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Baseline scenarios of heat-related ambulance transportations under climate change in Tokyo, Japan

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ABSTRACT

Background. Predictive scenarios of heatstroke over the long-term future have yet to be formulated. The purpose of the present study was to generate baseline scenarios of heat-related ambulance transportations using climate change scenario datasets in Tokyo, Japan.

Methods. Data on the number of heat-related ambulance transportations in Tokyo from 2015 to 2019 were examined, and the relationship between the risk of heat-related ambulance transportations and the daily maximum wet-bulb globe temperature (WBGT) was modeled using three simple dose–response models. To quantify the risk of heatstroke, future climatological variables were then retrieved to compute the WBGT up to the year 2100 from climate change scenarios (*i.e.*, RCP2.6, RCP4.5, and RCP8.5) using two scenario models. The predicted risk of heat-related ambulance transportations was embedded onto the future age-specific projected population.

Results. The proportion of the number of days with a WBGT above 28°C is predicted to increase every five years by 0.16% for RCP2.6, 0.31% for RCP4.5, and 0.68% for RCP8.5. In 2100, compared with 2000, the number of heat-related ambulance transportations is predicted to be more than three times greater among people aged 0–64 years and six times greater among people aged 65 years or older. The variance of the heatstroke risk becomes greater as the WBGT increases.

Conclusions. The increased risk of heatstroke for the long-term future was demonstrated using a simple statistical approach. Even with the RCP2.6 scenario, with the mildest impact of global warming, the risk of heatstroke is expected to increase. The future course of heatstroke predicted by our approach acts as a baseline for future studies.

Subjects Emergency and Critical Care, Public Health, Environmental Health, Healthcare Services
Keywords Statistical model, Global warming, Heatstroke, Adaptation, Forecasting, CMIP6

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INTRODUCTION

Heatstroke is a heat-related illness in which a patient becomes unable to control his or her own body temperature because of continuous exposure to a warm environment (*Bouchama & Knochel, 2002*). In the United States, 7,000 patients were reported to have died of heatstroke from 1979 to 1997 (*Centers for Disease Control and Prevention, 2000*). In France, over 15,000 excess deaths are estimated to have arisen from the 2003 heat wave (*Vandentorren et al., 2006*). Another study in the United Kingdom documented 892 excess deaths in the summer that resulted from three heatwaves in 2019 (*Brimicombe et al., 2021*),

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and called for a more inclusive approach to heat waves including an intensified mitigation policy against climate change. In Japan, heatstroke patients in the summer account for 1% of annual emergency transportations, and more than half of these are aged 65 years or older (*Fire & Disaster Management Agency (FDMA), 2022a*; *Fire & Disaster Management Agency (FDMA), 2022b*). As a "super-aged" nation, the country expects a continuing increase in the incidence of heatstroke, possibly with an exacerbation of prognosis because of aging within the elderly population.

In the area of climate change, physical studies of risks associated with natural disasters, including the highest temperature of the year (*Papalexiou et al., 2018*) and hydro-meteorological hazards (*Debele et al., 2019*), have been extensively conducted, but there have been relatively few studies of health-related outcomes. The small number of health-related studies include predictive analyses of the health effects—particularly mortality, as well as heat stress disorder—of uncomfortable temperatures; these have been conducted on a national scale (*Barnett, Tong & Clements, 2010*; *Fouillet et al., 2007*; *Kim et al., 2019*; *Lee, Röösli & Ragettli, 2021*; *Weinberger et al., 2019*), at a regional level (*Dimitriadou et al., 2022*; *Scovronick et al., 2018*), and on a global scale (*Guo et al., 2017*; *Mistry et al., 2022*). Heat-related health events are usually observed among elderly people, and therefore more effective countermeasures for protecting elderly people are required (*Rodrigues, Santana & Rocha, 2020*; *Ragettli et al., 2017*). *Sheffield et al. (2018)* showed that health effects of heat waves depend on age and race (or ethnicity), and occur even among children younger than five years old, who are considered as vulnerable as elderly people.

Predictive models of heatstroke have been studied with the eventual aim of preventing the disease and reducing the associated mortality. The wet-bulb globe temperature (WBGT) is known to be a useful environmental predictor of heatstroke events (*Budd, 2008*; *Ueno et al., 2021*). The unit of WBGT is the same as that of temperature. WBGT is divided into five levels to alert people to heatstroke, and action policies are provided for each level. The five levels are: less than 21 °C, 21 °C to 25 °C, 25 °C to 28 °C, 28 °C to 31 °C, and 31 °C or more (*Asayama, 2009*). In Japan, *The Ministry of the Environment (2022)* regularly communicates the risk of heatstroke, raising public awareness to promote prevention, and WBGT thresholds 28 °C and 31 °C are used for elevating the level of warning messages. When the WBGT exceeds 28 °C, the risk of developing heatstroke is said to increase, acting as a social trigger for the cancelation of events, for example, the cessation of exercise (*The American College of Sports Medicine, 2022*; *Japan Sports Association (JSPO), 2013*). In Japan, an epidemiological study was conducted to predict the prevalence of heatstroke among elderly patients in an indoor environment (*Kodera et al., 2019*). Moreover, machine learning has been employed to attempt to better predict such events over the course of time (*Ogata et al., 2021*; *Ikeda & Kusaka, 2021*). Nevertheless, predictive scenarios over the long-term future have yet to be formulated. Because of the availability of climate change forecast scenarios—such as those based on the Coupled Model Intercomparison Project Phase 6 (CMIP6)—climatological variables in high spatial and temporal resolutions are readily available for the long-term future (*e.g.*, up to the year 2100).

The purpose of the present study was to generate baseline scenarios of heat-related ambulance transportations in Tokyo, Japan using climate change scenario datasets. We specifically explored Tokyo, because Tokyo is the prefecture with the highest number of heatstroke transportations per year. Severe heatstroke cases are predicted for the long-term future using climatological data, particularly the WBGT because it is easily computed from meteorological variables (*Ono & Tonouchi, 2014*). While it is known that computing WBGT is technically complicated, a simplified WBGT exists as an approximation, acting as a publicly-used indicator of heat stress along with environmental stress index (*Kong & Huber, 2022*). Baseline scenarios will be useful for understanding the possible future course of heatstroke, thereby providing a basis on which interventions, particularly adaptation policies, can be designed.

MATERIALS & METHODS

Epidemiological data

To construct a forecast model, we used heat-related ambulance transportation data for the period from 2015 to 2019. The latest two years, 2020 and 2021, were omitted to disregard the impact of coronavirus disease (COVID-19) on associated behaviors (*e.g.*, a stay-home policy was in place during the pandemic). Specifically, we used a dataset on the daily number of people transported by ambulance for heatstroke, which records every single transportation event and is openly published by the *Fire & Disaster Management Agency (FDMA) (2022a)*. The ambulance transportation case data were structured by age group; in the following analysis, we analyze the data by dividing the population into three age groups: 0–17 years, 18–64 years, and 65 years or older. In addition to case data, data on the daily maximum WBGT were obtained from the Ministry of the Environment (2022). In addition, the population size for Tokyo for the period from 2015 to 2019 in the abovementioned three age groups was obtained (*Tokyo Metropolitan Government, 2022*) to calculate the risk of heat-related ambulance transportations. For instance, in 2019, the population sizes of 0–17 years, 18–64 years, and 65 years or older were 1.86 million, 8.25 million and 3.08 million, respectively, and of these, 553, 2,322 and 3,171 heatstroke cases called for ambulance transportation.

The Intergovernmental Panel on Climate Change (IPCC) released its AR6 on August 9, 2021. They found that, by at least the late 2030s, global average temperatures are likely to have increased by 1.5 °C above pre-industrial levels (*IPCC, 2021*). In the present study, we obtained climate change scenarios based on CMIP6, published by the National Institute for Environmental Studies (*Ishizaki, 2021*). Of the five different scenario models available, we selected two: (i) Model for Interdisciplinary Research on Climate version 6 (MIROC6), which was cooperatively developed by a Japanese modeling community to precisely reflect the meteorological conditions in Japan, and (ii) Meteorological Research Institute Earth System Model version 2.0 (MRI-ESM-2.0), which was developed by the Japan Meteorological Agency and offers accurate forecasts of rainfall and humidity. MRI-ESM-2.0 was adopted because humidity plays a critical role in calculating the WBGT. For each model, three different time-series scenarios—Representative Concentration Pathway (RCP) 2.6, RCP4.5, and RCP8.5—with daily climatological data from 1900 to 2100 were obtained for each 1-km square of geographic mesh. Using the two models and three time-series scenarios, the daily maximum temperature, relative humidity, total solar radiation, and average wind speed in a geographic space that contains the Imperial Palace of Japan, located in central Tokyo, were extracted to calculate the WBGT for each date (*Ono & Tonouchi, 2014*). The reason why we chose the area around the Imperial Palace as the location of our analysis is that data on the daily maximum WBGT were consistently available for this particular geographic space over the whole time period.

Mathematical model

For the purpose of prediction, we exploited the relationship between the number of heat-related ambulance transportations per million population and the daily maximum WBGT. These heatstroke data were used to predict the per capita risk because we subsequently used the estimate multiplied by the predicted age-specific population size during the forecasting process. The model was fitted by age group (*i.e.,* 0–17 years, 18–64 years, and 65 years or older). Several different statistical models were employed to describe the dose–response relationship. The first is a classical model that captures a monotonic increase in the risk of heatstroke as a linear function of the WBGT after the WBGT exceeds a threshold value; this is referred to as the hockey stick regression method (*Yanagimoto & Yamamoto, 1979*). This classical model was specifically revisited because there is an existing notion of a threshold around a WBGT of 28 °C. Using the daily maximum WBGT (T), the number of heat-related ambulance transportations per million population $n\,(T)$ was modeled as

$$E(n(T)) = \begin{cases} \beta_1, & \text{for } T < T_w \\ \beta_1 + \beta_2(T - T_w), & \text{for } T_w \le T \end{cases} \tag{1}$$

where T_w is the WBGT threshold above which the risk of heatstroke abruptly increases. β_1 is the constant risk at a WBGT below T_w; β_2 is the gradient of risk when the WGBT exceeds T_w. The model was independently fitted to each age group, and T_w was treated as a parameter because different age groups were expected to have different threshold levels (*i.e.,* different physical endurance levels).

The second model is an extension of the first. Frequently, the WBGT is expressed as one of five discrete levels, with the highest level being a WBGT of 31 °C or more; this implies another threshold that boosts the risk of heatstroke. With two threshold temperatures, T_{w1} and T_{w2}, the expected number of transportations per million population $n\,(T)$ was modeled as

$$E(n(T)) = \begin{cases} \beta_1, & \text{for } T < T_{w1} \\ \beta_1 + \beta_2(T - T_{w1}), & \text{for } T_{w1} \le T < T_{w2} \\ \beta_1 + \beta_2(T_{w2} - T_{w1}) + \beta_3(T - T_{w2}), & \text{for } T_{w2} \le T \end{cases} \tag{2}$$

where β_1 is the constant risk at a WBGT below T_{w1} and β_2 and β_3 are the gradients of risk when the WBGT exceeds 28 °C and 31 °C, respectively.

The third model is a phenomenological model that assumes an exponential increase in the risk of heatstroke. We allowed a threshold for this model as well. Let r be the exponential rate of increase in risk and let β_1 be the constant risk below the WBGT threshold. We have

$$E(n(T)) = \begin{cases} \beta_1, & \text{for } T < T_w \\ \beta_1 exp(r\,(T - T_w)), & \text{for} T_w \le T \end{cases}. \tag{3}$$

Assuming that the variations in the observed counts of heat-related ambulance transportations are sufficiently captured by a Poisson distribution with the expectation given by (1), (2), or (3), maximum likelihood estimation was performed to obtain optimal values of the parameters. The Akaike information criterion (AIC) was calculated to compare the model fit. The mean absolute error (MAE) of the prediction from the observed values was also calculated to evaluate the accuracy of prediction.

Future prediction scenarios of heat-related ambulance transportations

We consistently used the following formula to calculate the WBGT from readily available climatological data (*Ono & Tonouchi, 2014*):

$$T_{WBGT} = 0.735 \times T_{asmax} + 0.0374 \times RH + 0.00292 \times T_{asmax} \times RH + 7.619 \times SR - 4.557 \times SR^2 - 0.0572 \times WS - 4.064 \quad (4)$$

which is most frequently used in Japan to estimate the WBGT. T_{asmax} is the maximum daily temperature (°C), RH is the relative humidity (%), SR is global solar radiation (kW/m^2) measured by horizontally installed solar radiation meter , and WS is the average wind speed (m/s). A validation study of this approximate equation has excellently shown that 98.3% to 99.8% of WBGT estimate involved a bias less than 1.0 °C. In Japan, WBGT is physically measured in 11 different locations (weather observatories), and an approximate WBGT using Eq. (4) has been officially adopted in other 829 observatory stations. The MIROC6 and MRI-ESM-2.0 meteorological data were substituted into (4) to calculate the daily WBGT values from 2000 to 2100. Because the bifurcation of temperature change begins in 2015 in the two climate change models, data from 2000 to 2014 were calculated using common data.

In each future year, the proportion of days with a WBGT value falling into each of five discrete ranges was calculated. This was calculated as the number of days with a WBGT value in each range divided by the total number of days (365). Because climatological variables fluctuate from year to year, the abovementioned proportions were calculated for every five years.

We examined the projected trends in the number of heat-related ambulance transportations, explicitly accounting for future demography. To do so, we first calculated the WBGT from May 1 to September 30 in each year, and used models (1), (2), or (3) to calculate the risk per million population. Even in the long-term future, we assumed that the heatstroke risk would occur only between May and September. The predicted risk was embedded onto the projected age-specific populations aged 0–14 years, 15–64 years, and 65 years or older in the period 2015–2100 (*The Climate Change Adaptation Information Platform, 2022*). To calculate the 95% confidence intervals of our predictions of heat-related ambulance transportations, the parametric bootstrapping method was employed, because parameters were inferred by maximum likelihood method and the variance–covariance matrix was reasonably computed. To account for parameter uncertainties of models (1), (2), or (3), 5,000 bootstrap resampling experiments were conducted and the 2.5th and 97.5th percentile points were taken.

Data sharing statement

All datasets, including modeled climatological data for the period 2015–2100 and empirical data on heat-related ambulance transportations for the period 2015–2019 in Tokyo are openly shared as the online supporting material (Tables S1–S4).

Ethical considerations

The present study used publicly available information. Because no private information was used, ethical approval was not required.

RESULTS

Table 1 shows point estimates and 95% confidence intervals of the parameters for the three models. The models differed in the WBGT threshold value above which the risk of heatstroke begins to increase. It is worth noting that the estimated threshold temperature for elderly people (those aged 65 years or older) was lower than that for the other age groups in all three models. Of the three examined models, the exponential model yielded the smallest AIC for all age groups, and thus was deemed the best-fit model.

Figure 1 shows a comparison between the observed and predicted data for heat-related ambulance transportations, as predicted by using the WBGT. Both the dose–response phenomena of heatstroke incidence depending on the WBGT and variations in the risk depending on the WBGT should be noted. The observed data indicate that the risk of heatstroke became increasingly variable as the WBGT increased. In particular, there was a large variation in the risk of heatstroke in people aged 65 years or older, potentially reflecting the natural adaptation behaviors that may have been adopted when the WGBT became extremely high.

Figure 2 shows the distribution of MAE as a function of WBGT, by age group. In common with the abovementioned findings from Fig. 1, the MAE showed an increasing trend as the WBGT increased, and this phenomenon was observed for all three models that we examined. Using the hockey stick model, the maximum MAE was in people aged 65 years or older, with the value 31.1. Similarly, the maximum MAE with the two-step hockey stick model was 28.6 in the same age group. When the exponential model was employed, the maximum MAE was 28.1, again in people aged 65 years or older.

Figure 3 shows the time-dependent change in the proportion of high WBGT values in the long-term future, for each of the three climate change scenarios using two climate models (*i.e.,* MIROC6 and MRI-ESM-2.0). Using MIROC6, the number of days with a WBGT above 28 °C increased every five years by 0.16% for RCP2.6, 0.31% for RCP4.5, and 0.68% for RCP8.5. Similarly, using MRI-ESM-2.0, the number of days with a WBGT above 28 °C increased every five years by 0.20% for RCP2.6, 0.41% for RCP4.5, and 0.67% for RCP8.5. One noteworthy point is that the proportion of days with a WBGT above 31 °C monotonically increased in both models for all climate change scenarios.

Figure 4 shows the long-term forecast of heat-related ambulance transportations for the period 2000–2100 for each climate change scenario and model, using MIROC6. Even when the hockey stick model was employed with the RCP2.6 scenario (the combination that yielded the mildest impact of global warming), the total number of ambulance

Table 1 **Parameter estimates and model fit of dose–response model for heat-related ambulance transport as a function of WBGT in Tokyo, 2015–19.** Each model was fitted independently to the data by age group. We used heat-related ambulance transported data from 2015–19 retrieved from the Fire and Disaster Management Agency share. T_w represents threshold WBGT and its unit is Celsius degree. AIC stands for the Akaike Information Criterion, calculated assuming it follows a Poisson distribution. The hockey stick model assumes that the risk of developing heatstroke increases linearly when the WBGT exceeds the threshold T_w. Two-step hockey stick model assumes that the risk of developing heatstroke increases in a two-step manner, and the boundary thresholds are T_{w1} and T_{w2}. The exponential formula assumes that the risk of developing heatstroke increases non-linearly when the WBGT exceeds the threshold T_w. CI stands for the confidence interval as calculated from bootstrapping method.

	The hockey stick model				Two-step hockey stick model						Exponential model			
Age	AIC	T_w	β_1	β_2	AIC	T_{w1}	T_{w2}	β_1	β_2	β_3	AIC	T_w	r	β_1
0–17 years	2493.8	28.8	0.6	1.8	2467.3	28.0	30.8	0.6	0.8	3.0	2456.0	25.7	0.4	0.5
95% CI		(28.6–29.0)	(0.55–0.67)	(1.62–1.97)		(27.6–28.4)	(30.4–31.1)	(0.53–0.64)	(0.58–1.04)	(2.40–3.54)		(25.1–26.3)	(0.37–0.45)	(0.38–0.54)
18–64 years	1747.0	28.4	0.3	1.6	1650.8	26.1	30.6	0.2	0.5	3.1	1630.3	23.7	0.5	0.1
95% CI		(28.2–28.5)	(0.26–0.34)	(1.49–1.76)		(25.7–26.5)	(30.3–30.9)	(0.16–0.24)	(0.36–0.56)	(2.63–3.62)		(22.8–24.6)	(0.44–0.48)	(0.09–0.17)
65 years and older	3999.9	27.9	1.0	4.4	3671.2	25.5	30.5	0.6	1.4	9.0	3620.2	22.7	0.4	0.4
95% CI		(27.8–28.0)	(0.88–1.04)	(4.23–4.62)		(25.3–25.7)	(30.3–30.7)	(0.52–0.67)	(1.22–1.50)	(8.16–9.79)		(22.1–23.3)	(0.42–0.44)	(0.28–0.44)

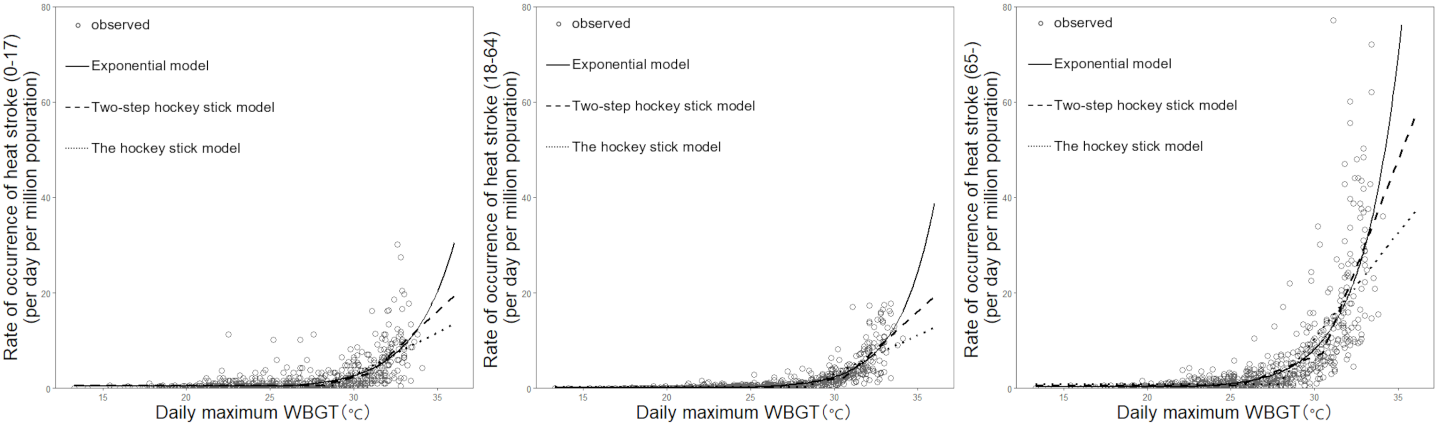

Figure 1 The risk of heat-related ambulance transportations as a function of wet-bulb globe temperature (WBGT): a comparison between observed and predicted data. The vertical axis is the number of cases per million population per day, and the horizontal axis is the daily maximum WBGT. The left, middle, and right panels show the age groups 0–17 years, 18–64 years, and 65 years or older, respectively. White circles represent observed values, solid lines show the exponential model, long dashed lines show the two-step hockey stick model, and dotted lines show the one-step hockey stick model.

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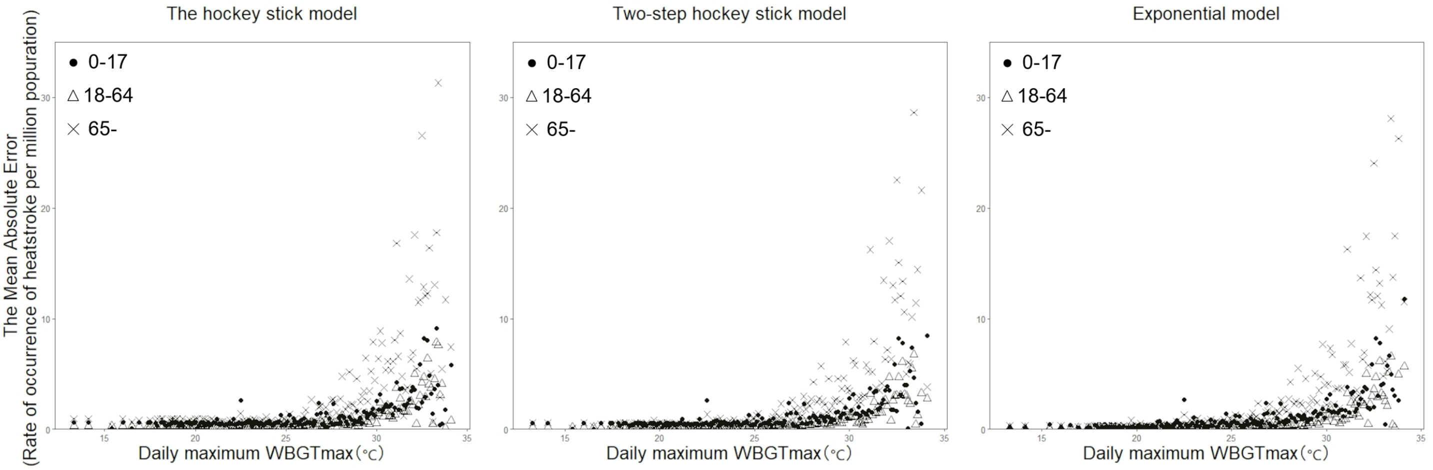

Figure 2 Mean absolute error between observed and predicted values, by age group. The mean absolute error (MAE) between the observed and predicted data is shown for each model. Dots, white triangles, and crosses represent the MAE values for the age groups 0–17 years, 18–64 years, and 65 years or older, respectively. The MAE was calculated by dividing the absolute difference between the observed and predicted values by the number of data points for each identical wet-bulb globe temperature (WBGT) value.

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transportations is predicted to increase. In 2100, the numbers of heatstroke patients transported in the groups aged 0–14 and 15–64 years are projected to be about three times higher than the numbers observed in 2000. Among people aged 65 years or older, the number of ambulance transportations is expected to be more than six times that observed in 2000. Figure 5 shows the same long-term forecast, based on MRI-ESM-2.0. In general, the forecast is qualitatively identical to that derived from MIROC6. The increase in risk

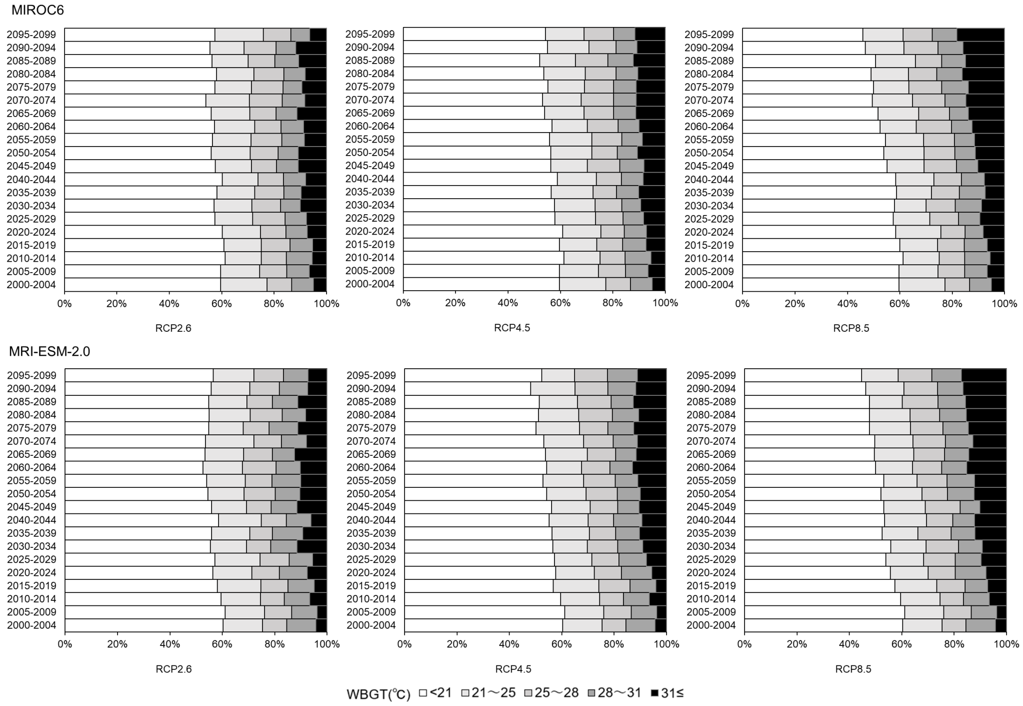

Figure 3 **Future wet-bulb globe temperature (WBGT) patterns in Tokyo for the period 2000–2100.** WBGT is represented as five discrete groups. The top two groups (*i.e.,* a WBGT of 28–31 °C and a WGBT above 31 °C) are regarded as having a particularly high risk of causing heatstroke. The proportion of days that have each range of WBGT values was calculated for every period of five years. The top and bottom panels show the projections for the MIROC6 scenario and the MRI-ESM-2.0 scenario, respectively. The left, middle, and right columns show the predictions for the RCP2.6, RCP4.5, and RCP8.5 temperature increase scenarios, respectively.

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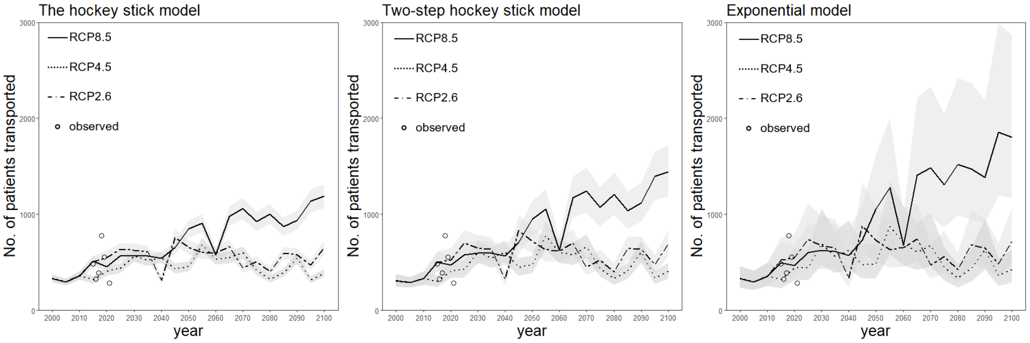
over time among elderly people tends to be greater than that among younger groups in both models.

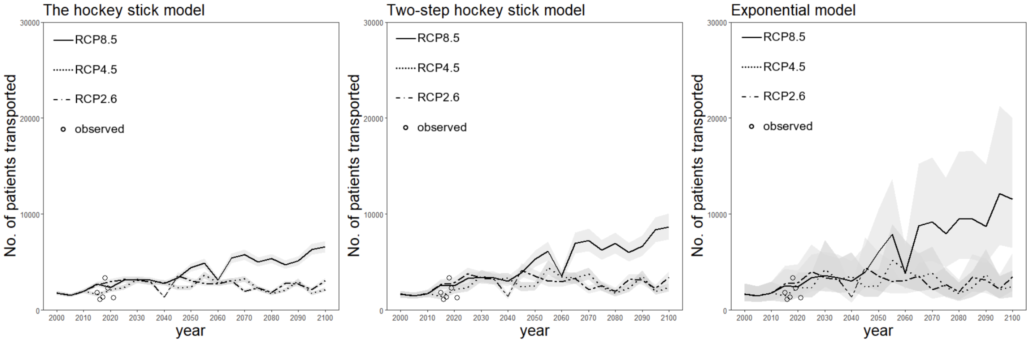
DISCUSSION

The present study developed a model to forecast heat-related ambulance transportations for the long-term future until 2100 in Tokyo, Japan in various climate change scenarios and using multiple climatological scenario models. In addition to the climatological scenarios and models, three dose–response models were employed to predict the heat-related ambulance transportations per million population as a function of the daily maximum WBGT, using observations from 2015–19 as the training data. The elderly age group was revealed to have a lower WBGT threshold than younger age groups. Our finding is consistent with published studies which reported that the elderly age group tends to have a difficulty in regulating body temperature under warm environmental conditions (*Meade et al., 2020*; *Larose et al., 2013*). Calculating the WBGT for RCP2.6, RCP4.5, and RCP8.5 for the scenario models, we have shown that the proportion of days with a WBGT between 28 °C and 31 °C and the proportion with a WGBT above 31 °C will monotonically increase.

Predicted number of heatstroke cases in MIROC6
(from 0 to 14 y.o.)



(from 15 to 64 y.o.)



(over 65 y.o.)

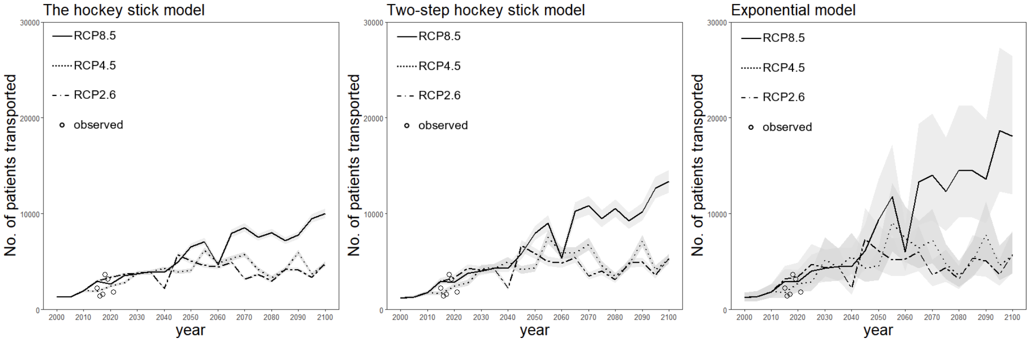


Figure 4 Predicted number of heatstroke cases in Tokyo for the period 2000–2100, using the MIROC6 scenario. The epidemiological prediction of the number of heat-related ambulance transportations for every period of five years is shown, using the daily maximum wet-bulb globe temperature (WBGT) derived from MIROC6. Predictions were made using the three statistical dose–response models. The 95% confidence intervals were calculated using the parametric bootstrapping method, and are represented by the shaded areas. The dotted and dashed line shows predictions with RCP2.6, the dotted line shows predictions with RCP4.5, and the solid line shows predictions with RCP8.5. The white circles represent observed data on heat-related ambulance transportations for the five-year period beginning in 2015.

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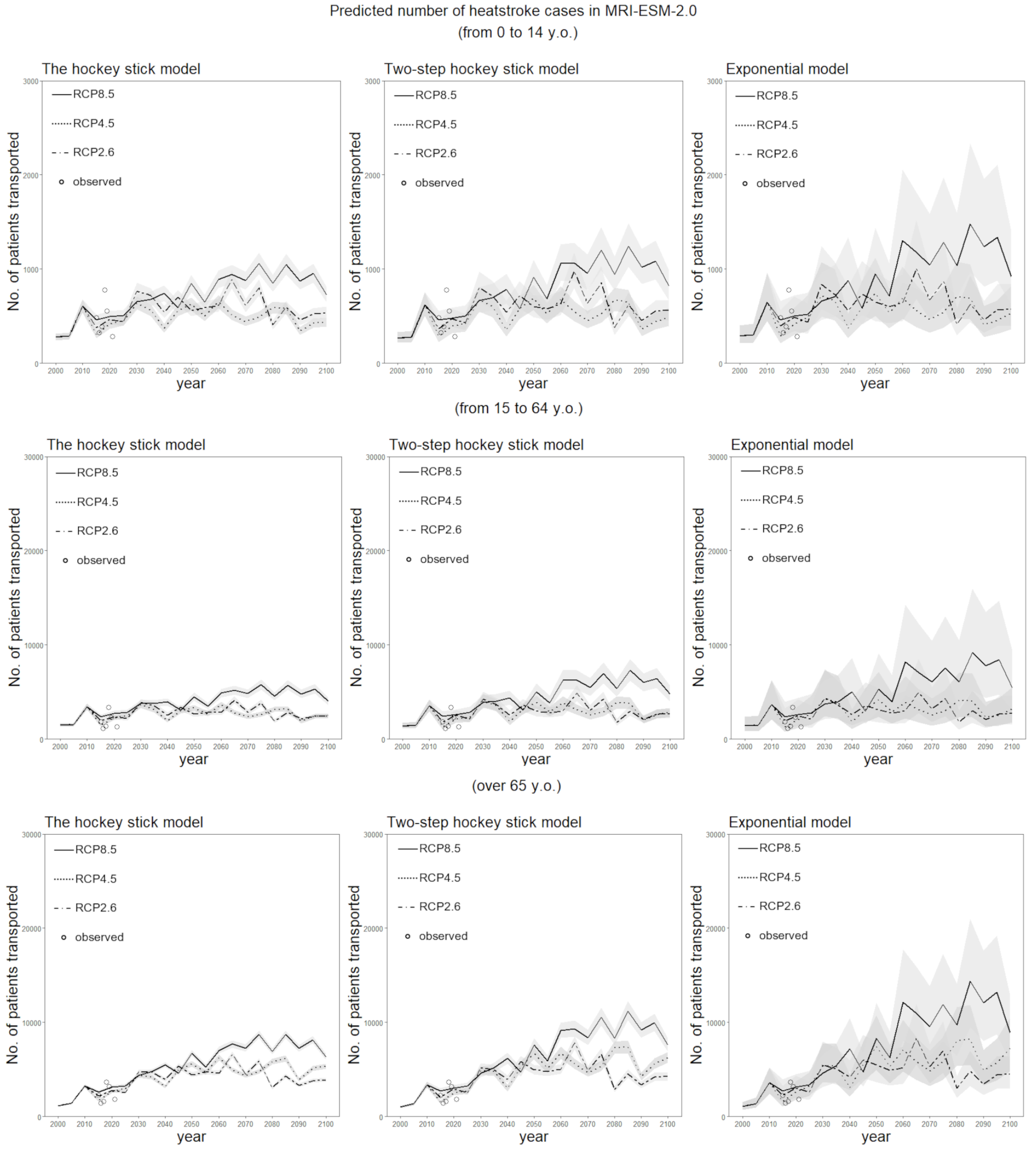

Figure 5 Predicted number of heatstroke cases in Tokyo for the period 2000–2100, using the MRI-ESM-2.0 scenario. The epidemiological prediction of the number of heat-related ambulance transportations for every period of five years is shown, using the daily maximum wet-bulb globe temperature (WBGT) derived from MRI-ESM-2.0. Predictions were made using the three statistical dose–response models. The 95% confidence intervals were calculated using the parametric bootstrapping method, and are represented by the shaded areas. The dotted and dashed line shows predictions with RCP2.6, the dotted line shows predictions with RCP4.5, and the solid line shows predictions with RCP8.5. The white circles represent observed data on heat-related ambulance transportations for the five-year period beginning in 2015.

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Embedding the predicted risk of heat-related ambulance transportations onto the future age-specific projected population, we were able to objectively predict the increased risk of heatstroke for the long-term future using a simple statistical approach. Even with the RCP2.6 scenario, which shows the mildest impact of global warming, the risk of heatstroke was predicted to increase.

To the best of our knowledge, the present study is the first to predict the risk of heatstroke using the proposed statistical dose–response modelling approach. The forecasting principles are simple and tractable (*e.g.*, using a dose–response model and embedding the risk onto the projected population), and yet the model captures the essential mechanisms of the elevated risk of heatstroke as a function of time. Only by quantifying the future risk of heatstroke, as practiced in the present study, can we understand the quantitative magnitude of the future increase. The future course of heatstroke predicted by our approach acts as a baseline for future studies. That is, various adaptation policies (*e.g.*, simply canceling outdoor events when the WBGT is extreme) will be planned according to the baseline risks, and we will examine how far the risk of heatstroke could be reduced by the adaptation efforts of society.

Of the three forecasting models that we examined, the exponential model yielded the smallest AIC value, indicating that the dose–response relationship between the risk of heatstroke and the WBGT is most appropriately captured by this model for all three age groups. This finding indicates that the elevation of the risk of heatstroke is accelerated as the WBGT increases. In the context of climate change, given that the higher the WBGT, the larger the error, it is statistically challenging to successfully quantify the risk of heatstroke with an extremely elevated WBGT in the future. The exponential model implies that the intrinsic risk of heatstroke with a very high WBGT is likely to be far greater than what we explored in this study using empirical data.

An important observation from the dose–response phenomena is that the variance of the risk increased as the WBGT increased. In fact, using the simple dose–response models, the MAE appeared to be large with high WBGT values. This variation was particularly noticeable among people aged 65 years or older. We believe that this variation was caused partly by natural adaptation behaviors. Because a high WBGT did not necessarily lead to large numbers of ambulance transportations of heatstroke patients, it is possible that dynamic changes in the WBGT may predict the risk of heatstroke better than the daily maximum WBGT. It has been speculated that the incidence of heatstroke is increased by an inability to take adaptation behaviors in each specific individual , such as participating in sports event or festivals among young individuals (*Kasai et al., 2017*) and continuously laying down in a warm room among elderly (*Abrahamson et al., 2009*). Also, the risk of heatstroke may be high when the WBGT suddenly increases. However, if a heat wave includes several consecutive days with high WBGT values, people may change their behavior to reduce the risk of heatstroke in the subsequent days. To capture the observed risk more accurately using available climatological variables is a subject for our future study.

As mentioned in the introduction, published studies using machine learning methods for heatstroke prediction modelling have already been widely recognized (*Ogata et al., 2021*; *Ikeda & Kusaka, 2021*). The aim of the present study was to generate a longer-term baseline scenario for heatstroke emergency transportation in Tokyo, using a dataset of climate change scenarios and possibly employing a more simplistic and yet tractable approach. To accomplish the goal, a statistical dose–response modelling approach based on an approximate WBGT value was shown to reasonably predict the number of heatstroke cases in future Japan.

There are three limitations that need to be discussed. First, the present study examined only empirical data from Tokyo; thus, it is unclear whether its findings are applicable to a wider geographic area of Japan. Forecasting must be extended to geographic regions other than Tokyo. Second, the present study relied on ambulance transportation data, which represent only a small fraction of heatstroke cases. Therefore, patients with mild heatstroke were not counted. However, we believe that the overall time trends were captured even though only severe cases of heatstroke were counted. Third, we must revisit the reliability of the forecasting model in the future. Wide variations in the numbers of heat-related ambulance transportations when the WBGT value is high imply that our model cannot capture the peaks and troughs of heatstroke incidence during summer days with high WBGT values, particularly among people aged 65 years or older. There is scope for improvement in the accuracy of the models.

Although several key tasks remain, we believe that the present study successfully provided a baseline scenario for heatstroke in Tokyo for the future, until the year 2100, using a simple statistical modeling approach. Various adaptation policies will be planned according to the baseline risks, and we will examine how far the risk of heatstroke could be reduced by the adaptation efforts of society.

CONCLUSIONS

In conclusion, we have shown that a simple dose–response model with WBGT as a predictor can reasonably quantify the future increase in the number of heat stroke cases. The present study developed a model to forecast heat-related ambulance transportations for the long-term future, until 2100 in Tokyo, Japan in various climate change scenarios and using multiple climatological scenario models. By calculating the WBGT for RCP2.6, RCP4.5, and RCP8.5 for the scenario models, we have shown that the proportion of days with a WBGT between 28 °C and 31 °C and the proportion with a WGBT above 31 °C will monotonically increase. Embedding the predicted risk of heat-related ambulance transportations onto the future age-specific projected population, we were able to objectively predict the increased risk of heatstroke for the long-term future using a simple statistical approach. Even with the RCP2.6 scenario, which shows the mildest impact of global warming, the risk of heatstroke was predicted to increase. The future course of heatstroke predicted by our approach acts as a baseline for future studies.

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Competing Interests

Hiroshi Nishiura is an Academic Editor of PeerJ.

Author Contributions

- Marie Fujimoto performed the experiments, analyzed the data, prepared figures and/or tables, and approved the final draft.
- Hiroshi Nishiura conceived and designed the experiments, analyzed the data, authored or reviewed drafts of the article, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

Raw data is available in the Supplemental Files.

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Possible adaptation measures for climate change in preventing heatstroke among older adults in Japan

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Introduction: Heatstroke mortality is highest among older adults aged 65 years and older, and the risk is even doubled among those aged 75 years and older. The incidence of heatstroke is expected to increase in the future with elevated temperatures owing to climate change. In the context of a super-aged society, we examined possible adaptation measures in Japan that could prevent heatstroke among older people using an epidemiological survey combined with mathematical modeling.

Methods: To identify possible interventions, we conducted a cross-sectional survey, collecting information on heatstroke episodes from 2018 to 2019 among people aged 75 years and older. Responses were analyzed from 576 participants, and propensity score matching was used to adjust for measurable confounders and used to estimate the effect sizes associated with variables that constitute possible interventions. Subsequently, a weather-driven statistical model was used to predict heatstroke-related ambulance transports. We projected the incidence of heatstroke-related transports until the year 2100, with and without adaptation measures.

Results: The risk factor with the greatest odds ratio (OR) of heatstroke among older adults was living alone (OR 2.5, 95% confidence interval: 1.2–5.4). Other possible risk factors included an inability to drink water independently and the absence of air conditioning. Using three climate change scenarios, a more than 30% increase in the incidence of heatstroke-related ambulance transports was anticipated for representative concentration pathways (RCP) 4.5 and 8.5, as compared with a carbon-neutral scenario. Given 30% reduction in single living, a 15% reduction in the incidence of heatstroke is expected. Given 70% improvement in all three risk factors, a 40% reduction in the incidence can be expected.

Conclusion: Possible adaptation measures include providing support for older adults living alone, for those who have an inability to drink water and for those without air conditioning. To be comparable to carbon neutrality, future climate change under RCP 2.6 requires achieving a 30% relative reduction in all three identified risks at least from 2060; under RCP 4.5, a 70% reduction from 2050 at the latest is needed. In the case of RCP 8.5, the goal of heatstroke-related transports approaching RCP 1.9 cannot be achieved.

KEYWORDS

emergency transportation, heatstroke, risk reduction, climate change, statistical model

1. Introduction

Heatstroke is an environmentally induced condition caused by exposure to a very warm environment and an inability to lower elevated body temperature (1). Depending on the mechanism of development, heatstroke is divided into classic heatstroke, caused purely owing to environmental conditions, and exertional heatstroke, induced by physical exercise (2). People who have difficulty adapting to a warm environment, including older adults and those people with chronic illnesses, are more likely to develop heatstroke (3–6). Morbidity of heatstroke is elevated with a transient increase in temperature such as heatwaves (7, 8). To reduce mortality, preventing heatstroke is more effective than treatment, involving simple yet realistic countermeasures to reduce heatstroke incidence (9). Published preventive measures of heatstroke include the installation of air-conditioners (10) and enhancement of public support for older adults (11).

The incidence of heatstroke is expected to increase in the future with rising temperatures owing to climate change. The Intergovernmental Panel on Climate Change has set a goal of limiting the increase in the global average temperature to 1.5°C by the end of the 21st century, as a mitigation measure (12). Among health problems associated with climate change, heatstroke is a disease for which measures to reduce risk are required worldwide (13). Health-related risk assessment of climate change has taken place under various scenarios of temperature increase across the world (13–20), and possible risk reduction via adaptation measures to climate change has been explored in recent years (21, 22). Population aging is also reported to increase the burden of heat-related health risks under climate change (23, 24), and heatstroke mortality is known to be highest among people aged 65 years and older, and the risk is even doubled among those aged 75 years and older.

In Japan, the government Ministry of the Environment (MOE) has taken the initiative to inform the public regarding the risk of heatstroke, using the wet bulb globe temperature (WBGT) as a standard indicator (25). The WBGT is classified into five discrete categories: less than 21°C, 21°C–25°C, 25°C–28°C, 28°C–31°C, and 31°C or higher (26). When the temperature exceeds 28°C, warnings are issued by the government via mass media. Despite various countermeasures, approximately 1000 annual deaths owing to heatstroke have been reported in Japan in recent years, and more than 80% of heatstroke deaths are among people over 65 years of age [(27); Supplementary material 1]. To consider prevention strategies of heatstroke-related deaths in Japan, a super-aged society, studies have been conducted using various statistical models (28, 29). We proposed a forecasting model using the maximum daily WBGT under several climate change scenarios (30). However, intervention studies have been limited to date.

The purpose of the present study was to identify possible adaptation measures among older adults in Japan in the context of a super-aged society and to estimate their effectiveness in preventing heatstroke. Identifying possible adaptation measures can help assist various stakeholders, including local governments, community caregivers and so on to consider future preparedness plans to mitigate the risk of heatstroke even under changing climate. Such contingency plan may decrease the disease burden and mortality of heatstroke. In this study, we first conducted a cross-sectional epidemiological survey to identify possible risk factors via survey and then modeled what is the potential that decrease in these risk factors could have in the future in preventing heatstroke. We also used a climate-driven prediction model to predict heatstroke-related ambulance transports under various climate change scenarios.

2. Materials and methods

2.1. Identification of risk factors

2.1.1. Cross-sectional survey

We carried out a cross-sectional epidemiological online survey among Japanese residents with family members or other relatives aged 75 years or older. We focused on this group, because the risk of heatstroke among people aged 75 years or older is known to be twice as high as that among people aged 65 years or older [(27); Supplementary material 1]. Participants were selected non-randomly from a list of registered users of a Japanese internet research company called Mellinks Ltd. Respondents did not receive remunerations, but upon completion of survey, they received local "points" that could be exchanged for valuable goods via the company. The internet-based survey was carried out from September 14 to 24, 2021, by navigating respondents to visit the website with questionnaire. The questionnaire was designed based on published studies (3–6), and we focused on heatstroke episodes from 2018 to 2019. Heatstroke episode was defined in our survey based on criteria adapted from the 'Heatstroke Treatment Guidelines 2015' (31) and a reference (1) which are known to have been comprehensive even among non-medical experts. A more detailed description is provided in Supplementary material 2. We specifically surveyed 2018–2019, because of retrospective nature of our study, and also to avoid the potential impact of the coronavirus disease 2019 (COVID-19) pandemic on the results of the questionnaire. Moreover, socioeconomic level and comorbidities were also surveyed in indirect manners. Not only exploring the presence of air conditioner, the survey questions included gender and the number of household occupants that are known to influence socioeconomic levels of life among older people (32). As for comorbidities, we investigated whether there were any pre-existing comorbidities that are associated with the risk of heatstroke, including depression, heart failure, hypertension, kidney diseases, and Parkinson's disease. A version of our questionnaire translated into English is available in Supplementary material 2.

2.1.2 Statistical analyses

The dichotomous (2-category) outcome was an episode of heatstroke from 2018 to 2019, and we investigated univariate and multivariate associations of explanatory variables with the occurrence of heatstroke episodes. First, we investigated the univariate statistical association between heatstroke and explanatory variables, estimating the odds ratio (OR) as the effect size measure. For the calculation of OR, we used a univariate logistic regression. Subsequently, among variables that were significantly associated with heatstroke in the univariate analysis, we selected variables into which we can intervene. To adjust for potential confounders among measured variables, one-to-one propensity score matching was carried out for each factor into which we expected to intervene (33). A logistic regression model was used to estimate propensity scores, involving four measured variables (i.e., age, sex, underlying comorbidities, and inability to move to a cooler place during hot weather). Using a caliper width with a propensity score standard deviation of 0.2, matching was performed using nearest-neighbor matching and non-replacement methods. The balance of baseline variables between the two propensity-matched groups was examined using standardized differences, and more than 10% was considered unbalanced, following the convention of matching procedure (34). Using the same propensity score, we conducted a sensitivity analysis with the inverse probability of treatment weighting (IPTW) method.

2.2. Future prediction scenario of heatstroke

2.2.1. Data source for prediction model

Three pieces of data in Tokyo were used: (i) the number of heatstroke patients transported by ambulance (35), (ii) daily maximum WBGT (25), and (iii) weather data from observatories (36). Data on the number of daily transported patients aged 65 years and older are routinely collected by the Fire and Disaster Management Agency (FDMA) from May to September each year. The FDMA data only shows a dichotomous age group indicating whether heatstroke patient is 65 years and older, not in the form of individual age of heatstroke patient. Two other datasets were obtained using publicly available data from the referenced source and collected during the FDMA collection period. To calibrate our model, all these datasets were prepared for the period of 5 years from 2015 to 2019. Climatological variables including WBGT from weather station data were used to predict the number of heatstroke-related ambulance transports. WBGT values were dealt with in the same manner as the unit of temperature, i.e., °C. WBGT values during the abovementioned 5 years represent direct measurements in Tokyo.

In this study, future climatological variables were obtained from climate change scenarios based on the Coupled Model Intercomparison Project Phase 6 published by the National Institute for Environmental Studies (NIES) (37). Three scenarios were extracted from NIES: (i) Model for Interdisciplinary Research on Climate version 6 (MIROC6), (ii) Meteorological Research Institute Earth System Model version 2.0 (MRI-ESM-2.0), (iii) the Institute Pierre-Simon Laplace climate mode (IPSL-CM6A-LR). We specifically examined these three scenarios because the carbon-neutral scenario is available as part of the representative concentration pathways (RCP). Future meteorological data were collected at RCP 1.9, 2.6, 4.5, and 8.5 by specifying the latitude and longitude of the weather stations in Tokyo, among which RCP 1.9 corresponds to a carbon-neutral scenario. Future WBGT by the year 2100 was calculated using meteorological data with an estimator developed by Ono et al. (38). To calculate the risk at population level, past demographic data were obtained from the 2015 census (39), and data in the future were extracted from the Climate Change Adaptation Information Platform (40).

2.2.2. Projection model

In our previous study (30), projections were made using a forecasting model that uses daily maximum WBGT. Letting T_d be the daily maximum WBGT on day d, the expected number of heatstroke-related transports was modeled as:

$$E\left(n\left(T_d\right)\right)=\begin{cases}\beta \text{ for } T_d<T_w \\ \beta exp\left(r\left(T_d-T_w\right)\right) \text{ for } T_w \geq T_d\end{cases} \tag{1}$$

where Tw is the WBGT threshold (e.g., 28°C) above which the dose–response increase in heatstroke is seen, β is the constant risk at WBGT below Tw, and r is the rate of risk increase as a function of WBGT. We demonstrated the usefulness of WBGT in projection, but projection using a simplistic model was unable to capture observed heatstroke counts when the temperature was greatly elevated for several consecutive days.

We thus attempted to improve the equation in the present study, additionally accounting for weather data related to heat (i.e., global solar radiation and a sequence of hot days) in the prediction. Because our earlier model was unable to capture the heatstroke count during heatwaves that continued for several days, heat acclimation was also considered (i.e., before and after natural adaptation was taken into account), which is in line with a published study (41). Dealing with global solar radiation (s_d) (kW/m^2), and similarly dealing with WBGT on d (u_d) as dichotomous (whether the daily maximum WBGT exceeded 31°C for 2 or 3 consecutive days), we modeled the daily number of heatstroke-related ambulance transports as

$$E\left(n\left(T_d\right)\right)=\begin{cases}\beta_0 \text{ for } T_d<T_{w,0}, \text{before adaptation} \\ \beta_1 \text{ for } T_d<T_{w,1}, \text{after adaptation} \\ \beta_0 \exp\left(r_0\left(T_d-T_{w,0}\right)+\gamma_{1,0}s_d+\gamma_{2,0}u_d\right) \\ \text{for } T_{w,0} \geq T_d, \text{before adaptation} \\ \beta_1 \exp\left(r_1\left(T_d-T_{w,1}\right)+\gamma_{1,1}s_d+\gamma_{2,1}u_d\right) \\ \text{for } T_{w,1} \geq T_d, \text{after adaptation}\end{cases} \tag{2}$$

where parameters β and r, as well as the threshold value of WBGT $T_{w,}$ were assumed to be varying via heat acclimation (subscript 0 denotes before adaptation and 1 denotes after adaptation) and $\gamma_{1,i}$ and $\gamma_{2,i}$ are coefficients for s_d and u_d, respectively, before $(i=0)$ and after $(i=1)$ natural adaptation representing the average daily temperature (°C) reached the highest value of the season. This particular model was identified as most reasonably capturing observed heatstroke-related ambulance transports (Fujimoto et al., under review). Assuming that the number of ambulance transports owing to heatstroke follows a Poisson distribution, maximum likelihood estimation was performed to obtain optimal parameter values. The Akaike information criterion (AIC) was computed and the model with the best fit was selected.

The best fit model was used for projection using weather data of RCP 1.9, 2.6, 4.5, and 8.5 in three climate change scenarios to yield the predicted number of heatstroke-related transports from 2020 to 2100. The number of heatstroke cases was calculated per 100,000 people.

Because the heatstroke incidence is greatly affected by temperature variations in each year, a 5-year arithmetic average was taken for each 5-year period. Relative risk per year was computed, comparing projections against the empirically observed 5-year median from 2015 to 2019 and the carbon-neutral scenario in the same year (RCP 1.9).

2.3. Intervention effectiveness

The *per capita* probability of heatstroke from May to September in Tokyo was empirically estimated as ranging from 0.12 to 0.08%; thus, we judged the incidence of heat stroke to be rare, and we adopted odds ratios as an approximation of risk ratio. To calculate the effect of intervention measures in reducing the incidence of heatstroke, we used the adjusted OR of factor v, q_v and the proportion of older adults having the risk factor v in year t, $p_{v,t}$. Among the population at risk with factor v, we observed $q_v p_{v,t}$ as the risk of heatstroke; among the remainder without factor v, the population at risk is $1-p_{v,t}$. Normalizing these, the fraction of heatstroke that occurs among people with factor v would be $q_v p_{v,t} / \left(q_v p_{v,t} + \left(1-p_{v,t}\right)\right)$. Similarly, the fraction of heatstroke among people without risk factor v would be $\left(1-p_{v,t}\right) / \left(q_v p_{v,t} + \left(1-p_{v,t}\right)\right)$. Of these, in the presence of interventions, only the $q_v p_{v,t}$ part of the numerator would be reduced by intervening the risk factor v for a fraction $i_{v,t}$ in year t. That is, at the population level, the relative risk reduction by intervening factor v by $i_{v,t}$ is:

$$k_v = \frac{q_v p_{v,t}\left(1-i_{v,t}\right)+\left(1-p_{v,t}\right)}{q_v p_{v,t}+\left(1-p_{v,t}\right)} \tag{3}$$

where k_v is the relative decrease in the number of heatstroke patients attained by intervention into risk factor v. Because we handled multiple risk factors, we calculated the projected number of heatstroke-related ambulance transports under interventions, $n'\left(T_d\right)$ as

$$E\left(\sum_d n'\left(T_d\right)\right) = \prod_v k_v \times \sum_d E\left(n\left(T_d\right)\right) \tag{4}$$

That is, the expected number of heatstroke-related transports per 100,000 population estimated for the period from May to September was obtained by multiplying the obtained preventive effect k_v for all examined risk factors. Computation was carried out, assuming that adaptation measures are implemented from 2030 and that it would take 5 years from 2030 to reach the plateaued level of intervention.

To calculate the future proportion of people with pre-determined risk factors among people aged 65 years and older (i.e., to calculate $p_{v,t}$), the following analyses were conducted. Due to data limitation of the FMDA's heatstroke transport data, which only specifies whether patients were 65 years and older, we calculated age-specific risk based on this age grouping. First, the projected rate of older adults living alone by 2040 was retrieved from the National Institute of Population and Social Security Research in Tokyo (42), and the estimate was used as empirical data for additional future projections. Because the size of the entire population of Japan will decrease (with deaths of the baby boomer generation), with a substantial decrease in the demand for older adult care, a quadratic equation was fitted to capture the forthcoming decline in the proportion of older people living alone and was fitted to the abovementioned data to 2040. Alternatively, in the case of a scenario in which the proportion of the older population living alone remains constant, a cubic exponential formula was used. As for the proportion of people who are unable to drink water independently, the proxy value was the percentage of those certified as having care need level 3 or more (i.e., a condition that requires total assistance in the activities of daily living) (43), retrieved from the Tokyo Metropolitan Government (44). Information on certification rates by sex and age group for care need levels 3, 4, and 5 for the years 2015–2020 were used; it was assumed that the care need level was determined by age and will not change after 2020. The age-dependent proportion of older adults with care levels 3–5 in 2020 was used to project the proportion of people who are unable to drink water independently through 2100 (40). Lastly, the percentage of households without air-conditioning was estimated using the observed percentage from 2011 to 2022 from the National Survey of Living Conditions (45) in Japan conducted by the Ministry of Health, Labour, and Welfare.

All calculations were performed using JMP statistical software, version 16.0 (SAS Institute Inc., Cary, NC, United States) and R software version 4.2.0 (The R Project for Statistical Computing, Vienna, Austria).

3. Results

3.1. Explanatory variables of heatstroke risk

The cross-sectional survey involved 576 participants, including 166 older adults with a history of heatstroke and 410 without a heatstroke history. Participants' characteristics and the results of univariate analysis are summarized in Table 1. Among explanatory variables of heatstroke episodes, (i) male sex, (ii) having an underlying medical condition, and (iii) living alone were significant. The OR and 95% confidence interval (CI) of these variables was 1.7 (95% CI: 1.2, 2.4), 2.5 (95% CI: 1.6, 3.8), and 2.1 (95% CI: 1.2, 3.5), respectively. Although not significant, the ORs of inability to drink water independently and absence of air-conditioning were 1.5 (95% CI: 1.0, 2.3) and 1.6 (95% CI: 0.9, 2.6), respectively.

Then, factors into which interventions could be made were further examined. Based on the results from univariate analysis, three intervention-related factors were (i) people living alone, (ii) being unable to drink water independently, and (iii) not having an air-conditioner. After propensity score matching and IPTW calculations, Table 2 shows the adjusted ORs for these factors: 2.5 (95% CI: 1.2, 5.4), 1.2 (95% CI: 0.7, 2.1), and 1.6 (95% CI: 0.8, 3.2), respectively. Although the 95% CIs from propensity score matching were widened compared with the results univariate analysis, IPTW analysis yielded significant results for all three variables (Table 2). Accordingly, we examined the effects of intervention for all three factors in a subsequent analysis. Supplementary Tables S1–S3 show the results of propensity score matching.

3.2. Future prediction scenario of heatstroke

In analyzing multiple models describing heatstroke-related ambulance transports from 2015 to 2019, Supplementary Table S4 shows the summary of model comparisons (including AIC values and mean squared error). The best fit model was identified as:

TABLE 1 Characteristics of participants with crude odds ratio, confidence intervals, and p-values for heatstroke.

Characteristic	Participants with heatstroke episode(s), N = 166^1	Non-heatstroke participants, N = 410^1	Odds ratio (95% confidence interval)	p-value
Age (years)	84.4 (7.8)	86.7 (6.9)	0.95 (0.9, 1.0)	<0.01
Gender (Male)	92/166 (55%)	174/410 (42%)	1.7 (1.2, 2.4)	<0.01
Underlying medical condition	53/166 (32%)	65/410 (16%)	2.5 (1.6, 3.8)	<0.01
Require nursing care	134/166 (81%)	301/410 (73%)	1.5 (1.0, 2.4)	0.08
Inability to move	55/166 (33%)	151/410 (37%)	0.9 (0.6, 1.2)	0.46
Living alone	28/166 (17%)	37/410 (9.0%)	2.1 (1.2, 3.5)	0.01
Inability to drink water	38/166 (23%)	68/410 (17%)	1.5 (1.0, 2.3)	0.10
Absence of air-conditioner	27/166 (16%)	45/410 (11%)	1.6 (0.9, 2.6)	0.11

[1] Mean (standard deviation); n/N (%).

Underlying medical conditions included four diseases (depression, heart failure, kidney disease, and Parkinson's disease) as these potentially lead to the inability to move if exacerbated. Requiring nursing care refers to the need for help in activities of daily living (e.g., eating and dressing). The inability to move describes whether an older adult is able to move to a cooler place in elevated temperatures. Inability to drink water indicates that the person is unable to drink water independently.

TABLE 2 Odds ratio of developing heatstroke.

Risk factors	Crude OR^1 (95% CI^2)	Adjusted OR^1 (95% CI)	
		PS^3-matched	IPTW^4
Living alone	2.1 (1.2, 3.5)	2.5 (1.2, 5.4)	2.1 (1.6, 2.7)
Inability to drink water	1.5 (1.0, 2.3)	1.2 (0.7, 2.1)	2.0 (1.5, 2.7)
Absence of air-conditioner	1.6 (0.9, 2.6)	1.6 (0.8, 3.2)	1.6 (1.2, 2.0)

OR^1, odds ratio; CI^2, confidence interval; PS^3, propensity score; IPTW^4, inverse probability of treatment weighting.

Directed acyclic graphs and confirmed variables are presented in Supplementary Figure S1.

A logistic regression model with six baseline independent variables (age, sex, underlying disease, inability to move, and two other factors) was used to estimate the propensity score.

$$E\left(n\left(T_d\right)\right)=\begin{cases}\beta_0 \ \text{for}\ T_d < T_{w,0}, \text{before adaptation}\\ \beta_1 \ \text{for}\ T_d < T_{w,1}, \text{after adaptation}\\ \beta_0 \exp\left(r_0\left(T_d - T_{w,0}\right)+\gamma_1 s_d+\gamma_2 u_d\right)\\ \text{for}\ T_{w,0} \geq T_d, \text{before adaptation}\\ \beta_1 \exp\left(r_1\left(T_d - T_{w,1}\right)+\gamma_1 s_d+\gamma_2 u_d\right)\\ \text{for}\ T_{w,1} \geq T_d, \text{after adaptation.}\end{cases} \qquad (5)$$

Compared with equation (2), it should be noted that γ_1 and γ_2 in equation (5) do not change before and after natural adaptation owing to the average daily temperature reaching the highest value of the season. The variable u_d indicates whether there were 3 consecutive days with the daily maximum WBGT exceeding 31°C. Maximum likelihood estimates of the parameter were estimated at $T_{w,0} = 22.1$, $T_{w,1} = 19.3$, $r_0 = 0.31$, $r_1 = 0.34$, $\beta_0 = 0.87$, $\beta_1 = 0.22$, $\gamma_1 = 0.04$, and $\gamma_2 = 0.58$, respectively. Using these parameters, projection scenarios of heatstroke were produced by the year 2100 for each RCP using three climate change scenarios, MIROC6, MRI-ESM-2.0, and IPSL-CM6A-LR. The predicted results are shown in Figure 1. Compared with the 5-year median number of heatstroke-related ambulance transports from 2015, even RCP 1.9 (i.e., carbon-neutral scenario) was projected to involve increased heatstroke-related transports under MIROC6 and MRI-ESM-2.0. Specifically, the MIROC6 model projected a maximum increase of 40%, while the MRI-ESM-2.0 model projected a maximum increase of 30% in heatstroke-related transports. Although there were differences depending on climate change scenarios, RCP 4.5 and RCP 8.5 showed increments in the number of heatstroke-related ambulance transports among people aged over 65 years compared with projections from RCP 1.9.

The results of relative risk calculations are shown in Table 3. Taking the baseline as the 5-year median from 2015 for the period from May to September, the number of heatstroke-related ambulance transports were increased for RCP 2.6, 4.5, and 8.5. Depending on the year, the number of heatstroke-related transports will increase by approximately 20% with RCP 2.6, 30% with RCP 4.5, and 50% with RCP 8.5. In particular, we found that after 2060, the relative increase compared with the baseline period will continue to exceed 50% with RCP 8.5. Using RCP 1.9 as a baseline, RCP 2.6 yielded an approximate 5–20% increase after 2060. In MIROC6, compared with the RCP 1.9 scenario, RCP4.5 climate scenario was expected to increase the number of heatstroke-related ambulance transport by more than 30% compared to RCP1.9, and RCP8.5 scenario more than 50%, in the second half of the 21st century.

3.3. Future prediction of intervention effectiveness

For the intervention scenarios, we calculated heatstroke-related ambulance transports, assuming a relative decrease in risk groups of 30% (i.e., 30% relative decrease in the number of older adults living alone) and similarly, relative decreases of 30, 50, 70, 90, and 100% for all three risk factors. Figure 2 shows the expected baseline number of heatstroke-related ambulance transports with two different future outcomes for the proportion of older people living alone (i.e., declining or remaining constant), along with results of the abovementioned interventions (i.e., adaptation policies). Figure 2 shows the results using MRI-ESM-2.0; the results with the two other climate change scenarios are shown in Supplementary Figures S2, S3 (Supplementary material 3).

Under a scenario in which the proportion of older people living alone declines over time in the future, a 30% relative reduction in the

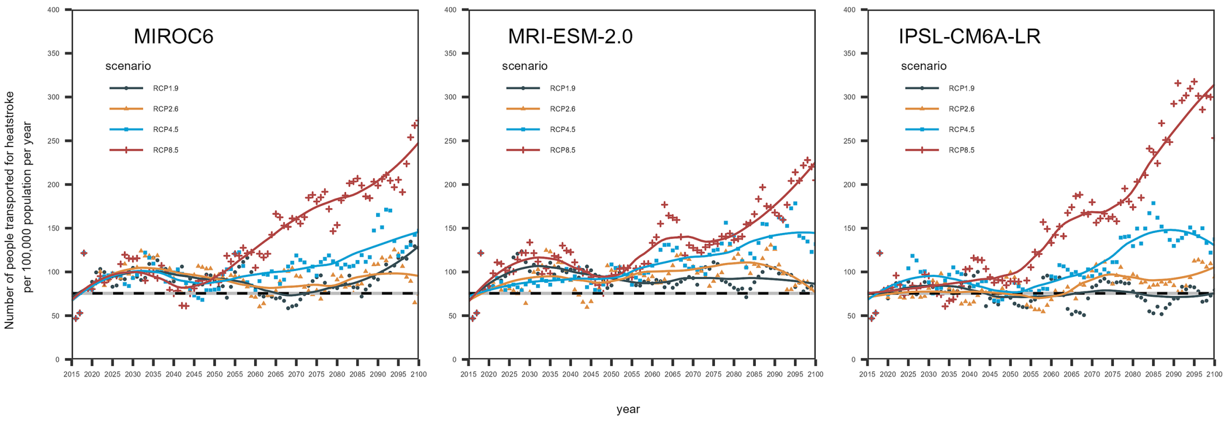

FIGURE 1
Projected number of heatstroke-related ambulance transports among older adults in Tokyo from 2015 to 2100 using three climate change scenarios (MIROC6, MRI-ESM-2.0, and IPSL-CM6A-LR). The vertical axis is the number of heatstroke-related ambulance transports per 100,000 population, and the horizontal axis represents the year. The dots are the 5-year average number of heatstroke-related transports per 100,000 population per year; the line represents the smoothed line. Smoothing was done using the LOESS method, with a span of 0.5. The colors of the dots and lines are the same for each RCP. The black dotted line at the bottom of the image shows the 5-year median since 2015 for the number of people transported by ambulance owing to heatstroke.

number of older adults living alone would result in an up to 15% decrease in the number of heatstroke-related transports. Similarly, concerted interventions (i.e., averting all three risks) would result in a 20% decrease in heatstroke by decreasing the proportions with risk factors at 30%. These findings were similar in another scenario where the future proportion of older adults living alone was maintained constant (Figure 2). In RCP 8.5, even with 100% relative reduction in all identified risks, the frequency of heatstroke could still not be lowered in comparison with the carbon-neutral scenario in some years.

4. Discussion

Using daily maximum WBGT values, additional meteorological information, and accounting for probable heat acclimatization during consecutive hot days in the summer season, we estimated the number of heatstroke-related ambulance transports in the future under various climate change scenarios. The proposed model can provide better fit to observed data than our earlier model (30), yielding a long-term prediction in Tokyo until the year 2100. We showed that to reduce the future burden of heatstroke below historical levels, heatstroke adaptation measures are vital, even with a carbon-neutral scenario. To be comparable to carbon neutrality, with future climate change under RCP 2.6, a 30% relative reduction in all three identified risks from 2060 is required, and under RCP 4.5, a 70% relative reduction from 2050 is needed. In the case of RCP 8.5, even a 100% reduction is not comparable to RCP 1.9 in some years, calling for serious mitigation measures.

To the best of our knowledge, our study is the first to combine an epidemiological survey and future projection of heatstroke in the context of adaptation measures. Although a few excellent machine learning-based predictions of heatstroke-related ambulance transports in Japan have been conducted (28, 29) and epidemiological studies of admitted patients with heatstroke have been reported (44, 45), no studies have examined risk factors of the onset of heatstroke, aiming to reduce this risk. Although our survey was cross-sectional, the snapshot survey of heatstroke history among older adults enabled us to cover the risk of broad-spectrum heatstroke (including mild cases), allowing for the calculation of ORs. Intervenable factors of heatstroke were found to be (i) living alone, (ii) inability to drink water independently, and (iii) the absence of air-conditioning. The adjusted OR allowed us to examine possible future scenarios under which the above risk factors were partially improved via social support (as part of a future adaptation policy). With an elevated risk of heatstroke in the future, intervenable factors (i)–(iii) above could alleviate the heatstroke risk in the future such that the number of cases can be maintained to a number comparable to a carbon-neutral scenario.

For the calculation of future interventions, obtaining adjusted ORs is key. Although the present study was cross-sectional, propensity score matching allowed us to adjust for observed measurable confounders. Among examined variables that can be intervened into, living alone yielded the highest OR value. Among all examined variables, having an underlying medical condition yielded the highest risk estimate (followed by living alone), but having a medical condition is not intervenable. Thus, not merely adjusting for confounders but also using the matching method was useful to adjust for known strong predictors. Considering that older adults tend to have difficulty in recognizing and objectively judging heat levels (5, 6), having peer or professional support, especially for people living alone, is deemed a reasonable option.

Classically, potential interventions among older adults have been restricted to the use of air-conditioning and frequent drinking of water to prevent dehydration (1, 3, 48), which is important, as dehydration can frequently develop into heatstroke. However, the effect sizes of lack of air-conditioning and an inability to drink water were smaller than that of living alone. The greater importance of living alone poses a challenge for adaptation measures because living with others cannot be achieved via peer support only and calls for concerted action by local governments. Japanese older adults generally have lower incomes than working-age adults, with the main income from pensions, and single-person households are expected to have

TABLE 3 Relative risk of the increase in heatstroke-related ambulance transports relative to 5-year median from 2015 to 2019 and carbon-neutral scenario.

Relative risk of increase in heatstroke-related ambulance transports										
Scenario	Baseline		2030s	2040s	2050s	2060s	2070s	2080s	2090s	2100
MIROC6	2015–19	RCP2.6	31.7 (19.4, 39.1)	20.1 (0, 29.1)	19.6 (0, 22.0)	1.8 (0, 27.6)	6 (0, 21.7)	14.8 (0.4, 30.3)	31.9 (0, 39.7)	0
		RCP4.5	25.3 (15.0, 38.2)	5.3 (0, 26.7)	24.6 (5.4, 38.4)	20.8 (4, 31.7)	32.5 (21.2, 36.5)	31.3 (27.6, 48.8)	45.6 (36.3, 55.9)	48.7
		RCP8.5	24.3 (5.0, 34.7)	5.4 (0, 19.2)	36.3 (14.3, 40.8)	48.6 (28, 54.6)	57.2 (48.5, 60.6)	60.9 (50.8, 63.5)	63.3 (60.5, 71.8)	72.4
	RCP1.9	RCP2.6	6.2 (0, 26.8)	5.0 (0, 19.8)	2.8 (0, 22.5)	6.9 (0, 41.9)	3.5 (0, 35.1)	10.3 (0, 20.5)	3.7 (0, 16)	0
		RCP4.5	1.4 (0, 23.7)	0 (0, 10.3)	6.8 (0, 31.5)	26.1 (0, 45.2)	25.1 (1.9, 47.9)	25.7 (9.6, 39.7)	15.6 (0, 44.7)	13.7
		RCP8.5	0 (0, 18.3)	0 (0, 5.5)	14.0 (3.4, 40.5)	53.0 (21.3, 62.4)	54.2 (43.6, 61.3)	54.2 (47, 63.8)	48.6 (39.5, 54.1)	53.5
MRI-ESM-2.0	2015–19	RCP2.6	29.2 (1.8, 39.5)	4.1 (0, 29.5)	24.3 (17.4, 28.7)	26.3 (13.6, 37.1)	23.7 (9.8, 42.2)	34.1 (23.1, 42.2)	14.2 (5.1, 40.0)	2.1
		RCP4.5	16.2 (10.0, 27.0)	15.5 (3.2, 27.7)	22.9 (11.4, 30.5)	36.6 (27.3, 42.4)	38.2 (22.6, 51.7)	41.8 (28.1, 51.3)	48.5 (38.6, 57.7)	42.7
		RCP8.5	35.7 (22.7, 43.5)	21.6 (0, 38.4)	27.3 (19.6, 31.0)	48.7 (36.5, 57.3)	42.7 (38.1, 47.6)	53.1 (44.7, 61.6)	63.1 (52.7, 66.9)	63.1
	RCP1.9	RCP2.6	6.8 (0, 15.3)	0 (0, 23.8)	7.7 (3.7, 17.6)	14.1 (0, 27.7)	4.4 (0, 34.5)	19.5 (11.1, 33.7)	0.9 (0, 17.0)	0
		RCP4.5	0 (0, 3.8)	0 (0, 13.4)	7.9 (0, 22.1)	25.4 (9.2, 37.0)	13.3 (0, 43.3)	31.5 (23.8, 42.2)	38.5 (18.1, 53.6)	34.3
		RCP8.5	11.6 (0, 24.6)	0 (0, 16.1)	11.9 (3.6, 19.6)	40.0 (22.7, 53.4)	24.1 (16.7, 40.6)	44.6 (38.9, 54)	54.9 (37.5, 65)	57.7
IPSL-CM6-LR	2015–19	RCP2.6	7.4 (0, 22.9)	0 (0, 19.7)	0 (0, 23.9)	3.3 (0, 20.0)	22.2 (12.4, 32.2)	14.3 (8.3, 22.2)	24.0 (1.9, 33.6)	20.1
		RCP4.5	15.5 (0, 28.2)	5.8 (0, 15.6)	4.7 (0, 13.9)	23.6 (19.4, 30)	29.4 (20.7, 46.3)	49.6 (41.7, 57.7)	46.0 (38.1, 49.9)	45
		RCP8.5	0 (0, 26.6)	23.4 (10.9, 34.9)	22.3 (0.1, 51.9)	54.7 (43.3, 59.9)	54.2 (51.7, 61.3)	67.2 (56.6, 72)	74.9 (73.6, 76.2)	70.2
	RCP1.9	RCP2.6	3.9 (0, 21.1)	8.0 (0, 20)	2.1 (0, 31.9)	23.6 (0, 40.3)	9.0 (0, 22)	29.0 (19.3, 41.5)	22.3 (0, 40.7)	16.1
		RCP4.5	8.3 (0, 28.6)	4.1 (0, 31.9)	11.6 (0, 27.3)	38.0 (2.2, 47.2)	18.8 (7.9, 38.2)	57.5 (40, 70.5)	44.8 (40.2, 56)	42.3
		RCP8.5	0 (0, 8.4)	24.1 (9.3, 41.1)	35.0 (20.8, 44.3)	61.8 (31.0, 71.7)	46.4 (44.2, 55.5)	73.8 (55.3, 80.8)	75.0 (71.9, 77.9)	68.7

RCP, representative concentration pathways.

Numbers in the table are 10-year median and range (minimum to maximum). There is no range for 2100 (there is a predicted number only for this particular year). RCP 1.9 is the climate scenario in which carbon neutrality is achieved; higher values after RCP are considered to result in greater temperature increases. The 5-year average of the number of heatstroke transports per 100,000 population for each year with RCP 2.6, RCP 4.5, and RCP 8.5 was calculated. The difference compared with the baseline for each year was then calculated, and the ratio of each year in the number of changes was calculated. As practiced in excess risk evaluation, the difference was taken over the course of the year for the data point at which the predicted value exceeded the baseline value. The units are percentages.

lower incomes than multiple-person households (32). These difficulties often lead to older adults having multiple risk factors, including a lack of air-conditioning, especially older adults who live alone.

There are four limitations of the present study. First, we cannot exclude the possibility of unadjusted confounders during propensity score matching and IPTW. We systematically searched for published studies and drew directed acyclic graphs, but using the selected survey and modeling method, we cannot exclude the presence of unmeasured confounders. Second, the sample size might have been small to sufficiently identify risk factors via propensity score matching. To ensure the representativeness, we checked the correlation of (i) the proportion of older adults aged 75 years and older and (ii) the participants per population size across prefectures, and the resulting

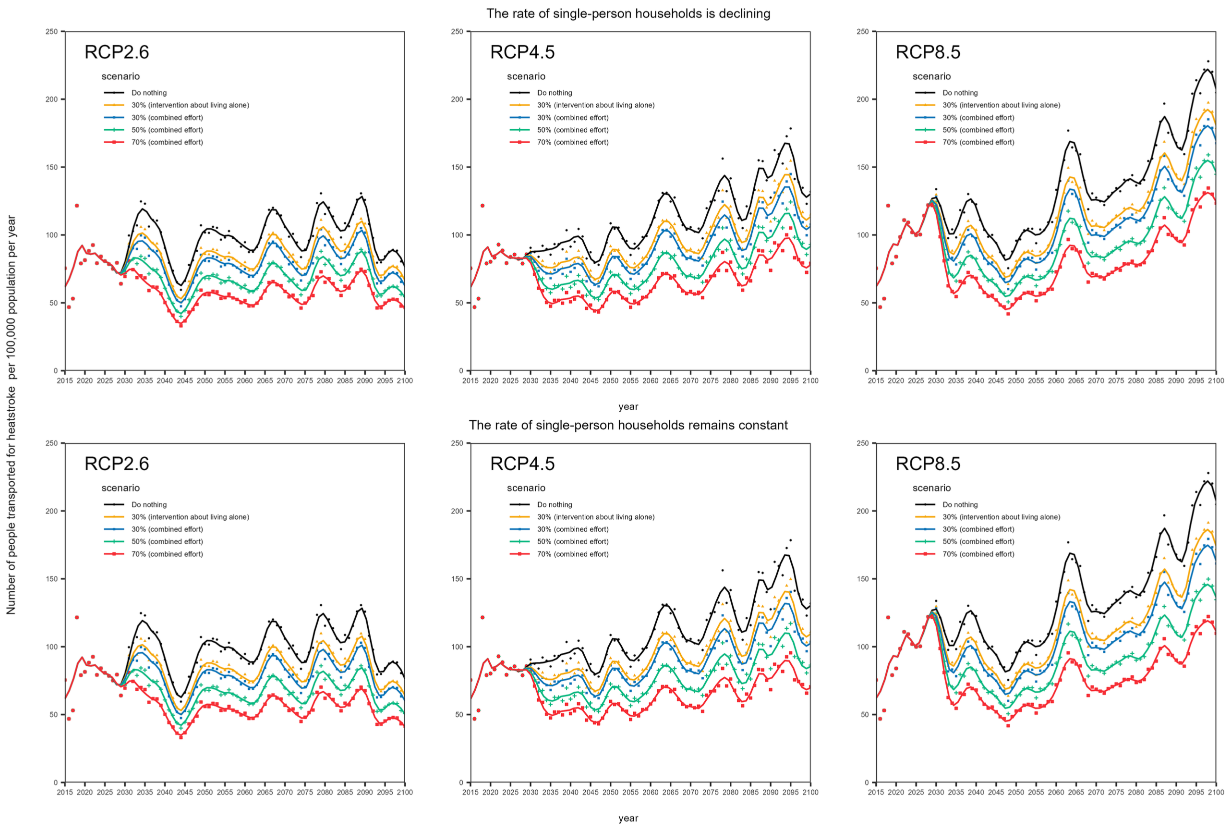

FIGURE 2
Projected effectiveness of interventions against heatstroke in Tokyo this figure shows the predicted results for heatstroke-related ambulance transports without and with intervention (adaptive policy) for each RCP, using MRI-ESM-2.0 in Tokyo. The dots represent the 5-year average number of heatstroke-related transports among older adults transported in each year, and the lines represent smoothing lines. LOESS was used as the smoothing method, with a span of 0.5. We assumed that the target will be achieved over a 5-year period starting in 2030. The top three panels show the effects of adaptation measures per RCP for a scenario in which the future proportion of older adults living alone declines along with the population from 2040. The bottom three panels show the effects of adaptation measures per RCP for a scenario in which the future proportion of older adults living alone is maintained constant. Combined effort means all three risk factors were assumed to be intervened into (i.e., living alone, inability to drink water independently, and absence of air conditioning).

R^2 being 0.94 reflects the fact that older people were geographically balanced in their sampling frequency. A larger sample size with additional variables is needed in future studies. Third, estimated ORs were retrieved from the survey of people aged 75 years and older; the actual population-based estimate for people aged 65 years and older may be smaller than our calculation. Thus, discussions over more precise policy-related goals require similar surveys addressing this point. Fourth, some parameters were retrieved for all of Japan whereas the proposed model was restricted to Tokyo. This model specifically captures the situation in Tokyo, which, despite having one of the lowest proportions of older adult people in Japan, still records one of the highest numbers of heatstroke incidents per year. Japan, with its elongated geography from north to south, has diverse summer temperature environments across its regions. However, it's well known that a dose–response relationship exists between the daily maximum WBGT and the number of heatstroke cases in Japan all prefectures (49). Given the availability of similar data like this study, it could be possible to apply this model to other regions of Japan. Nevertheless, differences in regional factors such as the urban heat island effect and population characteristics demand caution when generalizing these findings. Further studies are needed to identify risk factors for all of Japan and to develop a representative prediction model using different geographic and temporal settings.

Despite these limitations, we successfully estimated the future number of heatstroke-related ambulance transports using climate change scenarios in Japan. We found that even with a 70% relative reduction in all identified risk factors under RCP 2.6, 4.5, and 8.5, the resulting relative decrease in heatstroke would be approximately 40%. Even if carbon neutrality were achieved, we estimated that the number of ambulance transports owing to heatstroke would exceed the 5-year median in 2015. Aiming to achieve carbon neutrality as the temporary goal, it is advisable to implement adaptation measures to reduce the risk of heatstroke among older adults.

5. Conclusion

The number of heatstroke-related ambulance transports among people aged 65 years and older in Tokyo was projected through 2100 under various climate change scenarios. In a cross-sectional survey, intervenable factors for heatstroke were shown to be (i) living alone, (ii) inability to drink water independently, and (iii) absence of air-conditioning, and we estimated their effect sizes. To reduce the future burden of heatstroke below historical levels, heatstroke adaptation measures are vital, even in a carbon-neutral scenario. To be comparable to carbon neutrality, future climate change under RCP 2.6 would require a 30% relative reduction in all three identified risks from 2060, and RCP 4.5 would require a relative reduction of 70% or more from 2050. In the case of RCP 8.5, even a 100% reduction would not be comparable to RCP 1.9, calling for serious mitigation measures. If aiming to achieve carbon neutrality as the temporary goal, it is advisable to implement adaptation measures to reduce the risk of heatstroke among older adults. Based on our findings, a variety of stakeholders can smoothly consider future preparedness plans. For instance, local government could help establish a system that identifies a household at high risk of heatstroke in older people, prioritizing tailor-made interventions for those at risk as part of mitigation strategy (50). Furthermore, these insights could also assist community caregivers and senior citizens themselves to properly understand the forthcoming risk and potentially mitigate future heatstroke risks.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: original data, including modeled climatological data for the period 2015–2019 and empirical data on heat-related ambulance transports, are openly shared as online supporting material (32–34, 36, 37).

Ethics statement

Informed consent was obtained via internet from all participants in the cross-sectional survey. After the completion of the survey, Mellinks Ltd. collected and anonymized data in such a way that it could not be traced back to any personally identifiable information. The cross-sectional survey was approved by the Ethics Committee, Kyoto University Graduate School and Faculty of Medicine (no. R3120). The study complied with the Declaration of Helsinki, 2013.

Author contributions

MF: data curation, formal analysis, investigation, methodology, visualization, writing – original draft, and writing – review and editing. KH: methodology, supervision, and writing – review and editing. HN: conceptualization, methodology, formal analysis, supervision, writing – review and editing, and project administration. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2023.1184963/full#supplementary-material

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