-related deaths. These are likely to be the highest under a high greenhouse gas emissions scenario (i.e., Representative Concentration Pathway 8.5) (Collins et al., 2013), wherein excess heat-related deaths (2090–99 vs 2010–19) and heat wave-related deaths (2031–2080 vs 1971–2020) could reach up to 26 % and 136 %, respectively (Gasparrini et al., 2017; Guo et al., 2018).

As a means of preventing heat-related illness, air conditioning (AC) use allows and maintains cool indoor temperatures, helping reduce exposure to ambient heat (WHO, 2018). Evidence of reduced heat-related mortality risk in households with AC has been reported in several studies. In one county in Arizona, households with AC had a

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lower risk of mortality from internal causes (e.g., cardiovascular, respiratory, and kidney-related problems) during periods of hot temperatures than households without AC (Eisenman et al., 2016). Similarly, districts in Madrid where a high proportion of households have AC exhibited a lower risk of heat-related deaths than districts where a high proportion of households do not have AC (Lopez-Bueno et al., 2020). In several Chinese provinces, annual heat-related death rates were observed to decrease as household AC prevalence increased (Li and Gu, 2020). A multi-country study covering Canada, the USA, Spain, and Japan showed similar reductions in summertime heat-related death risk with increasing household-level prevalence of AC (Sera et al., 2020).

AC also has negative effects on the environment. Apart from the additional greenhouse gas emissions from the energy required to cool the indoor environment (Dong et al., 2021), AC units release anthropogenic heat from cooling spaces/rooms to the outdoor environment (Kikegawa et al., 2003; Ohashi et al., 2007; Salamanca et al., 2014). This can be a significant problem in cities because of their densely built-up environments, which absorb and retain heat. Thus, ACs contribute to the urban heat island phenomenon, which is characterised by hotter urban temperatures compared with neighbouring non-urban areas (Oke et al., 2017). This cascading urban warming from anthropogenic (i.e., human-induced) causes, including AC use and global warming, could lead to a "positive feedback" process that increases urban temperatures (Takane et al., 2017; 2019; 2020; Kikegawa et al., 2022). Takane et al. (2019) estimated that the positive feedback from AC use together with a + 3.0 °C rise in global temperatures could result in 8 % additional heat in residential areas of Osaka City, the second largest city in Japan. This added heat from AC use would considerably increase the heat stress experienced by the city's inhabitants (Takane et al., 2020). Moreover, Kikegawa et al. (2022) estimated an increase of 10 % in daytime temperatures in downtown commercial areas of Osaka from the positive feedback associated with AC use. These studies suggest that AC use has a non-negligible influence and creates positive feedback to the urban climate.

With rising sales of AC units for residential use (IEA, 2018), and the projected future rise in the intensity and frequency of heat events (Seneviratne et al., 2021), there is a need to measure the health benefits of AC. This analysis should take into account its negative effects to holistically evaluate and justify the future use of AC as a heat-adaptation option. Several studies have considered the health effects of additional air pollution from AC (Abel et al., 2018; Kouis et al., 2021), but none has considered the additional heat from AC units, which cannot be wholly avoided using clean and renewable energy. In this study, we investigate the net effect of AC use on heat-related mortality during the hottest month of August by considering the anthropogenic heat produced from AC use in selected Japanese cities.

2. Methods

2.1. Study sites

We selected seven Japanese cities, namely Osaka, Sakai, Kobe, Kyoto, Nara, Otsu, and Wakayama (Fig. 1). These are the capital and most populated cities of seven prefectures in the Kansai Region.

2.2. Modelling approach

We separately modelled urban temperatures and mortality risk functions. We then combined these modelling outputs to estimate the heat-related deaths attributable to AC use and its anthropogenic heat released in the environment (Fig. 2).

2.2.1. Simulated 2-m temperatures from an urban climate model

The simulated 2-m temperatures used in this study are based on the previous work of one of the study authors (Takane et al., 2019). In this section, we only describe the essential model descriptions and settings. For a detailed explanation of the modelling, readers are referred to the previous study (Takane et al., 2019).

The urban climate model used was the building effect parameterisation and building effect model (BEP + BEM) (Salamanca et al., 2010; Takane et al., 2017; 2019), widely used in the urban climate research community. The BEP + BEM can simulate the anthropogenic heat from AC use for cooling space/rooms (H_{AC}), which was calculated using the following equation:

$$H_{AC} = (SH_{out} + LH_{out}) + EC = \frac{COP + 1}{COP}(SH_{out} + LH_{out})$$

where SH_{out} and LH_{out} denote the sensible and latent heat loads from the

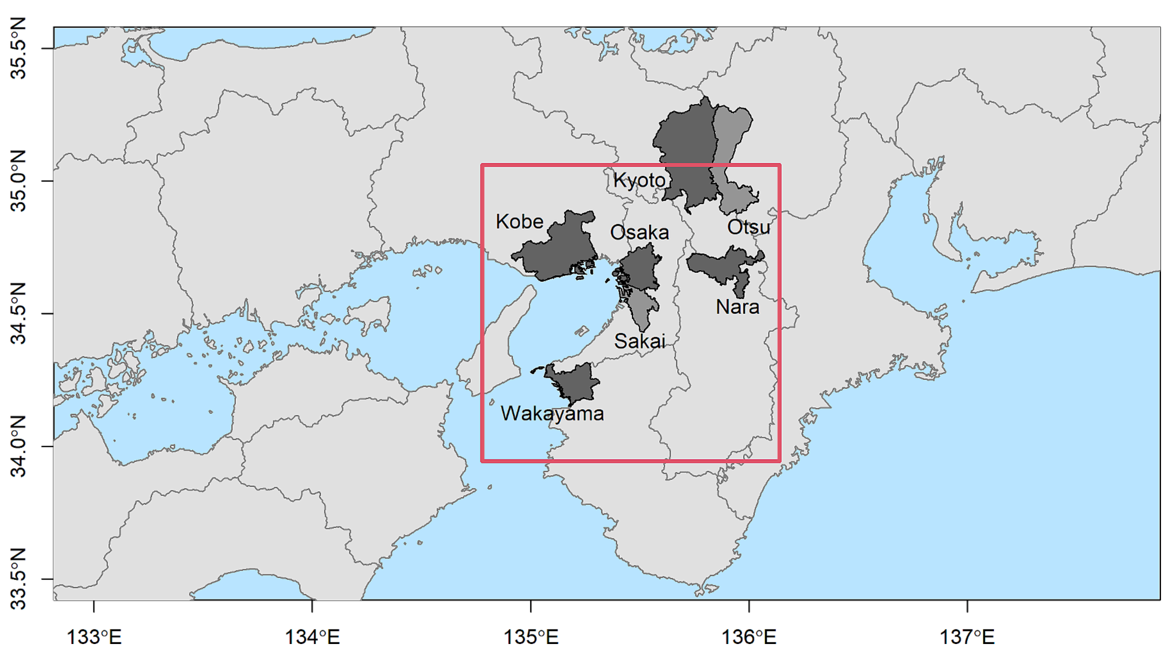

Fig. 1. Selected cities in Kansai, Japan. Dark grey polygons are administrative boundaries of the selected cities, and the red box is the boundary of the simulated outdoor temperatures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

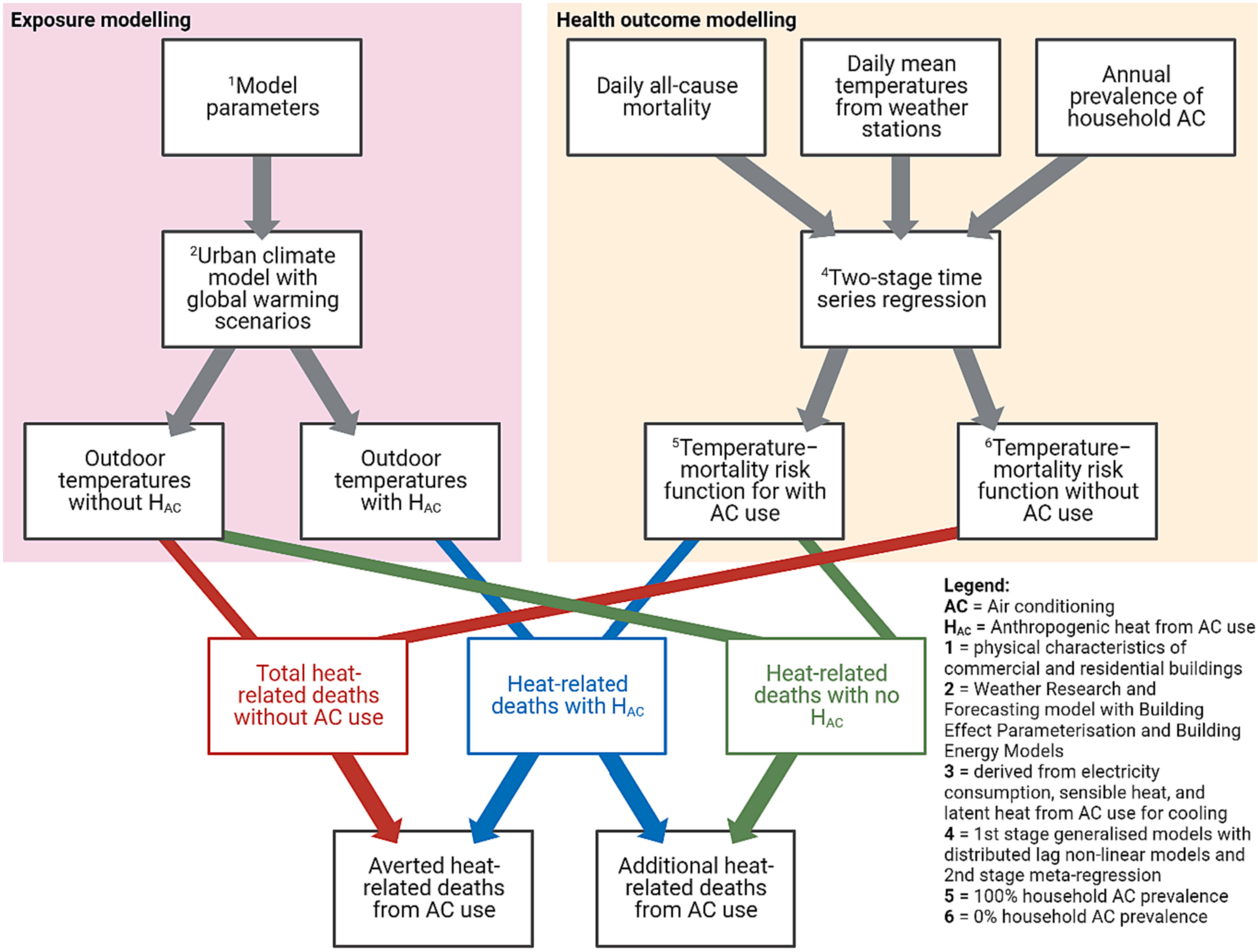

Fig. 2. Diagram of the modelling process. The purple section (left side) summarises the simulations of 2-metre temperatures and the yellow section (right side) summarises the modelling of heat–mortality risk functions. The red, blue, and green boxes are estimated heat-related deaths based on specific combinations of simulated temperatures and risk functions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

AC system for cooling, *COP* is the fixed coefficient of performance, and *EC* is the electricity consumption. The anthropogenic heat from the AC system were calculated from the total sensible and latent heat loads per building floor. The BEP + BEM model came with the following assumptions: (1) existence of individual AC units, (2) fixed or constant COP, (3) no anthropogenic heat from traffic, and (4) weekday conditions only. To simulate zero H_{AC}, the H_{AC} value was assumed to be 0 Wm^{-2}. The change in urban temperatures with no H_{AC} was aligned with the change in global warming temperatures.

The BEP + BEM was implemented through the Advanced Research Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) to simulate the "positive feedback" process of cascading urban heat explained in the introduction. The model domain for the WRF-BEP + BEM covered a portion of Kansai Region (Fig. 1) with 126 horizontal grid cells at 1-km resolution. The top of the model was located at 50 hPa with 35 vertical sigma levels and 50-m distance to the ground (WRF atmospheric first-layer height). The horizontal grid cells were classified as commercial and business, residential with fireproof apartments, or residential with wooden detached dwellings. Only the horizontal grid cells of Osaka City included the commercial and business, and residential with fireproof apartments categories, with the other grids categorised as residential with wooden detached dwellings. H_{AC} was simulated in each model grid cell.

As initial boundary conditions for the WRF-BEP + BEM is required, we used the climate simulations in August from 2000 to 2010 derived from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al., 1996) along with merged satellite and in situ global daily sea surface temperature (MGDSST) data (Kurihara et al., 2006). For climate simulations with global warming, we generated modified NCEP–NCAR and MGDSST data by changing atmospheric variables, such as, long-wave radiation.

Six future climate scenarios were simulated with background temperature increases relative to the current climate (global warming: +0.5, +1.0, +1.5, +2.0, +2.5, and + 3.0 °C). These were based on the ensemble mean results from four general circulation models used in the Climate Model Intercomparison Project 5 (CMIP5) (Taylor et al., 2012), namely CCSM4 (Gent et al., 2011), CESM1 (CAM5) (Meehl et al., 2013), GFDL-CM3 (Donner et al., 2011), and INM-CM4 (Volodin et al., 2010). However, the ensemble means of only three models (CCSM4, CESM1, and GFDL-CM3) were used for the + 3.0 °C global warming scenario, because INM-CM4 did not reach + 3.0 °C at 2100. The simulations considered the highest greenhouse gas emissions scenario of Representative Concentration Pathway 8.5. The outputs of the WRF-BEP + BEM were validated against observed 2-m temperatures and electricity consumption.

Hourly 2-m temperatures were aggregated into daily averages (Japan Standard Time) on each 1-km grid. Grids corresponding to the seven study sites were extracted based on shapefiles obtained from the Ministry of Land, Infrastructure, Transport and Tourism (https://nlftp.mlit.go.jp/). To determine suitable population weights for the study sites, gridded 2015 population data obtained from the Climate Change Adaptation Information Platform (A-PLAT) of the National Institute of Environmental Studies (https://adaptation-platform.nies.go.jp/socioeconomic/population.html/) was bilinearly re-sampled from 5 km to 1 km to align the grids with the gridded temperature data. Population-weighted daily temperatures for each of the seven cities were derived from the weighted means of the daily gridded temperatures and the re-sampled population grids. In comparison with weather station data, the simulated temperatures were lower across the seven study sites. To calibrate the simulated temperatures with H_{AC} to be similar with the weather station temperatures, additive linear scaling was performed that used the difference between the simulated and weather station temperatures. To preserve the temperature differences between with and without H_{AC} temperatures, the differences between daily temperatures with and without H_{AC} were subtracted to the calibrated temperatures with H_{AC} (Fig. S1).

2.2.2. Risk functions for summertime temperature–mortality associations

Daily counts of all-cause mortality from 52 Japanese cities between 1 January 1976 and 31 December 2009 were collected from the Japan Ministry of Health, Labour, and Welfare. Daily mean air temperatures (°C) on the same dates as the daily mortality statistics were collected from 47 Japan Meteorological Agency weather stations, mostly located in the capital cities of each prefecture. Forty-seven (47) prefectural annual prevalence of AC in households with at least two members from 1976 to 2009 were collected from the Asahi Shimbun (Asahi Newspaper Publishing).

In the 52 selected Japanese cities, the daily mortality data were matched with daily mean temperatures from the nearest meteorological station (Fig. S2 and Table S2) over the summer months of June–September. The dataset was split into sub-periods of 1976–1979, 1980–1984, 1985–1989, 1990–1994, 1995–1999, 2000–2004, 2005–2009. Two-stage time series analysis was performed to estimate the associations between summertime temperature and mortality (Sera et al., 2020).

In the first stage, the nonlinear lagged associations between daily summertime temperatures and mortality were estimated using a quasi-Poisson generalised linear model to account for overdispersion combined with a distributed lag nonlinear model by city and period:

$$ln[E(Y_t)] = \alpha + s(T_{t,l};\theta) + f(t, I;\beta) + \gamma MT_{t,l} + \lambda DOW$$

where $E(Y)$ is the expected daily mortality on day t; α is the intercept; s is the cross-basis function of temperature T and lag l, which represents the exposure–response relationship using a natural cubic B-spline function with two internal knots at the 50th and 90th percentiles of the temperature distributions, and the lag–response relationship using an unconstrained parameterisation of 0–2 days lag (Sera et al., 2020); f is the natural cubic B-spline function of day t with four degrees of freedom of the day including interaction with the indicators of year I to control for seasonality and long-term trends (Gasparrini et al., 2016); linear interactions between the midpoint of August M and the cross-basis variables are included to estimate the coefficients representing the exposure–lag–response association for August (Gasparrini et al., 2016); DOW is the indicator variable of the day of the week; and θ; β; γ, and λ denote the parameters of estimation. To reduce the dimensionality prior to the second stage, nine coefficients derived from the cross-basis function were reduced to unidimensional summary specifically to three coefficients that model the overall cumulative exposure–response relationship.

In the second stage, the city- and period-specific coefficients were pooled using a multilevel and multivariate *meta*-regression with restricted maximum likelihood estimation:

$$\theta^*_{i,j} = X_{i,j}\beta + Z_i b_i$$

where θ^* is the unidimensional coefficient for city i and period j; X is a matrix of fixed effect predictors which included continuous variables of period-specific calendar-year (mid-point), average temperatures, interquartile range of temperatures, and AC prevalence; and Z is a random city-specific terms with a random coefficient b, which have unstructured (co)variance matrices.

Using the *meta*-regression model, two temperature–mortality risk functions were derived for the theoretical lowest household AC prevalence of 0 % (*AC0*) and highest AC prevalence of 100 % (*AC100*). Zero AC prevalence was selected to simulate the scenario without H_{AC}. However, 0 % and 100 % AC prevalence were not recorded in any of the 52 Japanese cities from 1976 to 2009. The lowest AC prevalence was 1 % and the highest AC prevalence was 98 % (Fig. S3). The other *meta*-predictors were fixed at the latest calendar-year of 2007 (representing 2005–2009) and overall mean of the average and interquartile range of temperatures across 52 cities. The minimum mortality temperature (MMT), which represents the temperature with the lowest temperature–mortality risk, was derived from the *meta*-regression model, with the selection restricted between the 1st and 99th temperature percentiles.

2.2.3. Heat-attributable mortality calculation

The numbers of excess deaths attributable to heat in August were derived for the seven study sites by combining the modelled temperatures and risk functions without considering population changes and adaptation:

$$Y_{attr} = Y_{mod} \times \left\{ 1 - exp^{-\left[s^*(T_{mod};\theta^*) - s^*\left(T_{ref};\theta^*\right)\right]} \right\}$$

where Y_{attr} is the number of heat-related deaths; Y_{mod} is the average number of daily deaths in August based on historical data (2000–2009); s^* and θ^* are the overall cumulative coefficients from the *meta*-regression; T_{mod} is the modelled temperatures in August for 2000–2010 under a given global warming scenario; and T_{ref} is the reference temperature based on MMT. Heat-related mortality was calculated by summing the daily attributable deaths corresponding to days with temperatures above MMT.

Three types of excess heat-related deaths were calculated through varying combinations of simulated temperatures and risk functions: (1) heat-related deaths considering H_{AC}, referred to as $mort_{w/HAC}$, were calculated by combining temperatures with H_{AC} and *AC100* risk function; (2) heat-related deaths without considering H_{AC}, referred to as $mort_{w/oHAC}$, were calculated by combining the modelled temperatures without H_{AC} and the *AC100* risk function; and (3) the theoretical total, referred to as $mort_{noAC}$, was the combination of modelled temperatures without H_{AC} and the *AC0* risk function. The total number of heat-attributable deaths was the sum of all days in August over the period 2000–2010 under a given global warming scenario. Empirical 95 % confidence intervals that quantify the uncertainties of excess deaths from the risk function were derived using 1000 Monte Carlo simulations.

To calculate the theoretical excess heat-related deaths attributable to H_{AC}, $mort_{w/HAC}$ was subtracted from $mort_{w/oHAC}$. To calculate the theoretical number of heat-related deaths averted by AC use, $mort_{noAC}$ was subtracted from $mort_{w/HAC}$. Simple propagation error was used to estimate the 95 % confidence intervals. The deaths attributable to the positive feedback between H_{AC} and global warming were estimated by subtracting $mort_{w/oHAC}$ under a given global warming scenario (+0.5–+3.0 °C) from $mort_{w/oHAC}$ under the + 0.0 °C scenario (current climate).

2.2.4. Sensitivity analyses

To review the sensitivity caused by different model specifications for the risk functions, the statistical analysis used to estimate the risk function was repeated for both stages. In the first stage, sensitivity analysis was performed by (1) changing the exposure–response knots, (2) increasing the maximum lag up to 7 days, (3) reducing the number of degrees of freedom per summer, (4) excluding Sapporo because of its extremely cold weather and very low household AC prevalence, and (5) adding relative humidity as a cross basis (linearly modelled with a lag of up to 2 days). For the second stage, sensitivity analysis included (6) removing temperature related *meta*-predictors, (7) linear modelling of the year, (8) adding the regional location of the cities, and (9) switching the lowest AC prevalence from the historical lowest values. We also switched the AC prevalence for temperature–mortality risk functions from 0 % and 100 %, respectively, to the lowest and highest recorded AC prevalence, respectively, for each study site (Table S3). We applied these risk functions to re-calculate the heat-attributable mortality. The summary and results of the sensitivity analyses are presented in the supplementary.

2.3. Software

The urban climate modelling and simulations were performed using the WRF model (version 3.5.1) (Skamarock et al. 2008, https://www2.mmm.ucar.edu/wrf/). All analyses for the estimation of heat-related mortality were performed using the R software for statistical computing (version 4.2.1) with the following packages: *hyfo* for bias-correction of modelled temperatures with observed temperatures, *splines* for modelling natural cubic splines, *dlnm* for the first stage modelling, and *mixmeta* for the *meta*-regression.

3. Results

3.1. Urban temperatures from AC use

The overall average August temperatures with and without H_{AC} are 28.28 °C and 28.23 °C, respectively, under + 0.0 °C global warming (Fig. 3; Table S4). Osaka and Sakai have the highest temperatures among the study sites. The average temperature difference with and without H_{AC} is 0.046 °C and the sum of the temperature differences among city-level temperatures is 0.322 °C under + 0.0 °C global warming (Table S5). The average August temperature increases with every 0.5 °C increment in global warming, with higher urban temperatures from simulations with H_{AC} than without H_{AC}. The average August temperatures are 31.49 °C and 31.31 °C with and without H_{AC}, respectively, in the + 3.0 °C global warming scenario. The average temperature difference with and without H_{AC} is 0.181 °C and the sum of the temperature differences among city-level temperatures is 1.267 °C under + 3.0 °C global warming. Osaka and Sakai have the widest temperature difference while Wakayama has the narrowest temperature difference between the + 0.0 °C and + 3.0 °C scenarios. The temperature differences between the + 0.0 °C and + 3.0 °C global warming scenarios are 3.21 °C and 3.08 °C with and without H_{AC}, respectively.

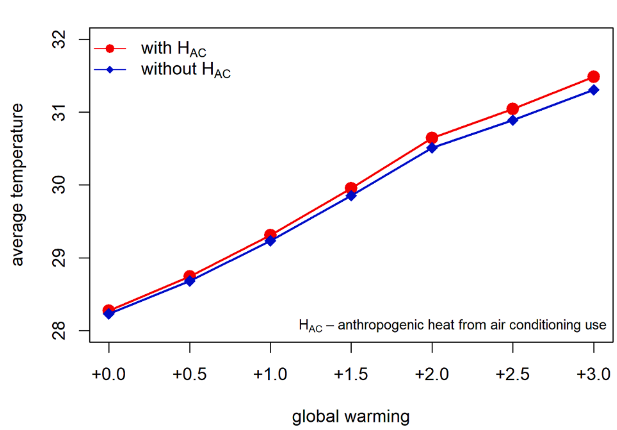

Fig. 3. Average August temperatures with and without anthropogenic heat from air conditioning use by global warming scenario in seven Kansai cities.

3.2. Associations between temperature and all-cause mortality

The risk functions for the pooled summertime temperature–mortality associations centered in August are J-shaped for both 100 % (*AC100*) and 0 % (*AC0*) household AC prevalence (Fig. 4) using the *meta*-regression model, which has a relatively low heterogeneity ($I^2 = 22$ %). The risk function for *AC0* is steeper at higher temperatures than risk function for *AC100*. At the 95th percentile temperature, taking the minimum mortality temperature (MMT) at the 30th percentile as a reference, the relative risks are 1.05 [95 % confidence interval (CI): 1.03; 1.08] for *AC100* and 1.11 (95 %CI: 1.03; 1.19) for *AC0*. The relative risks from MMT up to the 66th percentile are similar for both *AC0* and *AC100* (Fig. S4). The risk function for *AC0* has wide confidence intervals and overlaps with the risk function for *AC100*. Using the same pooled summertime temperature–mortality associations, the risk functions, MMTs, and 95th percentile temperatures of the seven cities are presented in Fig. S5.

3.3. Heat-related deaths attributable to AC use

The overall number of heat-related deaths attributable to H_{AC} is 59 in the + 0.0 °C scenario. This increases by a factor of more than five to 342 deaths in the + 3.0 °C global warming scenario (Fig. 5; Table S6). These unavoidable deaths constitute 3.1 % and 3.5 % of the overall possible heat-related deaths for the + 0.0 °C and + 3.0 °C global warming scenarios, respectively. More than half of these deaths (61 % and 54 % for the + 0.0 °C and + 3.0 °C scenarios, respectively) are from Osaka city. Only 5–8 % of the total heat-related deaths attributable to H_{AC} are from Nara, Otsu, and Wakayama. The total number of deaths averted from AC use is 686 under + 0.0 °C global warming and reaches 4,628 in the + 3.0 °C global warming scenario. Almost half (47 %) of the possible heat-related deaths could be averted by AC use in the highest global warming scenario (+3.0 °C). Majority of the averted deaths are from the most populated cities of Osaka, Kobe, and Kyoto.

The overall number of heat-related deaths in August without AC use is 1,900 in the + 0.0 °C scenario and 9,803 under + 3.0 °C global warming (Table S7). Most of these deaths occur in the highly populated cities of Osaka, Kobe, and Kyoto. The attributable fractions or proportions of all-cause deaths attributable to heat without protection from AC use are 4 % and 18 % under + 0.0 °C and + 3.0 °C global warming, respectively (Table S8). The number of heat-related deaths decreases by 36 % (686 deaths) from AC use in the + 0.0 °C scenario and could decrease by a further 47 % (4,628 deaths) under + 3.0 °C global warming. If H_{AC} is not taken into consideration, up to 56 % of heat-related deaths in August can be averted under + 3.0 °C global warming.

Lesser number of heat-related deaths attributable to H_{AC} are calculated when temperature–mortality risk functions for lowest and highest recorded AC prevalence are used (Fig. S6 and Table S9). In + 0.0 °C and + 3.0 °C scenario, 47 and 276 deaths are attributed to H_{AC}, respectively. Total number of averted deaths from AC use is 127 and 1,478 in + 0.0 °C and + 3.0 °C scenario, respectively.

4. Discussion

Our study estimated that a little more than 3 % of heat-related deaths were attributable to the anthropogenic heat from AC use during the hottest month of August over the period 2000–2010 in seven Japanese cities. Most of the deaths are from the cities of Osaka and Sakai because they have the most anthropogenic heat from AC use among the seven cities. The number of deaths attributable to AC use could increase considerably under high global warming scenarios because of hotter outdoor temperatures worsened by urban heat island effect and the

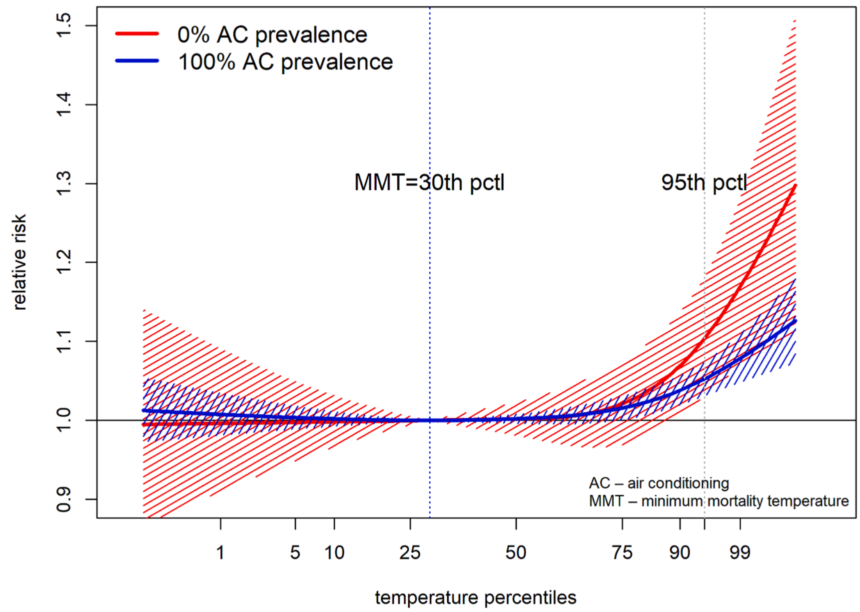

Fig. 4. Risk functions for the cumulative summertime temperature–mortality associations centered in August by household air conditioning (AC) prevalence. The red and blue polygons are the 95% confidence intervals of the mean risks for 0% AC prevalence and 100% AC prevalence, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

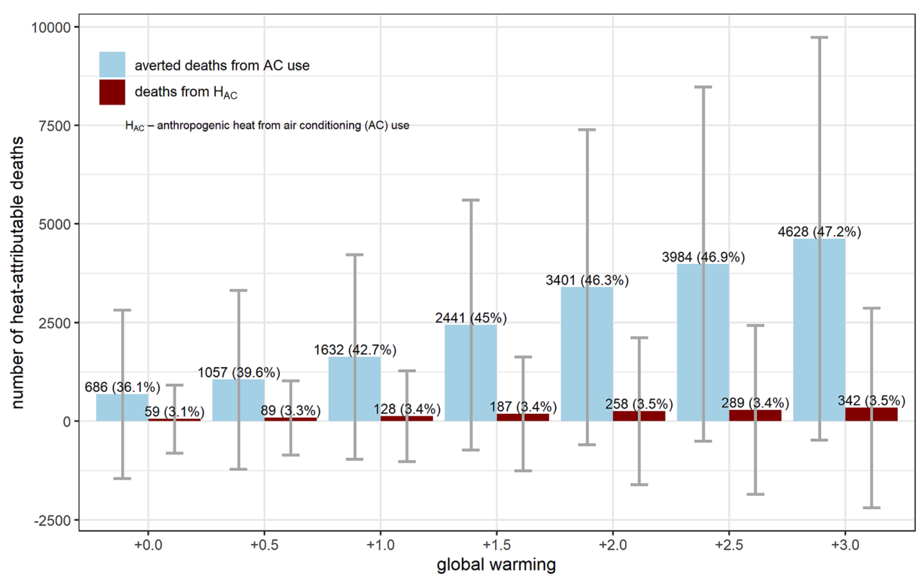

Fig. 5. Number of overall heat-related deaths attributable to air conditioning use by global warming scenario. The grey error bars are the 95% empirical confidence intervals of heat-related deaths.

anthropogenic heat from AC use.

These deaths are unavoidable because AC use has become essential for thermal comfort during summer. Anthropogenic heat from AC use can be reduced by using newer AC systems with better coefficients of performance (COPs), the adoption of increased building insulation, and reductions in internal heat gains (Takane et al., 2023), because they consume less electrical power to achieve useful cooling. Thus, it can be presumed that additional deaths can be prevented with the use of AC systems with better COPs. However, the energy efficiency from newer ACs could result in a rebound effect or increased usage of AC, (Mizobuchi and Takeuchi, 2019) leading to more electrical power consumption and anthropogenic heat from AC use.

Even if renewable energy is used to power AC, the deaths attributable to anthropogenic heat from AC use will still be unavoidable. However, greater usage of renewable energy for general energy needs would result in lower levels of global warming. This, in turn, could dampen the magnitude of additional heat-related deaths from AC use because of weaker positive feedback between global warming and anthropogenic heat from AC use. Moreover, a future with less hot outdoor temperatures would require less usage of AC.

Although there were some unavoidable deaths from AC use, a substantial proportion of heat-related deaths (36 %) were estimated to be averted by using AC, and almost half (47 %) of the heat-related deaths could be avoided under a high global warming scenario. This is the first estimation of the overall protective effect of AC use on heat-related mortality. In the literature, the protective effect of AC has been reported as: (1) a 2 % reduction in heat-related deaths for every 1 % increase in household AC prevalence (Eisenman et al., 2016; Lopez-Bueno et al., 2020), and (2) 14–20 % reduction from overall historical improvements in AC prevalence (Sera et al., 2020), but none considered a zero AC prevalence scenario. One caveat to this is that zero household AC prevalence is theoretical because the lowest AC prevalence in Japan was 19 % in one prefecture in 2009; most prefectures had $\geq$ 90 % AC prevalence the same year. This explains the wide confidence intervals of the risk function for 0 % AC prevalence.

Our findings on the sizeable protection from total AC use may inadvertently further support AC as a viable adaptive strategy in cities given that serious heat-related events could occur more often in the future under stronger climate change (Zhao et al., 2021). However, focusing on greater AC use in the future would be problematic to the environment considering its enormous energy consumption and the added greenhouse gas emissions from the production of AC and growing energy demand. (Davis and Gertler, 2015) Moreover, AC use would favour households with better socioeconomic status, (Pavanello et al., 2022) leaving poor households and the homeless vulnerable from heat. Consequently, urban poor might be the most exposed to the anthropogenic heat from AC use, especially at night wherein AC is used the most (Takane et al., 2019). A recent study, (Kim et al., 2023) determined that hot nights in Kansai region, where the study sites are located, increased the risk of all-cause mortality by 8 % (95 %CI: 6–10 %) during August to which anthropogenic heat from AC use could have contributed.

There are several limitations in this study. First is the assumption that city residents are exposed to outdoor temperatures regularly and all households with AC are using their AC for cooling during the hottest month of August. These assumptions do not reflect the true heat exposure and the AC protection received by the individuals who died. Actual AC use may depend on factors such as socio-economic situation, availability of urban spaces with proper ventilation or shade, human biophysical conditions, and individual preferences. Moreover, during very hot summer temperatures, people tend to spend more time indoors and in common/public spaces with cooling, thus reducing exposure to dangerous temperatures. In this case, the deaths attributable to AC use may be overestimated. To better measure these variables, personal heat sensors could be used to measure and monitor an individual's surrounding temperatures through time and space. Second is the conservative estimation of anthropogenic heat from AC use. The urban temperatures simulated in our study assumed a constant COP and did not account for the dip in COP from hotter outdoor temperatures. Third is the wide empirical confidence intervals of the modelling outputs making the results uncertain. The overall uncertainty of the outputs could further widen because the uncertainty of the modelled temperatures was not taken into account.

In this study, we were only able to account for anthropogenic heat from AC use. AC use has other negative impacts, such as the air pollution created in generating the energy for AC use. A study in Thessaloniki, Greece, estimated that up to 250 additional annual cardiorespiratory deaths in 2080–99 may be attributable to air pollution from burning brown coal, which could generate energy for AC use (Kouis et al., 2021). Another negative impact is that the greenhouse gas emissions from generating energy for AC use will further contribute to global warming (Davis and Gertler, 2015). The greenhouse gas emissions from AC use will generally depend on the source of energy; thus, renewable energy sources could effectively curb these emissions. Refrigerant leakage from AC units could also contribute to climate change given the high global warming potential of refrigerants such as hydrofluorocarbons (Xiang et al., 2014). Concerns over hydrofluorocarbon refrigerant leakage may be ameliorated in the future with the shift towards alternative refrigerants with low global warming potential (Sun et al., 2019). Estimations of negative health impacts from AC use would be improved if air pollution and additional greenhouse gas emissions could be incorporated into simulations of the urban climate.

Given the numerous areas for improvements, further research on the negative impacts of AC use in urban spaces should be pursued in the future. Considering that AC use is associated with socio-economic conditions, exploring the health impacts of AC use in cities from middle-income countries with large wealth disparity and considerable urban poor populations would be necessary to further understand the benefits and limitations of AC use. Furthermore, assessing the health impacts of various combinations of sustainable cooling solutions, green urbanism, and AC use would help produce pieces of evidence for effective adaptation to urban heat.

In summary, this study found a relatively small, albeit unavoidable, proportion of heat-related deaths attributable to anthropogenic heat from AC use. In contrast, AC use was estimated to avert almost half of heat-related deaths especially under high global warming scenarios. The heat-related mortality numbers attributable to AC use are somewhat uncertain given the very wide empirical confidence intervals of the risk functions. Although our findings generally support the health protective value of AC use, adopting AC systems as a strategy for adapting to climate change in cities would still come with major socioeconomic, environmental, and societal challenges that should be carefully considered (Lundgren-Kownacki et al., 2018).

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.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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