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Published

2024

Journal Title

Environmental Research

Version

Accepted Manuscript (AM)

DOI

10.1016/j.envres.2024.119869

Journal Pre-proof

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PII: S0013-9351(24)01774-2

DOI: https://doi.org/10.1016/j.envres.2024.119869

Reference: YENRS 119869

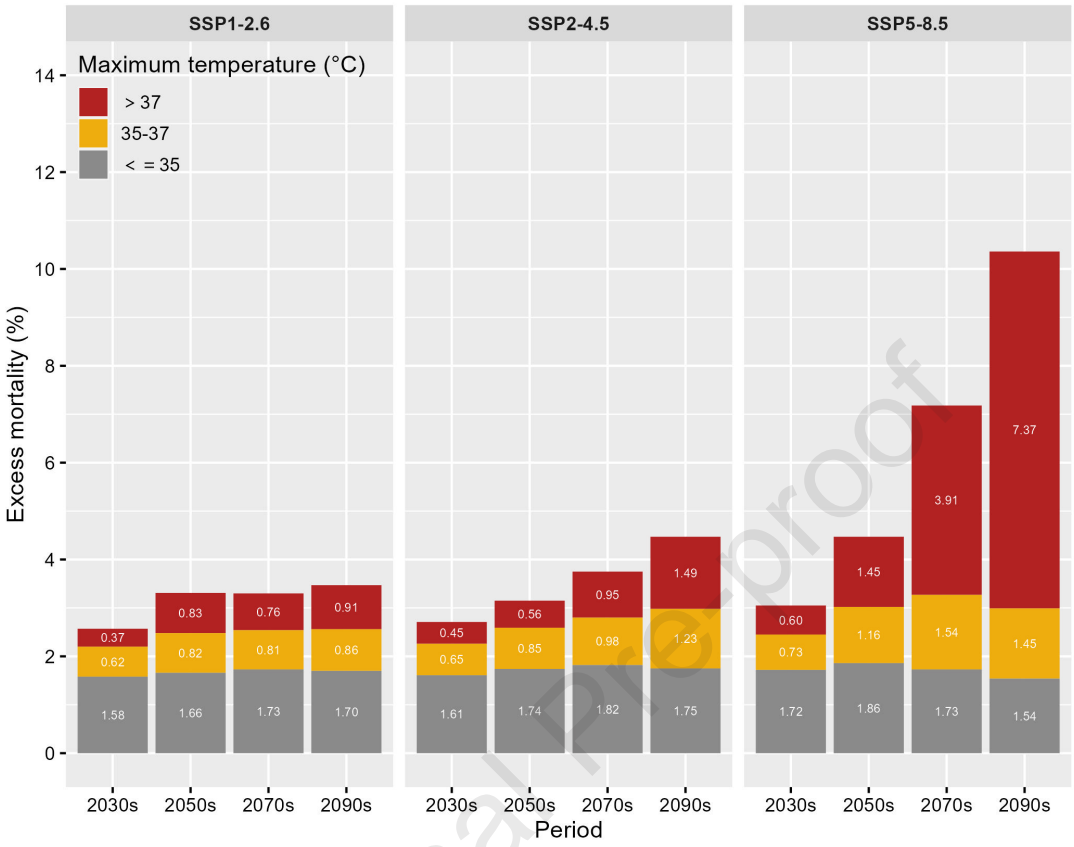
To appear in: *Environmental Research*

Received Date: 15 July 2024

Revised Date: 26 August 2024

Accepted Date: 27 August 2024

Please cite this article as: Yi, W., Bach, A., Tong, S., Cheng, J., Yang, J., Zheng, H., Ho, H.C., Song, J., Pan, R., Su, H., Xu, Z., Quantifying the historical and future heat-related mortality above the heat alert thresholds of the inaugural Chinese national heat-health action plan, *Environmental Research*, https://doi.org/10.1016/j.envres.2024.119869.



Quantifying the historical and future heat-related mortality above the heat alert thresholds of the inaugural Chinese national heat-health action plan

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Abstract

Background: China published its inaugural national heat-health action plan (HHAP) in 2023, but the mortality burden associated with temperatures exceeding the heat alert thresholds specified by this HHAP (maximum temperatures >35, 37, or 40 °C) remains unknown. We aimed to estimate the historical and future mortality burden associated with temperatures above the heat alert thresholds of the Chinese national HHAP.

Methods: We conducted time-series analyses to estimate the mortality burden associated with temperatures exceeding the three heat alert thresholds from 2016-2019 in Jiangsu Province (including 13 cities, population ~80.7 million), China. A quasi-Poisson regression in conjunction with a distributed lag non-linear model was used to estimate the dose-response association between maximum temperature and mortality risk from 2016-2019, adjusting for potential covariates. We then projected the future mortality burden associated with temperatures exceeding these thresholds under three distinct levels of greenhouse gas (GHG) emission scenarios via scenario shared socioeconomic pathways [SSP] 1-2.6 (low), SSP2-4.5 (intermediate), and SSP5-8.5 (high), respectively, by assuming that there will be no adaptation to heat. Climate scenarios derived from the General Circulation Model (GCM) under the Coupled Model Intercomparison Project Phase 6 (CMIP6) were used.

Results: From 2016-2019, temperatures above 35 °C were associated with 0.51% of mortality, including 0.40% associated with 35 °C – 37 °C and 0.11% associated with >37 °C. Heat-related mortality risk was most prominent in those who were single/divorced/widowed and had <10 years of education. Under SSP2-4.5, compared with the 2020s, the excess mortality associated with >37 °C would increase by 1.4 times in the 2050s and 1.7 times in the 2090s. Under SSP5-8.5, the annual number of days with maximum temperature >37 °C would approximately double every 20 years (67 days annually in the 2090s). Consequently, compared with the 2020s,

the excess mortality associated with >37 °C would increase by 2.8 times in the 2050s and 18.4 times in the 2090s.

Conclusion: Significant mortality risk is associated with temperatures above the lowest heat alert threshold of the Chinese national HHAP (35 °C). If the high GHG emission scenario occurred, the annual number of days and excess mortality associated with maximum temperatures >37 °C would largely increase in the coming decades.

Keywords: Climate change; Heat-health action plan; Inequality; Mortality

Introduction

Exposure to heatwaves (i.e., prolonged days of extreme heat) is associated with an increased risk of mortality (Chen et al., 2022; Liu et al., 2023; Xu et al., 2016). Effective heat-health action plans (HHAPs), early warnings of the imminent heatwaves, along with a series of heat-health risk reduction actions, can save lives (Jay et al., 2021; Kapwata et al., 2022). Setting the heat alert thresholds is a crucial step in the development of HHAPs, because it determines when to trigger an HHAP (McGregor et al., 2015).

In June 2023, the Chinese National Administration of Disease Prevention and Control issued the first national HHAP in China (CNADPC, 2023). The release of the Chinese HHAP aims to remind the public and pertinent departments to pay attention to the health risks posed by hot weather and take precautionary measures to protect people's lives and property. The public is advised to pay close attention to weather forecasts and warning information, arrange travel and activities accordingly, and prevent heat-related health issues (e.g., heat stroke). This HHAP stated that, if the maximum temperature exceeds 35 °C (for three consecutive days), 37 °C (within the next 24 hours), or 40 °C (within the next 24 hours), yellow, orange, and red heat warnings should be issued, respectively. Quantifying the mortality burden associated with temperatures above these heat alert thresholds is useful because it can illustrate (in a perfect world) how many heat-related deaths could be prevented under this HHAP in China.

As climate change progresses, extreme heatwaves, once rare, will become more common (e.g., the 2022 extreme heatwaves in China) (Masson-Delmotte et al., 2021; Zhang et al., 2023). Previous studies have predicted that the number of heatwave days and heat-related mortality will gradually increase in the future (Gasparrini et al., 2017; Liu et al., 2023), but the number of heat-related deaths preventable under the HHAP in China is unknown. Though it is not easy to quickly change the occurrence of extreme heatwaves, we can invest in building society's

heat resilience (e.g., allocation of cooling resources). To effectively invest in building the heat resilience of society, it is essential to estimate the future death burden associated with temperatures above prescribed heat alert thresholds under climate change scenarios.

In this study, we aimed to: (1) quantify the historical death burden associated with temperatures above the heat alert thresholds of the national HHAP in 13 cities of Jiangsu Province, China; and (2) project the future death burden associated with temperatures above these heat alert thresholds under various climate change scenarios.

Methods

Study site

This study was conducted in Jiangsu Province, an eastern coastal province of China. Jiangsu has a low altitude, a humid subtropical climate, and a large population (population in 2019: 80.7 million (Jiangsu Provincial Bureau of Statistics, 2020)). According to the report released by the Cross Dependency Initiative (XDI) in 2023, Jiangsu has the highest physical risk of damage from extreme weather and climate change in 2050 across 2600+ jurisdictions worldwide (XDI Initiative, 2023). It has 13 cities including Nanjing (the capital city), Wuxi, Xuzhou, Changzhou, Suzhou, Nantong, Lianyungang, Huai'an, Yancheng, Yangzhou, Zhenjiang, Taizhou, and Suqian (Figure S1).

Ethics

Before the commencement of the data collection, we obtained the ethics approval for this study from the Institutional Ethics Board at the School of Public Health, Anhui Medical University (ethics approval number: 20210619).

Historical deaths, climate, and air pollution data

Individual-level mortality data for all 13 cities of Jiangsu Province from 1st January 2016 through 31st December 2019 were provided by the Jiangsu Provincial Center for Disease Control and Prevention. The mortality data included information on each decedent's death date, death age, primary cause of death, gender (male, female), marital status, and educational attainment. The primary cause of death was coded with the International Classification of Diseases, Tenth Revision (ICD-10). We dichotomised death age into '0-74 years' and '75+ years' following our previous work (Yang et al., 2021), dichotomised marital status into 'married' and 'single/divorced/widowed', and dichotomised educational attainment into '<10 years of education' and '≥10 years of education'.

Data on ambient temperature and dewpoint temperature from the 1st January 2016 to 31st December 2019 were obtained from the European Centre for Medium-Range Weather Forecasts Reanalysis Fifth Generation (ERA5) dataset, and the dataset had 9km*9km spatial and hourly temporal resolutions (Muñoz-Sabater et al., 2021). We used the maximum value of hourly ambient temperature within each day as the daily maximum temperature, and then averaged the daily maximum temperature values across all grid cells in each city to get the city-level daily maximum temperature values. We averaged hourly ambient temperature and dewpoint temperature values within each day to get the daily mean temperature and dewpoint temperature, respectively. We then calculated the daily relative humidity (Alduchov and Eskridge, 1996) and the details for relative humidity calculation are provided as supplementary materials.

Daily 10km*10km data on $PM_{2.5}$ (particulate matter with a diameter of 2.5 micrometers or less) and 8-hour maximum O_3 (ozone) from 1st January 2016 to 31st December 2019 were obtained from the Tracking Air Pollution in China dataset (http://tapdata.org.cn). The out-of-bag cross-validation results showed that $PM_{2.5}$ predictions of this dataset had good agreement with the

ground observations (Geng et al., 2021). We averaged the daily $PM_{2.5}$ and O_3 values across all grid cells in each city to get the city-level $PM_{2.5}$ and O_3 data, respectively.

Projected temperature data

Data on daily maximum temperature from 1st January 1980 to 31st December 2099 (spatial resolution: 0.25°*0.25°) were obtained from the National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections dataset (https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6). This dataset includes global downscaled climate scenarios derived from the General Circulation Model (GCM) under the Coupled Model Intercomparison Project Phase 6 (CMIP6) and across three greenhouse gas emission scenarios (called Shared Socioeconomic Pathways [SSPs]).

We obtained a series of projected daily maximum temperatures from 10 GCMs, including ACCESS-CM2, ACCESS-ESM1-5, BCC-CSM2-MR, MIROC6, MPI-ESM1-2-HR, MPI-ESM1-2-LR, MRI-ESM2-0, NESM3, NorESM2-LM, and NorESM2-MM. We used three SSP scenarios, including SSP1-2.6, SSP2-4.5, and SSP5-8.5 (Thrasher et al., 2022). SSP1-2.6 is the low CO_2 emission scenario where CO_2 emissions are strongly reduced and cut to net zero after 2050. SSP2-4.5 is the intermediate CO_2 emission scenario where CO_2 emissions hover around current levels before beginning to decline by 2050. SSP5-8.5 is the high CO_2 emission scenario where CO_2 emissions approximately double by 2050 (the worst-case scenario). We extracted simulated daily maximum temperature series for each city by associating the coordinates with the corresponding cells of the grid, and then calibrated them with the historical data using the bias-correction method developed in the Inter-Sectoral Impact Model Intercomparison Project (Vicedo-Cabrera et al., 2019).

Statistical analysis

Historical association between maximum temperature and mortality risk

In this study, we conducted two-stage analyses to estimate the exposure-response association between daily maximum temperature and mortality risk in Jiangsu Province from 2016 to 2019. Stage 1: we used a quasi-Poisson regression in conjunction with a distributed lag non-linear model (DLNM) to estimate the city-specific association between maximum temperature and mortality risk. In this model, we included a linear function of $PM_{2.5}$, O_3, and relative humidity (Vaidyanathan et al., 2019). We adjusted for seasonal and long-term trends using a natural cubic spline with 7 degrees of freedom (*df*s) per year (Yang et al., 2021). We also adjusted for the day of the week as a categorical variable. To capture the non-linear and lagged association between maximum temperature and mortality, we applied a bidimensional cross-basis spline function with a lag period of 21 days (Gasparrini et al., 2015). For the spline, we placed three internal knots at the 10th, 75th, and 90th percentiles of the maximum temperature distribution. We identified the temperature corresponding to the lowest risk of mortality (minimum mortality temperature [MMT]), and we estimated the city-specific relative risk of mortality by comparing the risk at each heat alert threshold (e.g., 35 °C) to the MMT. Because the ERA5 data showed that the maximum temperature in Jiangsu Province did not reach 40 °C from 2016 to 2019, we were unable to estimate the relative risk of mortality at 40 °C in this study. Stage 2: based on the city-level temperature-mortality associations, we conducted a multivariate meta-analysis based on restricted maximum likelihood to quantify the association between maximum temperature and mortality for the whole of Jiangsu Province (Gasparrini et al., 2012). Previous studies have reported that climatic, socioeconomic, and demographic factors could modify the association between temperature and mortality (Zanobetti et al., 2013). To account for the effect modification of city-level characteristics, we included a multivariate meta-regression by including city-specific average population density, gross domestic product (GDP) per capita, and a 'city' indicator (i.e., city as a categorical variable) as meta-predictors. We

tested the residual heterogeneity with Cochran Q test and I^2 statistic (Gasparrini et al., 2012; Gasparrini et al., 2015). City-level data on average population density and per capita GDP data from 2016 to 2019 were collected from the Jiangsu Provincial Bureau of Statistics (https://tj.jiangsu.gov.cn/index.html).

After quantifying the relative risk of mortality at each heat alert threshold, we used the backward method (Gasparrini and Leone, 2014) to estimate the death numbers and fractions attributable to three temperature segments (i.e., attributable fraction): ≤35 °C, 35 °C – 37 °C, or >37 °C. The 95% empirical confidence intervals (eCIs) of attributable numbers and fractions were estimated with Monte Carlo simulations (Gasparrini and Leone, 2014).

To understand if there was a disparity in heat-related mortality risk across subpopulations, we estimated the relative risks of mortality at the heat alert thresholds in subpopulations with different combinations of sociodemographic characteristics (e.g., males aged under 75 years who were single/divorced/widowed and had <10 years of education) (Son et al., 2019). We also conducted stratification analyses by each sociodemographic characteristic (e.g., males vs females).

Projections of mortality burden associated with future climate warming

Following the heat-health risk projection methods detailed in Vicedo-Cabrera et al. (Vicedo-Cabrera et al., 2019), we projected the death burden associated with future climate warming (i.e., attributable death number and fraction). The excess mortality in future scenarios was predicted under the assumption that the heat-mortality dose-response relationship would not vary over time (i.e., no adaptation). Specifically, we conducted three-step analyses: (1) based on the exposure-response association between daily maximum temperature and mortality risk (yielded in the abovementioned stage 1 analyses of the historical association assessment), we used the modelled series of daily maximum temperatures (i.e., 1980-2099) to calculate the

death numbers attributable to temperatures above the MMT for each city and for each combination of GCMs and SSPs; (2) we calculated the attributable death numbers as GCM-ensemble averages by city, decade, and SSP; and (3) we aggregated the city-specific attributable death numbers to derive the projected value for Jiangsu Province. Based on the attributable death numbers in Jiangsu Province, we then computed the attributable death fraction as GCM-ensemble averages by decade and SSP, using the related total number of deaths as the denominator. Through Monte Carlo simulations, we obtained 95% eCIs for the attributable death number and fraction. We further separated the projected death fraction attributable to temperatures above the MMT in Jiangsu Province into death fraction attributable to three temperature segments: ≤35 °C, 35 °C – 37 °C, or >37 °C. Following common practice (Gasparrini et al., 2017; Yang et al., 2021), we called the projected attributable death fraction as 'excess mortality' in the sections below.

Sensitivity analyses

We conducted five sensitivity analyses to test the robustness of the main findings: (1) we changed *df*s for seasonal and long-term trends of mortality from 6 to 9 per year; (2) we performed a sensitivity analysis without adjusting for air pollutants in the model; (3) we added an interaction term between temperature and air pollutant ($PM_{2.5}$) in the model; (4) we added an interaction term between temperature and GDP per capita in the model; (5) we restricted the analyses to the summer season (June to August) and used a natural cubic spline with 3 *df*s to adjust for within-season variation and long-term trend in the summer season analyses.

Results

Descriptive information

There were 2,245,652 recorded deaths in Jiangsu Province from 2016 to 2019. These deaths mainly occurred in females aged 75+ years who were single/divorced/widowed and had <10 years of education (19.42%), males aged 75+ years who were married and had <10 years of education (18.10%), and males aged 0-74 years who were married and had <10 years of education (17.69%) (Figure S2). Daily maximum temperatures ranged from -6.21 °C to 38.94 °C, and the daily average number of deaths in Jiangsu Province was 1,537 (standard deviation [SD]: 260) (Table 1).

Historical mortality burden associated with temperatures above the heat alert thresholds

The curve of the exposure-response association between maximum temperature and mortality risk was U-shaped (Figure 1). Exposure to 35 °C was associated with a 24% (95% CI: 14%, 34%) increased risk of mortality, compared with the MMT (20.6 °C). This increased risk of mortality was most prominent in individuals who were single/divorced/widowed and had <10 years of education (Table 2). Stratification analyses by each sociodemographic characteristic showed that females, those aged 75+ years, those who had <10 years of education, and those who were single/divorced/widowed groups had a higher risk of heat-related mortality, compared with their counterparts (Table S1). The results of meta-regression analyses showed that there was moderate residual heterogeneity (I^2=68.4%) after including population density, GDP per capita, and the city indicator, as meta-predictors, but the effects of these predictors in univariate and multivariate models were not statistically significant (Table S2).

From 2016 to 2019, there were 23 days when the maximum temperature was >35 ℃ and 3.5 days when the maximum temperature was >37 ℃. The total death numbers attributable to the three temperature segments (≤35 °C, 35 °C – 37 °C, or >37 °C) were 34,112 (95% eCI: -4,082, 69,637), 8,996 (95% eCI: 6,299, 11,468), and 2,525 (95% eCI: 1,942, 3,095), respectively, equating to 8,528, 2,249, and 631 annual deaths. The death fractions attributable to the three

temperature segments (≤35 °C, 35 °C – 37 °C, or >37 °C) were 1.52% (95% eCI: -0.18%, 3.10%), 0.40% (95% eCI: 0.28%, 0.51%), and 0.11% (95% eCI: 0.09%, 0.14%), respectively.

Future mortality burden associated with temperatures above the heat alert thresholds

Under the SSP1-2.6, the annual number of days with maximum temperature >35 °C was projected to increase across the coming decades, from 14 days in the 2030s (i.e., 2030-2039) to 24 days in the 2090s (i.e., 2090-2099) (Figure 2A). The annual number of days with maximum temperature >37 °C was projected to increase from 4 days in the 2030s to 9 days in the 2090s (Figure 2B). Under the SSP5-8.5, the annual number of days with maximum temperature >35 °C was projected to substantially increase, from 19 days in the 2030s to 91 days in the 2090s (Figure 2A). The annual number of days with maximum temperature >37 °C was also projected to increase significantly from 6 days in the 2030s to 67 days in the 2090s (Figure 2B).

Under the SSP1-2.6, compared with the 2020s, the excess mortality associated with temperatures >37 °C was projected to increase by 1.4 times in the 2050s (0.83% vs 0.34%), and by 1.7 times in the 2090s (0.91% vs 0.34%) (Figure 3). In contrast, under the SSP5-8.5, compared with the 2020s, the excess mortality associated with temperatures >37 °C was projected to increase by 2.8 times in the 2050s (1.45% vs 0.38%), and by 18.4 times in the 2090s (7.37% vs 0.38%).

Sensitivity analysis results

The results of sensitivity analysis show that the main modelling outcomes changed little when changing the *df*s for seasonal and long-term trends of mortality from 7 to 6 (Figure S3), 8 (Figure S4), or 9 (Figure S5). There were no substantial changes in the results after removing air pollutants from the model (Figure S6), after adding the interaction term between maximum temperature and $PM_{2.5}$ (Figure S7), and after adding the interaction term between maximum

288 temperature and annual GDP per capita (Figure S8). The summer season analyses yielded a
289 wider confidence interval of the relative risk (Figure S9).

290

291 **Discussion**

292 In this study, we estimated that from 2016 to 2019, 0.51% of mortality was associated with
293 temperatures above 35 °C in Jiangsu Province, including 0.40% mortality associated with
294 35 °C – 37 °C and 0.11% mortality associated with >37 °C. In contrast, 1.52% of mortality was
295 associated with temperatures ≤35 °C (i.e., temperatures lower than the first heat alert threshold).
296 A nationwide study in China assessing the mortality burden associated with non-optimal
297 temperatures (i.e., temperatures below or above the minimum mortality temperature) found
298 that 0.63% of mortality was associated with mean temperatures above 29.0 °C (Chen et al.,
299 2018), which was roughly consistent with our finding. Previous studies predicted significant
300 increases in the number of heatwave days and heat-related mortality in the future (Gasparrini
301 et al., 2017; Liu et al., 2023), which were in line with our projection findings. The main
302 contribution of our study was that we considered the three heat alert thresholds in the Chinese
303 HHAP in the estimation of historical and future heat-related mortality, which facilitates our
304 findings to inform heat adaptation policies. Numerous risk factors (e.g., smoking, physical
305 inactivity, heat) impact public health (Murray et al., 2020). When decision-makers allocate
306 stretched public resources to various public health protection programs aiming to mitigate these
307 risk factors, they often need to consider the health burden associated with each risk factor. As
308 such, our 0.51% estimation could be used to facilitate the decision-making of public resource
309 allocations to the implementation of the Chinese HHAP.

310 The disruption of thermal regulatory mechanisms during hot weather could cause heat-related
311 illnesses (e.g., heat stroke) or trigger the exacerbation of pre-existing chronic diseases (e.g.,

heart failure). Body heat production is produced by metabolism and labor. Under normal conditions, heat removal is accomplished by radiation, convection, conduction, and evaporative cooling (Jay et al., 2021). When the heat load exceeds a certain level, our ability to dissipate excess heat decreases. Without timely cooling measures, core body temperature increases, which could lead to heat-related illnesses and/or an exacerbation of chronic diseases.

It is a common research practice to compare the heat-health risk between two broad groups of individuals (e.g., males vs. females) and identify which group is more at-risk (Benmarhnia et al., 2015). Given that each individual has multiple sociodemographic characteristics, we estimated the heat-related mortality risk in individuals with different combinations of sociodemographic characteristics, observing that those who were both single/divorced/widowed and had <10 years of education had the highest risk of heat-related mortality. In China, it is common for older adults who are single/divorced/widowed to live alone, and the HHAP has recognised individuals living alone as an at-risk subpopulation during heatwave days (CNADPC, 2023). Our finding emphasised the need to target individuals who are single/divorced/widowed (often living alone) and less educated when a heatwave occurs. Previous cohort studies have reported the health inequality associated with sociodemographic factors (e.g., educational attainment) in China (Lu et al., 2023; Zhu et al., 2023), and our results indicate that heat (as an environmental stressor) could exacerbate the existing health inequality across different sociodemographic groups.

An HHAP with a very high heat alert threshold (e.g., maximum temperature of 40 °C) is mainly aimed at preventing the mortality peaks during extreme heatwaves (i.e., disaster-oriented), but it may miss the opportunity to prevent the majority of heat-related mortality associated with low- or moderate-intensity heatwaves (Gasparrini et al., 2015; Xu et al., 2023). An HHAP with a low heat alert threshold (e.g., maximum temperature of 30 °C) is to prevent as much heat-related mortality as possible (i.e., prevention-oriented), but it could trigger heat warnings too

frequently, possibly causing warning fatigue in the general public (Kovats and Hajat, 2008). Hence, setting the heat alert thresholds is generally a trade-off between protecting public health as much as possible and avoiding triggering early warnings too frequently. Our projection results reveal that, if CO_2 emissions were strongly reduced and cut to net zero after 2050 (i.e., SSP1-2.6) or hovered around current levels and began declining after 2050 (i.e., SSP2-4.5), the excess mortality associated with temperatures >37 °C would slightly increase from the 2030s to 2090s. However, if global economic growth continued to depend on fossil fuels and overconsumption lifestyles (i.e., SSP5-8.5), the excess mortality associated with temperatures >37 °C would double every 20 years. If this SSP5-8.5 scenario occurred, the Chinese HHAP would need to trigger the orange warnings for most days throughout the summers, which would likely cause warning fatigue.

Strengths and Limitations

The first strength of this study is that we conducted the estimations of historical and future heat-related mortality burdens in alignment with the heat alert thresholds specified in the inaugural national HHAP in China, increasing the policy relevance of our findings. Second, we examined heat-related mortality risk across subpopulations with different combinations of sociodemographic characteristics, suggesting the need to target individuals who are both single/divorced/widowed and have lower educational attainment.

Our study has six limitations. First, although the climate and air pollution data were the best spatially refined gridded data we could have obtained, the spatial resolution was coarse and could have been subject to measurement bias. Second, we were only able to obtain mortality data in one province of China. Although the population of the province is big, we acknowledge that generalising our findings to other regions needs to be done with caution. Third, although the four-year mortality data (i.e., 2016-2019) was the longest mortality data we could have

obtained, we acknowledged that our findings could have been more informative if mortality data covering a longer period had been obtained. For example, we missed the year 2022, a year when China experienced the most severe heatwaves since temperature records began in 1961. It was reported that, compared with the historical benchmark (1986-2005), the number of days exposed to heatwaves per capita in 2022 increased by 293%, and heat-related deaths increased by 342% in China (Zhang et al., 2023). Fourth, we were unable to take into account heat adaptation in the projection because the time period that the mortality data covered was short (2016 to 2019) and we did not take into account population ageing in the projection. One study from China predicted that the number of deaths among people aged 65-79 years would steadily decline after 2040, and the number of deaths among those aged over 80 years would continue to increase (Liu et al., 2023). This study also found that advanced aging would increase the risk of heat-related excessive mortality. Another study found that, although human adaptation would offset some excess heat-related mortality, heat-related mortality would still increase (Huang et al., 2023). Fifth, our study did not project future heat-related cause-specific mortality, because we believe future mortality from different causes (e.g., cardiovascular, respiratory, renal) could be driven by different risk factors. Sixth, we only considered the heat alert threshold (>35 ℃) but not its duration (≥3 days), because we wished to seamlessly estimate the mortality burden attributable to the three temperature segments (≤35 °C, 35 °C – 37 °C, or >37 °C). There may have been 2 consecutive days when the maximum temperatures were 36 °C, and these days would not have met the criterion of either '35 °C & ≥3 days' or '>37 °C', and hence the mortality burden attributable to these days would have been underestimated if we had considered both the 35 °C and its duration (≥3 days). However, we acknowledged that considering only the heat alert threshold (35 ℃) but not its duration (≥3 days) would have overestimated the mortality burden attributable to temperatures above the yellow alert threshold of Chinese HAPP.

Conclusion

Our study shows that 0.51% of mortality is associated with temperatures above the lowest heat alert threshold of the Chinese national HHAP, and individuals who are both single/divorced/widowed and less educated need extra protection during heatwaves. If the low or intermediate GHG emission scenario occurred, the excess mortality associated with temperatures >37 °C would slightly increase from the 2030s to 2090s. If the high GHG emission scenario occurred, the annual number of days and excess mortality associated with temperatures >37 °C would largely increase in the coming decades.

Funding

National Natural Science Foundation of China (Grant Number: 42375184)

CRediT authorship contribution statement

Conceptualisation: ZX, HS, WY

Data curation: HZ, ZX, JC

Formal analysis: WY

Funding acquisition: HS

Methodology: WY

Project administration: HS, ZX, WY

Supervision: ZX, HS

Visualisation: WY

Writing - original draft: WY, ZX

Writing - review & editing: WY, AB, ST, JC, JY, HZ, HCH, JS, RP, HS, ZX

410

411 **Declaration of interests**

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

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Figure legends

Figure 1. The exposure-response association between maximum temperature and mortality risk in Jiangsu Province, China

Figure 2A. The annual number of days with projected maximum temperature >35 °C and >37 °C across the coming decades under SSP1-2.6, SSP2-4.5, and SSP5-8.5.

Figure 2B. The annual number of days with projected maximum temperature >37 °C across the coming decades under SSP1-2.6, SSP2-4.5, and SSP5-8.5.

Figure 3. The projected excess mortality associated with temperatures ≤35 °C, 35 °C – 37 °C, or >37 °C across the coming decades under SSP1-2.6, SSP2-4.5, and SSP5-8.5.

Table 1. Descriptive statistics of climate factors, air pollutants, and deaths in the 13 cities of Jiangsu Province, China, from 2016 to 2019

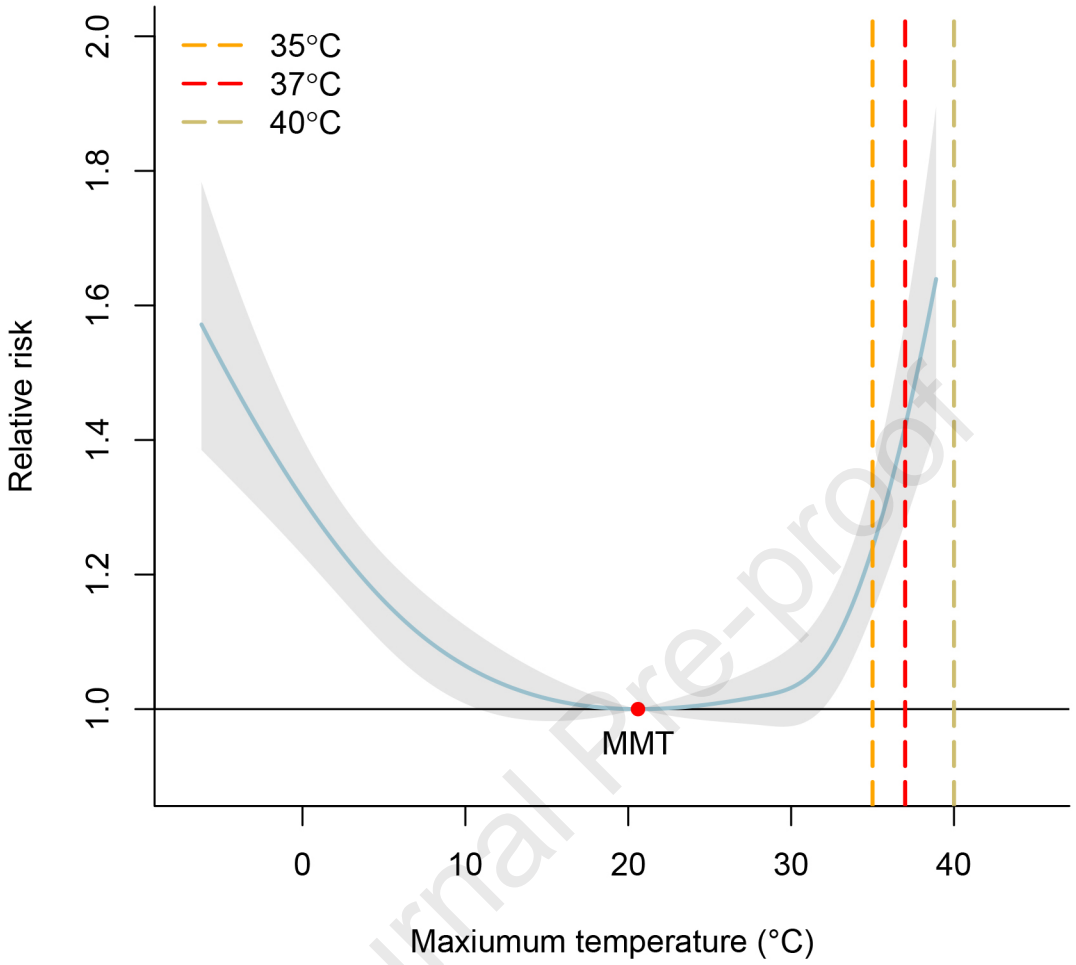
City	Maximum temperature (℃)		Relative humidity (%)		$PM_{2.5}$ (μg/m^3)		O_3 (μg/m^3)		Deaths	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Nanjing (capital city)	-4.73-37.64	20.86	38.19-97.54	75.25	1.29-205.64	48.19	15.92-222.58	99.57	58-180	108
Wuxi	-5.05-38.82	20.67	36.58-98.39	76.10	1.21-253.72	45.61	15.42-229.75	99.09	56-182	98
Xuzhou	-4.51-37.24	20.61	21.72-97.85	68.05	1.66-266.91	59.37	21.66-221.94	101.64	87-354	168
Changzhou	-5.00-38.19	20.82	37.54-98.48	76.17	1.45-262.86	48.67	14.38-225.31	98.73	45-243	113
Suzhou	-4.95-38.94	20.72	36.92-97.94	76.85	1.13-241.46	43.94	17.35-219.52	97.34	76-275	138
Nantong	-5.82-37.66	20.06	33.80-97.00	76.88	1.59-237.71	39.54	23.93-204.71	95.59	121-506	212
Lianyungang	-5.72-36.49	19.67	23.13-95.8	70.81	1.36-277.07	45.80	24.40-204.09	98.19	39-173	79
Huai'an	-5.78-37.08	20.15	29.11-97.92	73.19	1.11-238.47	41.98	22.83-207.72	98.96	47-212	91
Yancheng	-6.21-37.07	19.86	28.34-96.18	73.68	1.29-230.35	38.68	23.71-203.82	96.61	93-413	157
Yangzhou	-5.53-37.21	20.53	33.28-98.64	74.75	1.44-217.45	46.27	22.20-219.54	99.94	9-359	96
Zhenjiang	-4.94-37.6	20.72	34.56-98.45	75.72	1.19-235.47	47.79	14.87-229.86	98.93	29-117	57
Taizhou	-5.64-37.42	20.67	32.92-98.47	75.15	1.78-245.84	48.19	20.59-220.04	98.54	61-448	126
Suqian	-5.36-37.07	20.17	26.69-97.13	71.79	1.19-247.48	46.71	23.70-210.23	99.24	47-206	94

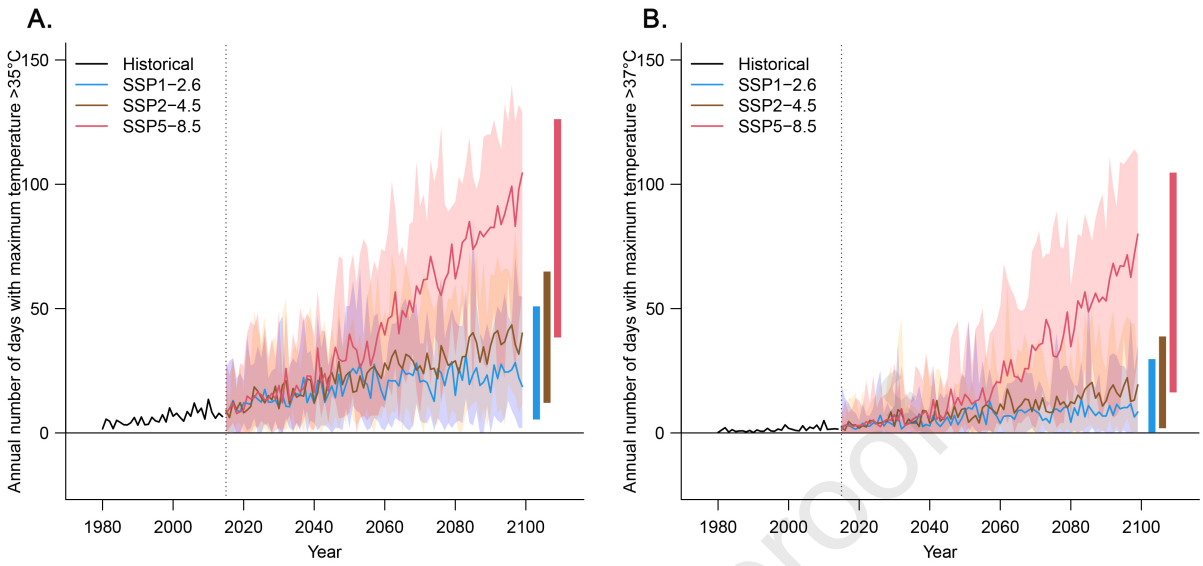
O_3, ozone; $PM_{2.5}$, particulate matter with a diameter of 2.5 micrometers or less; all variables follow a normal distribution, so we presented the mean values.

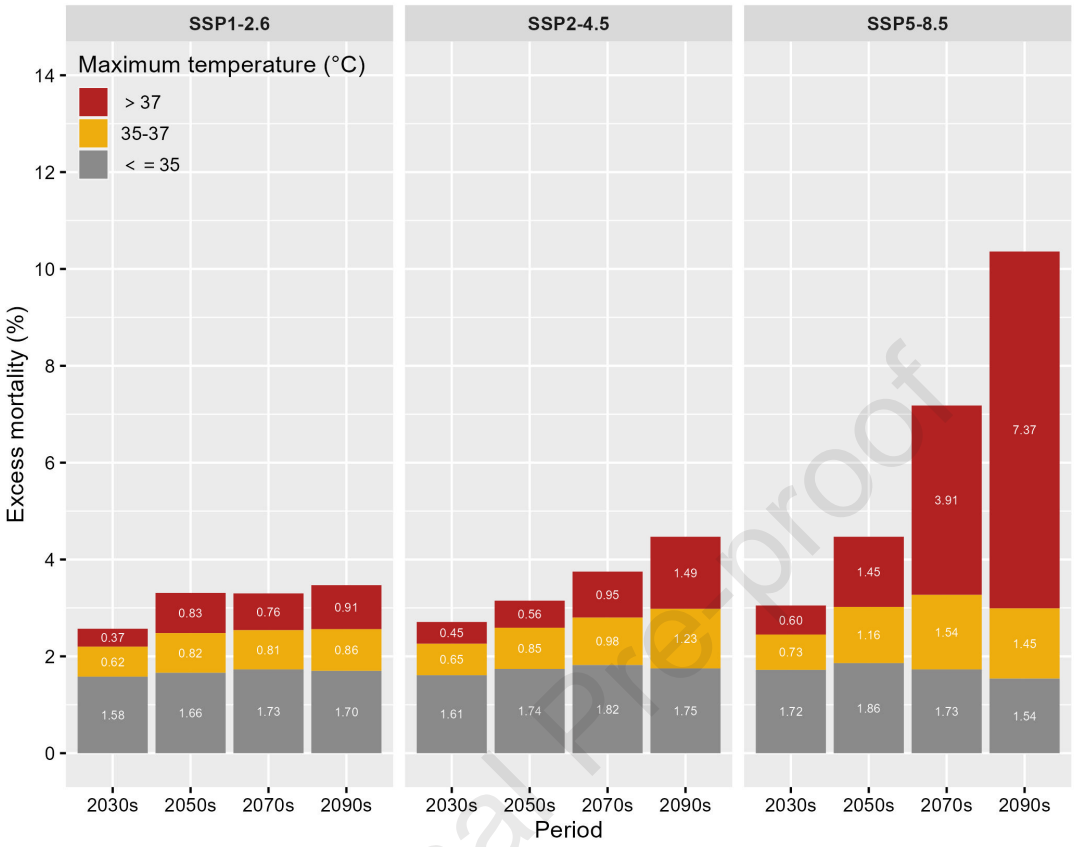
Table 2. Mortality risk associated with hot weather (35 °C *vs.* MMT [20.6 °C])

Age	Sex	Education	Marital status	RR and 95% CI (35℃ *vs.* MMT)	Number of deaths
0-74 years	Male	<10 years of education	Married	1.04 (0.97-1.12)	348,615
0-74 years	Male	<10 years of education	Single/Divorced/Widowed	1.28 (1.12-1.45)	70,789
0-74 years	Male	≥10 years of education	Married	0.99 (0.85-1.16)	50,023
0-74 years	Male	≥10 years of education	Single/Divorced/Widowed	1.01 (0.79-1.29)	8,047
0-74 years	Female	<10 years of education	Married	1.07 (0.98-1.17)	187,810
0-74 years	Female	<10 years of education	Single/Divorced/Widowed	1.24 (1.08-1.43)	39,647
0-74 years	Female	≥10 years of education	Married	1.09 (0.92-1.31)	16,477
0-74 years	Female	≥10 years of education	Single/Divorced/Widowed	1.01 (0.63-1.65)	3,264
≥75 years	Male	<10 years of education	Married	1.07 (0.99-1.16)	356,603
≥75 years	Male	<10 years of education	Single/Divorced/Widowed	1.28 (1.15-1.43)	201,748
≥75 years	Male	≥10 years of education	Married	1.12 (0.95-1.32)	37,566
≥75 years	Male	≥10 years of education	Single/Divorced/Widowed	0.98 (0.77-1.24)	9,602
≥75 years	Female	<10 years of education	Married	1.14 (1.03-1.26)	241,779
≥75 years	Female	<10 years of education	Single/Divorced/Widowed	1.28 (1.16-1.42)	382,664
≥75 years	Female	≥10 years of education	Married	0.88 (0.69-1.14)	9,123
≥75 years	Female	≥10 years of education	Single/Divorced/Widowed	1.10 (0.82-1.48)	6,598

RR, relative risk; CI, confidence interval; MMT, minimum mortality temperature







Highlights

1. Maximum temperatures above 35 °C were associated with 0.51% of mortality.
2. Those single/divorced/widowed and had <10 years of education were more vulnerable.
3. Chinese heat-health action plan will be triggered frequently as climate changes.

Declaration of interests

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

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