The graded heat-health risk forecast and early warning with full-season coverage across China: a predicting model development and evaluation study

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Summary

Background Due to global climate change, high temperature and heatwaves have become critical issues that pose a threat to human health. An effective early warning system is essential to mitigate the health risks associated with high temperature and heatwaves. However, most of the current heatwave early warning systems are not adequately developed based on the heat-health risk model, and the health impact of hot weather has not been well managed in most countries.

Methods This study proposed a "full-season coverage and population health-oriented graded early-warning" concept and developed a heat-health surveillance, forecast and early warning (HHSEW) model. The exposure-response (E-R) relationship between temperature and mortality was analyzed through a two-stage approach using time-series analysis data from 323 counties across China for the period 2013–2018. The premature mortality curve at each temperature percentile was plotted and four temperature-percentile points on the curve were determined as the thresholds of the pre-warning and warning levels 1–3 based on the variations in the rates of the segmental slopes on the curve. The HHSEW model was evaluated by comparing the frequency, the mortality risk of all-cause and cause-specific diseases, the predicted numbers of premature deaths, and the heat-related health economic burden at each warning level with those of the current high temperature early warning systems.

Findings The HHSEW model determined five levels, including seasonal surveillance, pre-warning, and warning levels 1–3. There was a gradual increase in the mortality risks of all-cause and cause-specific diseases along with the increase of warning levels. The risk of all-cause mortality increased by 9.79% (95% CI: 8.59%–11.01%), 22.62% (95% CI: 19.49%–25.83%), 28.36% (95% CI: 24.72%–32.10%), and 33.87% (95% CI: 28.89%–39.06%) at the pre-warning level, warning level 1, warning level 2, and warning level 3, respectively. Through our HHSEW model, 94,008 heat-related all-cause deaths were predicted annually in the 337 major cities of China, which was much larger than the number (14,858) of the China Meteorological Administration (CMA) heatwave early-warning system currently used in China. It was estimated that the proper implementation of the HHSEW-based early warning system would save 220 billion CNY in heat-related health burden compared to the current heatwave early-warning system.

Interpretation The HHSEW model has been proven to surpass the current heatwave early warning system. With its full-season coverage and graded warning levels for heat-related health risks, the HHSEW model and system can provide timely early warnings to the public, leading to significant health benefits. This methodology, labeled "full-season coverage and population health-oriented graded early-warning", should be implemented globally to mitigate the escalating health risks associated with high temperature.

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Research in context

Evidence before this study

It is well-known that heat-related health risks might be reduced through the systematic development of heatwave early warning systems for alerting the government and the public to impending dangerous hot weather. Few multi-center studies on the development of heatwave early warning systems having full-season coverage, health risk-oriented, and based on the graded warning levels have been completed and published. We searched the PubMed database for studies on heatwave or high temperature-related health risk early warning systems, published from Jan 1, 2010, to August 20, 2024, using the following search terms: ((“heatwave” OR “heat wave” OR “high temperature”) AND (“early warning” OR “early-warning”) AND (English [Language])). This search yielded 97 studies, most of which were focused on heat-related health risk assessment but did not include the early warning approach. Only 8 studies were based on the heatwave health risk early warning system.

The World Meteorological Organization (WMO) and the World Health Organization (WHO) have indicated the necessity and urgency of heat-health risk early warning systems for increased preparedness and response to heatwaves and reducing health impacts. A few developed countries such as the US (‘Hot Weather-Health Watch/Warning System in Philadelphia’), England (‘Hot Weather and Health’ guidance), France (‘Heat Health Watch Warning System’), Portugal (‘the Watch Warning System for Heatwaves’), and Spain (National High Temperature Plan) have analyzed the heatwave early warning systems based on the population health risk assessment.

However, most of the current heat-health early warning systems do not have full-season coverage (mainly heatwave-event-triggered) or reasonable grading of warning-levels based on the scientific health risk assessment. Some of them are based on the limited local data and do not apply to other cities, while others do not have enough temporal coverage, and focus only on the warning days that are recognized as ‘heatwave days’, the high temperature days with low to medium risks are neglected. Furthermore, most of these studies did not conduct model evaluations based on mortality risks from various diseases, nor did they compare with existing meteorological early-warning systems.

Added value of this study

This study proposed a concept of “full-season coverage and population health-oriented graded early warning of high temperature” and developed a heat-health surveillance and early warning (HHSEW) model based on the multi-center epidemiological study covering 6 main climate-architecture regions across China. This HHSEW model is the first health-risk-centered heatwave early warning model in developing countries to issue graded heat-health risk information, including the seasonal surveillance, pre-warning, and 3 graded warning levels, in the 6 climatic-architecture regions across China and covering the whole summer season (from 1st June to 30th September). It has been verified that there is a stepwise increase in health risk with the upgrading of warning levels in the HHSEW model. The mortality risks of all-cause death and some cause-specific diseases increased by 22%~45% at the highest level (warning level 3). Through the HHSEW model, a total of 94,008 heat-related all-cause deaths was predicted annually during the summer seasons of 2013–2018 in the 337 major cities of China, which is 5 times larger than the figure of the China Meteorological Administration (CMA)-early warning system. It is estimated that if these warnings were issued promptly and health protection measures were effectively applied, over 90 thousand heat-related premature deaths could be avoided or 262 billion CNY of economic burden could be saved annually, which are much more than that of the current heatwave warning system.

Implications of all the available evidence

The HHSEW model is a critical development in heat-health risk management and could yield considerable health benefits for the population. In the background of global warming, the implementation of the heat-health early-warning model is of great significance for more comprehensively and effectively protecting the public health from high temperature and heatwaves. Especially, the modeling framework and strategy could help to guide other developing countries and regions to promote heat-related health risk surveillance and early warning for the protection of the population health.

Introduction

Global climate change stands as the most significant threat to human health, representing the greatest challenge of the 21st century. With the intensification of global warming, the frequency, intensity, and duration of high temperature are expected to increase in the future. Heat exposure has been conclusively linked to elevated risks of morbidity and mortality, including heat stress, heat strokes, and exacerbation of cardiovascular and respiratory conditions.[1–5] The Global Burden of Disease study reported that in 2019, high temperatures contributed to over 300,000 premature deaths worldwide.[6] The 2020 Lancet Countdown on health and climate change highlighted a rise in the global economic impact of heat-related mortality, with the proportion of gross world product increasing from 0.23% in 2000 to 0.37% in 2018.[3] The catastrophic heatwaves across the Northern Hemisphere in 2022 and 2023 resulted in significant loss of life and property. Numerous countries and regions are grappling with extreme and perilous heatwaves, profoundly impacting human health and livelihoods. Particularly, lower-income countries in continental Asia and Pacific Island States in the Western Pacific region are disproportionately affected by climate change and heatwaves, yet they lack sufficient scientific evidence and have not effectively managed the associated risks.[7–9] As the world confronts the unavoidable and escalating high-temperature exposure, quantitative and precise health risk predictions, along with timely public warnings, are essential strategies to mitigate the health impacts of heatwaves.

The effectiveness of early warning systems in mitigating the health impacts of high temperatures is well-documented, earning strong endorsements from the World Health Organization (WHO) and the World Meteorological Organization (WMO).[10–12] Although many countries have established heatwave early warning systems, these are often grounded in traditional methods that rely primarily on absolute temperature and its duration, rather than comprehensive health risk assessments. For instance, the China Meteorological Administration (CMA) uses a combination of temperature and duration to forecast heatwaves, categorizing them into three levels: yellow, orange, and red.[13] A similar three-tiered warning framework is employed by Australia's National Heatwave Warning System,[14] and India's Multi-Hazard Early Warning System classifies warnings into four levels: green, yellow, orange, and red.[15] Other nations, including Hungary,[16] Greece,[17] Slovenia,[18] and South Africa,[19] also base their early warning systems solely on temperature. However, this approach is neither scientifically robust nor appropriate for nationwide warnings due to the vast regional diversity, where temperature ranges and local adaptability to heat can vary significantly.[20,21] A limited number of countries and cities, mainly in developed regions, have integrated health risk assessments into their heatwave warning models and systems, such as France's Heat Health Watch Warning System,[22] England's "Hot Weather and Health" guidance,[23] Portugal's Heat–Health Warning System (ÍCARO),[24] Spain's National High Temperature Plan,[25] and Philadelphia's Hot Weather-Health Watch/Warning System.[26] Empirical evidence from these systems indicates that early warnings grounded in health risk assessments yield significantly greater health benefits compared to those based solely on temperature.[10,11,22–29]

In China, a few city-level early warning systems have been developed based on health risk assessments,[30–33] yet these systems are limited by localized data and are not applicable to other regions. Additionally, most global warning systems, particularly in developing countries, do not provide full seasonal coverage and only issue alerts when temperatures surpass a specific threshold.[26,34] Research has consistently demonstrated that the full spectrum of non-optimal temperature effects can pose various degrees of health risks.[6,35–44] Therefore, non-optimal temperatures should not be overlooked, and health risk early warnings should encompass the entire summer season, rather than focusing solely on heatwave days. The WHO and WMO have recommended full-season coverage for heat-health surveillance and early warning systems,[12] a practice already adopted by many high-income countries.[22–26] However, recent studies have struggled to establish a robust grading algorithm for heat-health surveillance that covers the entire hot season. This underscores the urgent need to develop a health-oriented, full-season warning model and system that accurately quantifies health risks, enabling effective public communication and reducing the health threats posed by high temperatures.

Currently, there is a significant gap in the development of a nationwide public health heat surveillance, forecast and early warning system that provides comprehensive seasonal coverage and is grounded in health risk assessments for large populations. Such a system would offer a rational grading approach to support public health information services and decision-making. Therefore, this study explores the development of a heat-health risk surveillance, forecast, and early warning (HHSEW) model that covers the entire summer season, aiming to establish a scientifically sound grading method for warning levels based on health risk assessments across China. Given China's vast territory and its diverse geographical and meteorological conditions, this study also proposes the development of regional models tailored to the climatic regions identified in the national-level model.

Methods

Study design

The concept of "full-season coverage and population health-oriented graded early warning of high temperature" was introduced, encompassing three core elements. First, the study spanned multiple climatic regions, utilizing regional temperature percentiles as the basis for establishing thresholds across all warning levels (see the methodology for determining temperature as an indicator in Part 1 of the Supplementary Material). Second, the HHSEW system provided comprehensive monitoring throughout the summer season (June 1st–September 30th), thereby ensuring full-season coverage. Third, the early warning levels, including seasonal surveillance, pre-warning, and warning levels 1–3, were determined by assessing health risks associated with high temperatures. This approach led to the creation of a multi-step modeling framework, resulting in the development of the HHSEW model, which integrates meteorological data, mortality surveillance data, air quality monitoring data, and sociodemographic data across China (Fig. 1).

Datasets

County-level daily mortality data from 323 counties were obtained from the Chinese Centers for Disease Control and Prevention (China CDC), covering the period from January 1, 2013, to December 31, 2018. These counties were selected based on four criteria: 1) inclusion in the national mortality monitoring sites of the China CDC or possession of well-established resident mortality registration systems; 2) annual average mortality rates exceeding 4.5‰; 3) consistent temporal trends in death monitoring datasets; and 4) annual mortality rate fluctuations below 20%. This study collected the mortality data through our environmental health data platform - Chinese Environmental Public Health Tracking and Risk Assessment and has received ethical approval (The Ethical Review Committee of National Institute of Environmental Health, Chinese Center for Disease Control and Prevention; The approval number: 202102). This dataset, representing over 222 million people across seven major regions in China (see the map in Fig. 1), includes nearly 6.36 million deaths, of which 5.93 million were non-accidental, 2.72 million were due to circulatory diseases, and 0.72 million were attributed to respiratory diseases. Causes of death were categorized according to the 10th Revision of the International Classification of Diseases (ICD-10), with mortality recorded as daily death counts for all causes (codes A00–Z99 in ICD-10).

Meteorological data were sourced from the European Centre for Medium-Range Weather Forecasts (ECMWF) (https://cds.climate.copernicus.eu/) and used to calculate daily average temperature and relative humidity (https://www.weather.gov/media/epz/wxcalc/vaporPressure.pdf). The original data, with temporal and spatial resolutions of hourly and 0.1° × 0.1°, 0.125° × 0.125°, were processed into daily values for 2900 counties across China. Daily concentrations of fine particulate matter ($PM_{2.5}$) and ozone (O_3) were obtained from the National Urban Air Quality Real-Time Release Platform (https://air.cnemc.cn:18007/).

For model evaluation, city-level meteorological and air quality data were collected from 337 cities across China, with sociodemographic data sourced from the Sixth National Census.

All data processing was conducted using R 4.0.2 and ArcGIS 10.2.

Development of heatwave health risk early warning model

Simulation of the exposure-response (E-R) relationship between temperature and mortality

The temperature-mortality association was analyzed using a two-stage approach with time-series data from 323 counties across China.

In the first stage, a generalized linear model (GLM),[20,36–40] as shown in Formula (1), was constructed to estimate the county-specific exposure-response

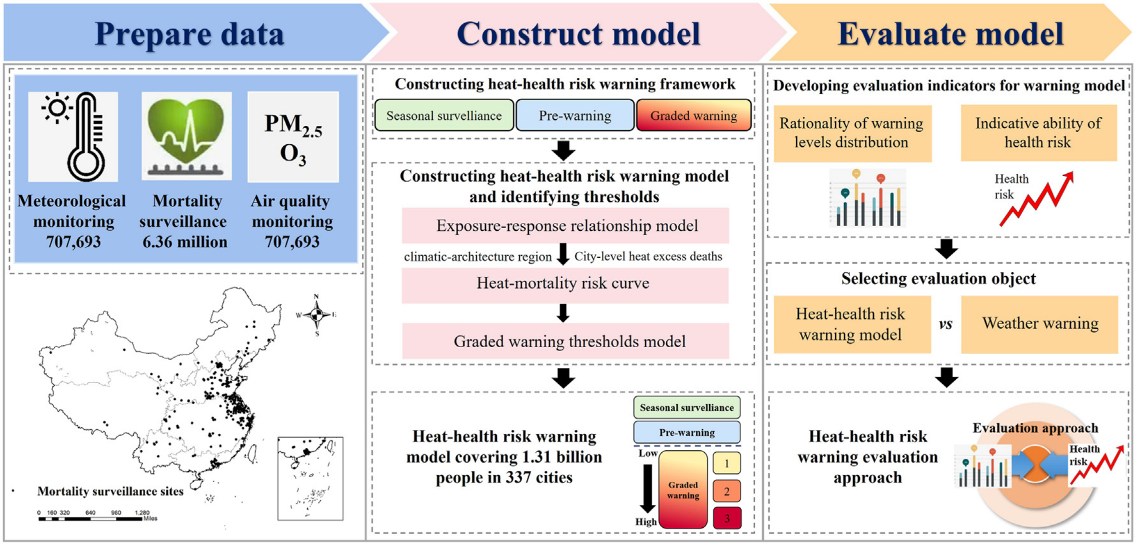

Fig. 1: Technical flowchart of the heat health surveillance, forecast and early warning model (HHSEW model).

(E-R) relationship between daily mean temperature and all-cause mortality during the summer seasons (June 1st–September 30th for each year from 2013 to 2018).

$$LogE(Y_t) = Intercept + \beta Tmean_t + ns\big(Rh, df_1\big) + ns\big(time, df_2\big) + dow \tag{1}$$

Here, Y_t denotes the number of all-cause deaths on day t, while β represents the regression coefficient for the E-R relationship between temperature and mortality. $Tmean_t$ is the daily mean temperature on day t. The term $ns(Rh, df_1)$ represents a natural cubic spline controlling for humidity with 3 degrees of freedom (df_1 = 3); $ns(time, df_2)$ represents the natural cubic spline of time with 2 degrees of freedom (df_2 = 2) per year, used to control for long-term trends, as referenced in our previous studies.[20,38] The variable *dow* is a categorical variable representing the day of the week.

In the second stage, the E-R relationship between temperature and mortality was aggregated at both regional and national levels using a meta-analysis based on the county-level E-R relationships obtained in the first stage. According to the National Standard of Climatic Regionalization for Architecture (GB 50178-93), architectural climatic regionalization (abbreviated as climatic-architecture region) comprises seven regions, denoted as region-I through region-VII, to ensure buildings are well-suited to different climatic conditions. To more accurately represent the characteristics of each region, these were renamed as follows: Severe Cold Region, Cold Region, Hot-Summer & Cold-Winter Region, Hot-Summer & Warm-Winter Region, Temperate Region, Severe Cold & Cold Western Region, and Severe Cold & Cold Northwestern Region. Early warning systems were then developed for the regions where significant E-Rs between temperature and mortality were observed.

Sensitivity analyses were conducted to assess the model's stability. First, time series with three and four *df* per year were employed to project long-term and seasonal trends. Second, daily average concentrations of $PM_{2.5}$ and O_3 (as indicators of air pollution) were incorporated into the model. Third, the model was adjusted by adding a lag-day variable (lag 1~lag 6) to evaluate the mortality risk associated with heat effects on four types of mortality (all-cause, total non-accidental, circulatory disease, and respiratory disease) across different lag days.

Determination of thresholds of each warning level

Premature mortality for every 0.1% increase in daily mean temperature across all cities in China was calculated using Formulas (2) and (3), based on the E-R relationship between daily mean temperature and all-cause mortality within each climatic-architecture region.

$$RR_{j\%} = exp\big[\beta * \big(X_{j\%} - X_{ref}\big)\big] \tag{2}$$

$$P_{j\%} = Death_n * \big(RR_{j\%} - 1\big) \big/ RR_{j\%} \tag{3}$$

Here, $RR_{j\%}$ represents the relative mortality risk at the j% temperature; j% denotes the temperature percentile; $X_{i,j\%}$ indicates the temperature at each temperature percentile; X_{ref} is the average daily mean temperature during the warm season from 2013 to 2018; $P_{j\%}$ refers to excess mortality; and $Death_n$ represents the average daily mortality.

The premature mortality curve at each temperature percentile was plotted to identify the inflection point. The optimal number of breakpoints was determined, followed by fitting a linear regression model to estimate early warning temperature thresholds for each climatic-architecture region at various stages, based on the changes in the slopes of the optimal piecewise linear model. Threshold settings underwent multiple rounds of experimentation to assess their accuracy and sensitivity in representing heat levels, ultimately leading to the selection of thresholds that satisfied two key conditions: 1) a reasonable frequency distribution across warning levels, and 2) health risks showing a consistent upward trend with increasing warning levels. After iterative adjustments and comparisons, the final warning level thresholds were established. The temperature percentile corresponding to 0.5% of the cumulative excess deaths was chosen as the pre-warning level threshold. Although this temperature range may not pose significant health risks to the general population, it could considerably impact vulnerable groups. Therefore, issuing an "alert" or "pre-warning" along with public health advice was recommended to safeguard these populations. The thresholds for warning levels 1 and 2 were determined using the "segment" function in R 4.0.2, identifying the two points with the highest rates of change in the segmental slopes of the curve, where health risks escalate rapidly. These points were set as threshold markers. For extreme high-temperature (warning level 3), the threshold was uniformly set at the 99.5th percentile of the relative temperature range, signaling the highest level of health risk warning for heatwaves, which were relatively rare but severe occurrences in the region.

Model evaluation

China's current heatwave warning system, managed by the China Meteorological Administration (CMA), categorizes warnings into three levels: yellow, orange, and red (Table S3). Using these CMA warning levels and the output from the HHSEW model developed in this study, all summer days from 2013 to 2018 across 337 cities in China were classified according to their respective warning levels based on national meteorological data. A comparative analysis was then conducted to examine the frequency distribution and mortality risk at different warning levels between the CMA system and the HHSEW model, assessing whether the HHSEW model offers a more rational frequency distribution and improved health risk detection.

A two-stage time-series analysis was employed to investigate the county-level association between warning-level events and all-cause mortality (A00–Z99), total non-accidental causes (A00–R99), circulatory diseases (I00–I99), respiratory diseases (J00–J99), and eight other cause-specific diseases. In the first stage, a GLM was developed to estimate the county-specific E-R relationship between warning-level events and mortality Formula (4).

$$LogE(Y_t) = Intercept + \beta_1 Var_t + ns(Rh, df_1) + ns(time, df_2) + dow \tag{4}$$

Here, Y_t denotes the number of deaths on day t; β represents the function for the E-R relationship between Var_t and mortality; and Var_t is the factor variable representing the warning level event on day t. If $Var_t = 0$, it corresponds to seasonal surveillance events based on the HHSEW model and indicates no warning according to the CMA system. $Var_t = 1, 2, 3,$ and 4 represent pre-warning, warning level 1, warning level 2, and warning level 3 events, respectively, as classified by the HHSEW model. Similarly, $Var_t = 1$ also indicates a scenario where the CMA did not issue an early warning, but the HHSEW model issued a pre-warning or any level of early warning; $Var_t = 2, 3,$ and 4 correspond to the yellow, orange, and red warning levels in the CMA system. The terms $ns(Rh, df_1)$, $ns(time, df_2)$, and dow retain the same definitions as provided in Formula (1).

In the second stage, a meta-analysis was conducted to derive the national-level association between warning-level events and mortality, based on the relationships established in the first stage. Using the estimated mortality risks at each warning level from both the HHSEW model and the CMA-based early warning system, we predicted heat-related all-cause premature deaths across 337 cities in China during the summer seasons from 2013 to 2018. A comparative analysis of the predictive capabilities for health risks between the HHSEW model and the current CMA-based early warning system was also performed (detailed calculations are provided in the Supplementary Material).

By adopting the HHSEW model and integrating meteorological forecasting data, a heat-health early warning system was developed that can automatically predict and disseminate heat-health risk information to the public. This system operates on both national and local platforms, offering forecasting and real-time graded heat-health risk information. To quantify the potential health benefits of the HHSEW model, we estimated the economic burden that could be mitigated by issuing heat-health risk early warnings through the HHSEW model, in comparison to the CMA-based early warning system currently used in China (detailed calculations are provided in the Supplementary Material).

All analyses were performed using R software (version 4.0.2) with packages including timeDate, tidyr, knitr, dplyr, nlme, mgcv, splines, Matrix, and metaphor. The code is available upon request.

Role of the funding source

The funders had no involvement in the study design, data collection, data analysis, data interpretation, or the writing of this report.

Results

The two-stage analysis revealed that all-cause mortality risk increased by 1.90% (95% CI: 1.74%–2.07%) for every 1 °C increase in daily mean temperature. Significant impacts of daily mean temperature on all-cause mortality were observed across all climatic-architecture regions, except for Region VI (Severe Cold & Cold Western). Specifically, the risk of all-cause mortality increased by 2.86% (95% CI: 1.69%–4.05%) in Region IV (Hot Summer & Warm Winter), 2.20% (95% CI: 1.97%–2.43%) in Region III (Hot Summer & Cold Winter), 1.59% (95% CI: 1.15%–2.03%) in Region I (Severe Cold), 1.52% (95% CI: 1.26%–1.78%) in Region II (Cold), and 0.97% (95% CI: 0.36%–1.58%) in Region VII (Severe Cold & Cold Northwestern) for every 1 °C increase in daily mean temperature (Fig. 2). In Region V (Temperate), a 1.40% (95% CI: −0.05% to 2.86%) increase in all-cause mortality risk was observed for every 1 °C rise, suggesting a near–significant association between temperature and mortality. No significant association was found in Region VI (Severe Cold & Cold Western region), likely due to limitations in data coverage, leading to its exclusion from subsequent analyses. Sensitivity analysis indicated minimal changes in E-R values after including air pollutants in the main model, adjusting degrees of freedom, or adding a lag day variable, demonstrating the robustness of the main model (Fig. S3, Table S4).

As the percentile of daily mean temperature increased, a corresponding rise in mortality risk was noted across all climate-sensitive architectural regions (Fig. 3, Table S5). The pre-warning level was defined at the point corresponding to 0.5% of cumulative excess deaths from heat, with thresholds for Severe cold & cold (northwestern) region, Severe cold region, Cold region, Hot summer & Cold winter region, and Hot summer &

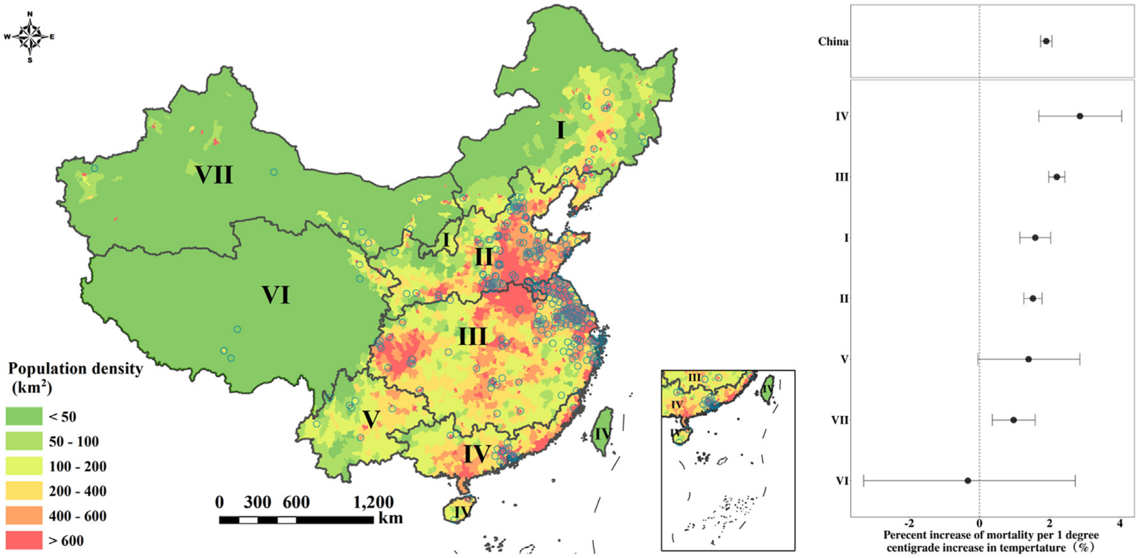

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Fig. 2: Map of architectural climatic regionalization in China and monitoring sites (left) and the increase in the mortality risk from all-cause mortality for every 1 °C increase in the daily mean temperature of each climatic-architecture region. I: Severe Cold Region; II: Cold Region; III: Hot Summer & Cold Winter Region; IV: Hot Summer & Warm Winter Region; V: Temperate Region; VI: Severe Cold & Cold Western Region; VII: Severe Cold & Cold Northwestern Region.

Warm winter region set at the 91st percentile of daily mean temperature. The pre-warning threshold for the temperate region was set at the 92nd percentile. Warning levels 1, 2, and 3 reflected increasing intensity in excess mortality risk across different temperature percentiles. For each region, the threshold for warning level 1 was set at the 94th–96th percentile of daily mean temperature, warning level 2 at the 96th–98th percentile, and warning level 3 at the 99.5th percentile (Fig. 4, Table S6).

The overall and annual average number of days at each warning level, as determined by the HHSEW model, showed a decreasing trend with increasing warning levels, consistent with the trends observed in the CMA-based warning system. Between 2013 and 2018, the HHSEW-based system issued a total of 543 days for seasonal surveillance, 94 days for pre-warning level, 44 days for warning level 1, 40 days for warning level 2, and 11 days for warning level 3 across all cities. In comparison, the CMA-based warning system recorded 713 days

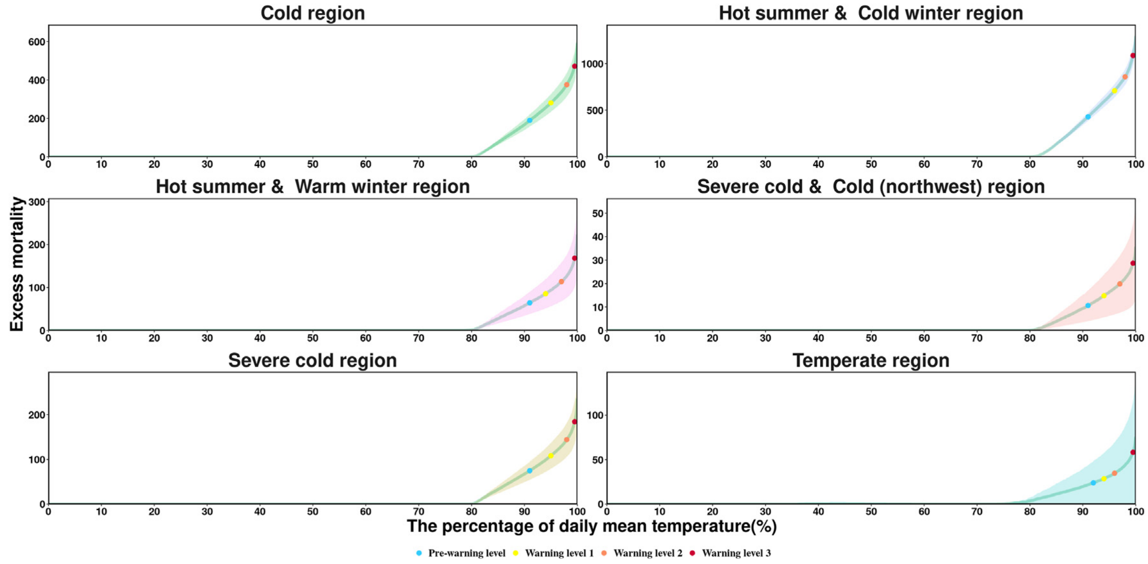

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Fig. 3: Determination of the early-warning threshold in each climatic-architecture region.

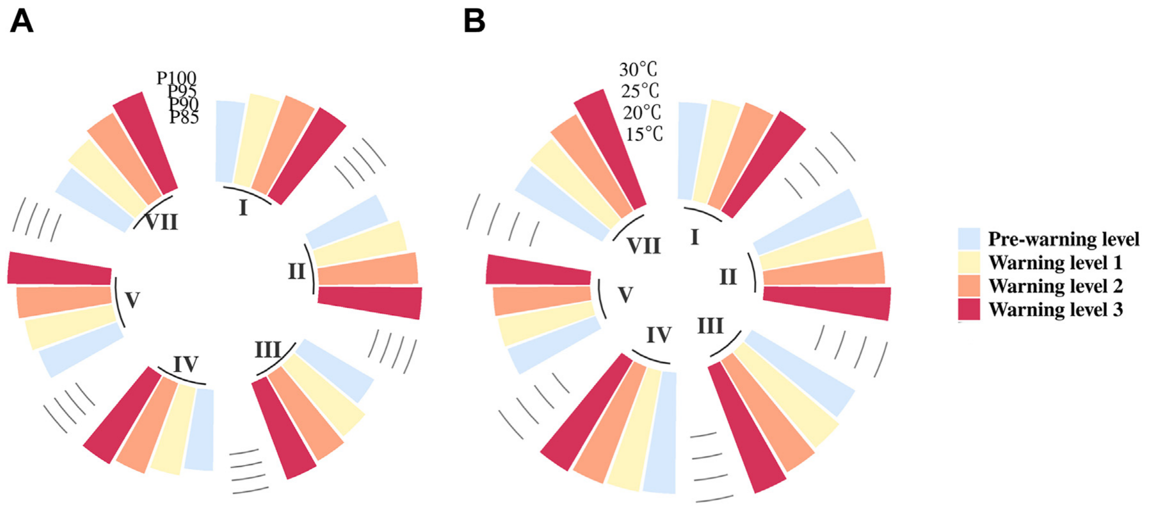

Fig. 4: Relative and absolute thresholds of each early-warning level in each climatic-architecture region. (A) The relative thresholds (temperature percentile). (B) The absolute thresholds (absolute temperature). I: Severe Cold Region; II: Cold Region; III: Hot Summer & Cold Winter Region; IV: Hot Summer & Warm Winter Region; V: Temperate Region; VII: Severe Cold & Cold Northwestern.

with no warning, 10 days at the yellow level, 7 days at the orange level, and 1 day at the red level. The annual average number of days at each warning level issued by the HHSEW model were 91 days (74.24%) for seasonal surveillance, 16 days (12.78%) for pre-warning, 7 days (6.04%) for warning level 1, 7 days (5.43%) for warning level 2, and 2 days (1.51%) for warning level 3. For the CMA-based warning system, the annual average was 118 days (94.4%) with no warning, 2 days (1.6%) at the yellow level, 1 day (0.8%) at the orange level, and 0 days (0.0%) at the red level (Fig. S4). A comparison between the HHSEW model and the CMA-based warning system revealed that on certain days when temperatures did not reach the CMA's heatwave warning thresholds, temperature-related health risks still triggered warnings under the HHSEW model.

High temperatures at warning levels 1–3 in both the HHSEW model and the CMA-based warning system (yellow to red levels) adversely affected all-cause mortality, total non-accidental causes, circulatory diseases, respiratory diseases, and other cause-specific diseases (Fig. 5). GLM analysis revealed a stepwise increase in the impact

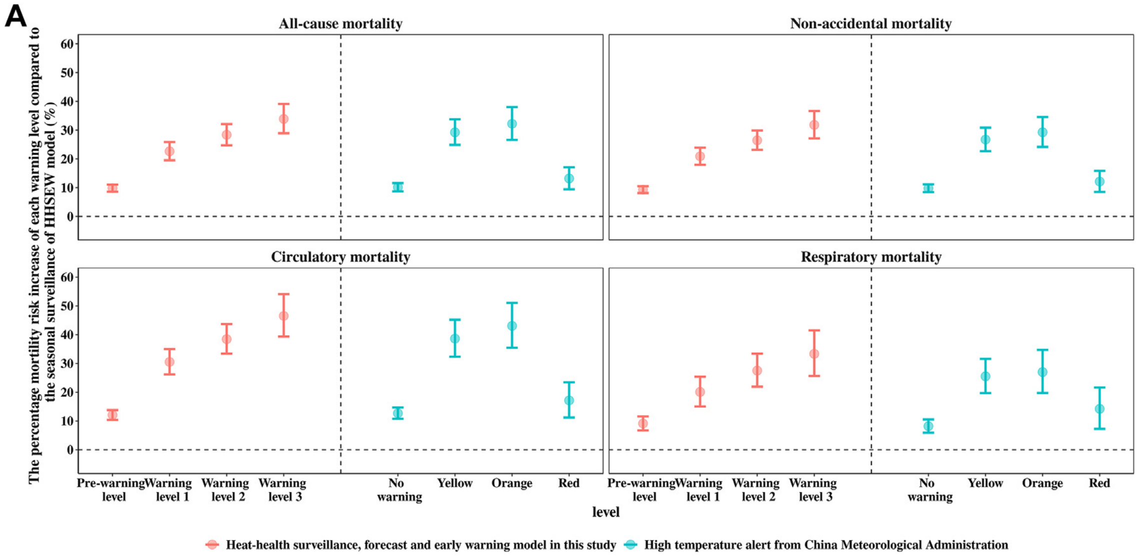

Fig. 5: The percentage mortility risk increase of each warning level compared to the seasonal surveillance of HHSEW model. (a, the mortality risks of all-cause, total non-accidental, circulatory diseases, and respiratory diseases; b, the mortality risks of cause-specific diseases).

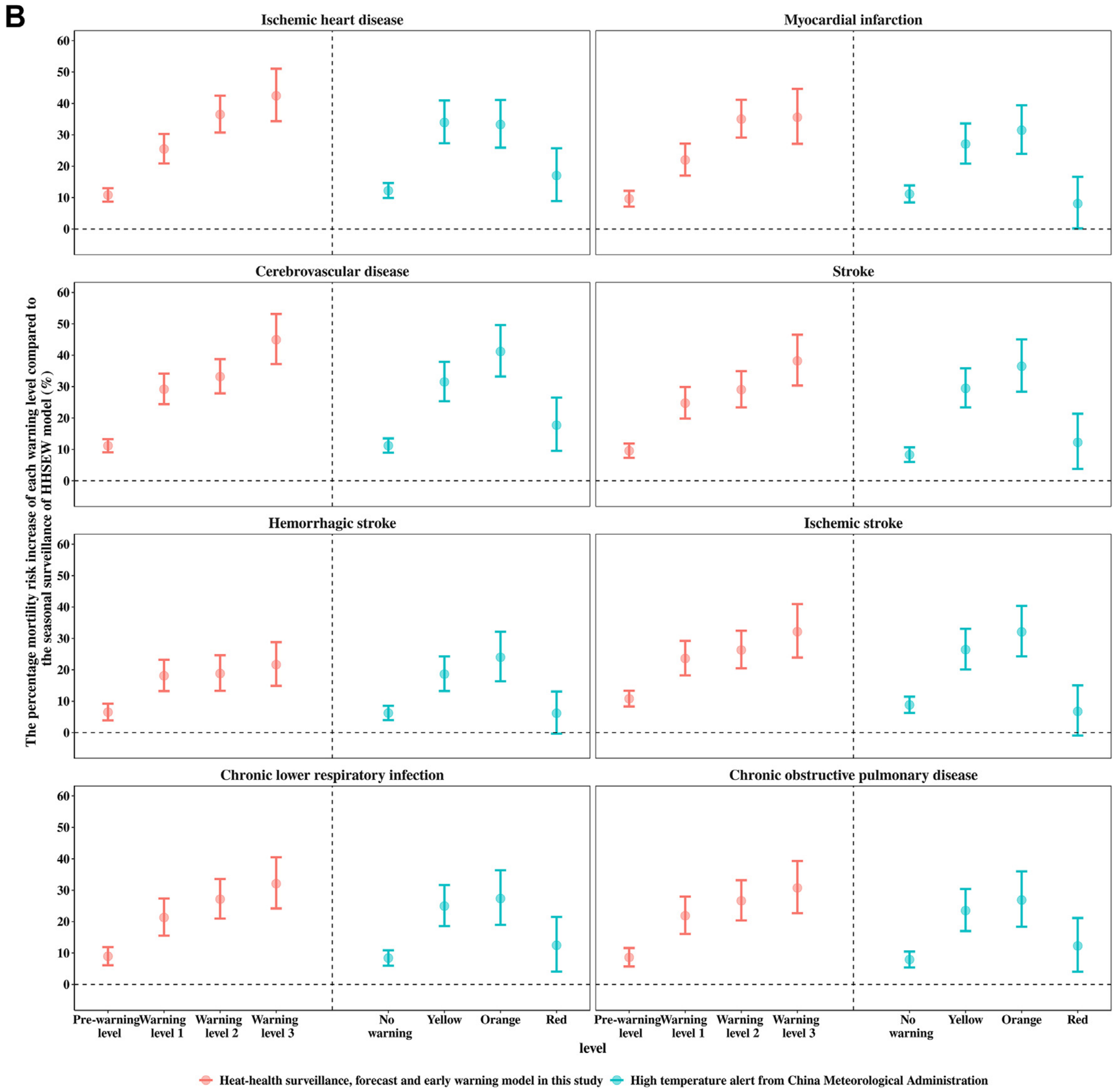

Fig. 5: Continued.

of the HHSEW model's pre-warning level and warning levels 1, 2, and 3 on all-cause mortality, total non-accidental mortality, circulatory disease mortality, and respiratory disease mortality (pink bars in Fig. 5a). Specifically, the HHSEW model's pre-warning level, warning level 1, warning level 2, and warning level 3 were associated with increases in all-cause mortality risk by 9.79% (95% CI: 8.59%–11.01%), 22.62% (95% CI: 19.49%–25.83%), 28.36% (95% CI: 24.72%–32.10%), and 33.87% (95% CI: 28.89%–39.06%), respectively. In comparison, the CMA-based warning system's yellow, orange, and red levels increased all-cause mortality risk by 29.21% (95% CI: 24.84%–33.72%), 32.18% (95% CI: 26.59%–38.02%), and 13.17% (95% CI: 9.43%–17.04%), respectively. Additionally, when the CMA-based warning system did not issue an early warning, but the HHSEW model issued a pre-warning or higher level warning, the all-cause mortality risk increased by 10.12% (95% CI: 8.72%–11.54%) (blue bars in Fig. 5a).

Mortality risk for cause-specific diseases also exhibited significant stepwise increases from the pre-warning level to warning levels 1–3, compared to the seasonal surveillance level. Notably, mortality risk from ischemic heart disease, myocardial infarction, cerebrovascular disease, stroke, hemorrhagic stroke, ischemic stroke, chronic lower respiratory infection, and chronic obstructive pulmonary disease increased by 10.83% (95% CI: 8.70%–13.00%), 9.63% (95% CI: 7.16%–12.16%), 11.16% (95% CI: 9.09%–13.28%), 9.57% (95% CI: 7.33%–11.85%), 6.51% (95% CI: 3.89%–9.20%), 10.80% (95% CI: 8.33%–13.32%), 8.96%

(95% CI: 6.12%–11.88%), and 8.61% (95% CI: 5.70%–11.60%) at the pre-warning level. The mortality risk for each disease continued to rise with higher warning levels, peaking at warning level 3, which showed increases of 42.44% (95% CI: 34.32%–51.04%), 35.59% (95% CI: 27.13%–44.61%), 44.93% (95% CI: 37.18%–53.13%), 38.20% (95% CI: 30.35%–46.53%), 21.65% (95% CI: 14.91%–28.79%), 32.15% (95% CI: 23.92%–40.93%), 32.09% (95% CI: 24.19%–40.49%), and 30.74% (95% CI: 22.71%–39.29%) (pink bars in Fig. 5b). These results indicate that the HHSEW model effectively identifies health risks in a hierarchical manner for cause-specific diseases. In contrast, the CMA-based warning system did not show a consistent increase in mortality risks across various diseases with higher warning levels (blue bars in Fig. 5).

Using the estimated mortality risks associated with each warning level from both the HHSEW model and the CMA-based early warning system, heat-related all-cause mortality was predicted for the summer seasons. The HHSEW model projected an annual total of 94,008 heat-related deaths across 337 cities in China during the summers of 2013–2018. This included 29,974 deaths at the pre-warning level, 26,564 at warning level 1, 27,850 at warning level 2, and 9620 at warning level 3. In comparison, the CMA-based warning system predicted only 14,858 deaths, distributed as 5737 at the yellow level, 9030 at the orange level, and 91 at the red level.

The HHSEW model was utilized to develop heat-health early warning systems, incorporating both national and local platforms capable of delivering real-time graded heat-health risk information to the public through mobile applications, WeChat official accounts, and the websites of national and local CDCs (Fig. 6). By integrating meteorological forecast data, the system provides real-time heat-health risk forecasts for the next 7 days. This information, including five levels of heat-health risk predictions, is disseminated daily like a weather forecast. When a warning level threshold is reached, early warnings are issued along with corresponding health protection advice. The implementation of the HHSEW-based early warning system could result in significant health benefits. If these warnings were issued promptly and health protection measures were effectively applied, over 90,000 deaths could be prevented annually. In economic terms, this could translate

Heat-health surveillance and early warning system

Shandong Prov.

Jinan City

Laiwu County

2021/08/01 Start

2021/08/26 End

Laiwu county

The distribution of heat-health surveillance and early warning levels

Ambient temperature

Date 2021/08/01 - 2021/08/26

web 4C/FPO

Fig. 6: A demo of the national platform (left) and local platform (right) of the heat-health early warning system (considering Jinan as an example).

to an annual saving of approximately 262 billion CNY in economic burden, which is 220 billion CNY more than what could be saved with the currently used CMA heatwave early-warning system in China.

Discussion

This study introduces a health-risk-centered, multi-climate-region, and full-seasonal approach to heat-health risk management, resulting in the development of a HHSEW model based on temperature and mortality data from 323 counties across China. The HHSEW model is the first health-focused heatwave early warning system in developing countries, offering graded heat-health risk information—including seasonal surveillance, pre-warning, and three warning levels—across six climatic-architecture regions and covering the entire summer season. The model has demonstrated a clear stepwise increase in health risk corresponding to each warning level and has outperformed the existing heatwave warning system in accurately estimating health risks. National and city-level heat-health early warning systems have been implemented using the HHSEW model, with pilot programs already issuing warnings to the public. Projections suggest that, if fully deployed across 337 major cities in China and accompanied by effective health protection measures, the HHSEW-based system could prevent over 90,000 heat-related premature deaths annually and save approximately 262 billion CNY in economic burden—significantly more than the current system. These findings highlight the substantial potential health benefits of the HHSEW model, making it a valuable tool for the government in providing targeted climate-health services and for the public in accessing reliable heat-health risk information.

Compared to previous heatwave or heat-health early warning models, the HHSEW model offers the significant advantage of full-season coverage for heat-health risk management, spanning from June 1st to September 30th. Traditional heatwave and heat-health warning systems, widely implemented across various countries, typically neglect the health risks associated with non-heatwave days, issuing warnings only when temperatures exceed specific thresholds. However, non-optimal temperatures on these non-heatwave days can still have substantial impacts on public health, particularly among vulnerable populations.[41–44] A multi-center study in China found that 14.33% of non-accidental mortality was attributable to non-optimal temperatures, with moderate heat (22.8–29.0 °C) and extreme heat (29.0–31.6 °C) events accounting for 2.08% and 0.63%, respectively. The current heatwave early warning system in China, managed by the CMA, defines heatwaves based solely on temperature thresholds of 35 °C and their duration, issuing various levels of warnings without considering the quantitative health impacts of heat. This approach falls short in providing comprehensive, full-season heat-health risk management. The HHSEW model addresses this gap by establishing graded warning levels based on actual health risks from high temperatures, significantly enhancing the ability to monitor and identify heat-health risks. Notably, the HHSEW model identifies considerable health risks even at the pre-warning level, where temperatures do not reach the CMA-defined warning threshold but still result in a 9.79% increase in all-cause mortality. This underscores the necessity of a full-season heat-health risk management system that includes seasonal surveillance, pre-warning, and graded warnings, delivering timely and precise heat-health information to the public.

Given the substantial variability in climate characteristics, population adaptability, and vulnerability across different regions of China, the HHSEW model was developed using local health monitoring data to provide region-specific warning levels for each climatic-architecture region. This tailored approach enhances the model's sensitivity and adaptability. Nationally, the model indicates a 1.90% (95% CI: 1.74%–2.07%) increase in all-cause mortality for every 1 °C rise in daily mean temperature, consistent with previous research.[45] Significant impacts of daily mean temperature on all-cause mortality were observed in all climatic-architecture regions except Region VI (severe cold and cold (western) region), where data limitations were present. The variation in impacts across different regions aligns with findings from prior studies,[46,47] highlighting the need for region-specific HHSEW models and localized heat-health risk management strategies to effectively and precisely mitigate health risks using scientifically grounded warning levels.

Determining warning thresholds is a critical aspect of the HHSEW model. A review of recent literature reveals two predominant approaches for setting heat-health risk warning thresholds: one based on temperature or its percentiles,[17,48,49] and another based on epidemiological studies that model the relationship between heat and mortality.[23,26,27] This study integrates the strengths of both methods by determining thresholds based on health risks attributable to temperature, providing a more sensitive approach to identifying heat-health risks. Traditionally, studies and systems that establish thresholds based on epidemiological relationships between temperature and population mortality have used absolute temperature as the exposure metric, setting thresholds when predicted excess mortality reaches or exceeds a specific value.[23,50] However, environmental epidemiological studies have shown that using relative temperature (i.e., percentile temperature) as a threshold for heatwaves offers a better estimation of health impacts, as it accounts for regional differences in temperature range and population adaptability.[20,21,51] In this study, temperature percentiles were used as the exposure metric to determine thresholds for various warning levels, with an emphasis on the "increase" in excess mortality rather than the absolute excess mortality itself. This approach allowed for the development of region-specific thresholds based on local relative temperatures and associated health risks, representing a significant advancement over previous heat-health evaluation methods.

Model evaluation results indicated that heat-related mortality risk increased progressively with higher warning levels in the HHSEW model (Fig. 5), demonstrating its capability and sensitivity in identifying health risks. The HHSEW model also performed well in indicating heat-related mortality risks for two major disease categories: respiratory diseases and circulatory diseases. It is estimated that adopting the HHSEW model-based early warning system could prevent a significant number of excess deaths, proving its superiority over existing heatwave warning systems. Additionally, the HHSEW model identifies health impacts at the pre-warning level, addressing the risks of high temperatures that have not yet reached extreme heat levels. This facilitates timely interventions to prevent health hazards associated with elevated temperatures.

The adoption of the HHSEW model and its early-warning system enables the government to provide timely and reliable warnings of public health risks associated with high temperatures. Currently, the HHSEW model is recognized by the China CDC as a key technology to be promoted and applied in the nationwide pilot project on environmental health risk assessment.[52,53] This HHSEW-based early-warning system has already been implemented in several pilot cities in China, including Jinan, Qingdao, and Shenzhen, where it has been used to issue heatwave and related health risk information to local residents. Significant health benefits were observed following the system's adoption during the summer of 2022.[38] The HHSEW model and early-warning system are expected to be rolled out in more cities across China in the near future. The early-warning system serves as a smart management tool, providing heat-health warnings and corresponding health tips at each warning level. This information helps the public, communities, and policymakers take proactive measures to mitigate the health impacts of heatwaves. For vulnerable populations, such as individuals with cardiovascular or respiratory conditions, the system offers specific health risk information and protective recommendations. These health alerts and tips can be accessed *via* modern devices, such as mobile phones and wearables, enabling patients to take precise preventive measures in advance, thereby reducing the health hazards associated with heatwaves.

The HHSEW model offers several advantages, including full-season coverage, a population health-oriented system, and graded early warnings for heatwaves. However, certain limitations should be acknowledged. First, while this study included mortality monitoring sites across 323 counties in China, fewer sites were represented in the western regions, specifically Region VI (Severe Cold and Cold Western Region), due to the smaller population size and limited monitoring infrastructure. As monitoring systems improve, it is anticipated that more sites will be established, enhancing the representativeness of the study across all regions of the country. Second, this study focused on mortality as the primary health endpoint for model evaluation, without considering additional outcomes such as morbidity, hospital admissions, outpatient visits, and other health effects. Mortality was chosen due to the generally higher quality and broader availability of mortality data, making it the most objective endpoint for assessing heatwave-related health impacts. Nonetheless, future research should aim to expand the scope of health endpoints associated with high temperatures. Third, due to the incomplete spatiotemporal coverage of local meteorological station data, this study relied on a reanalysis of meteorological data from the ECMWF, which offers comprehensive coverage and has been widely used in previous research. Although monitoring data would be preferable, the ECMWF dataset provides a robust alternative. Fourth, the study's data period spans six years (2013–2018), which is shorter than the periods typically used in environmental epidemiological studies in Europe and the U.S. However, this dataset is currently the most comprehensive and reliable national dataset available. While a longer data period would be ideal, the onset of the global COVID-19 pandemic in 2019 has likely affected more recent data, introducing confounding factors related to policies and infectious diseases. As a result, the 2013–2018 dataset was selected, and many high-quality publications have been based on this data. As the HHSEW model continues to be applied in cities across China, updates and verification with post-pandemic data are planned once the COVID-19 situation stabilizes. Finally, this study used region-specific E-R relationships to determine early warning levels for each climatic-architecture region, rather than city-specific E-R relationships, due to the limited availability of mortality data for individual cities. Nevertheless, the available data is sufficiently representative for each region based on reasonable climate zoning, making the use of region-specific E-R relationships appropriate for cities within each region.

In conclusion, this study presents an approach for HHSEW model framework that features full-season coverage and graded levels based on the quantitative assessment of health risks from high temperatures. Given its advantages, this technology shows significant promise for widespread application. Currently, many countries in the Western Pacific region, particularly lower-income nations in continental Asia and the Pacific Island States, face severe threats from climate change and heatwaves, yet lack effective heat-health risk warning systems.[9] The technical methods outlined in this study could serve as valuable references for these regions. However, despite the benefits, the HHSEW model can be further refined for localized applications by incorporating local monitoring data on mortality and morbidity related to heat-sensitive diseases.[44,52,54] This would enhance the early warning system's relevance and accuracy for local heat-health risk assessments. Moreover, the health impacts of heatwaves may be influenced by additional factors such as air pollutants.[55–58] Considering these combined effects, future research aims to conduct more comprehensive studies to develop an even more robust HHSEW model.

Contributors

TL contributed to the research concept. TL, CC and QW designed the study. QW wrote the paper. TL, QW and CC revised the manuscript according to the reviewers' comments with the assistance of HX and YL. HX, YZ, MW, MZ and CC reviewed the previous studies, cleaned the data and conducted the data analysis. YL and JL verified the data, re-run the R-codes, and re-plotted the figures. HX and YL had access to raw data. All the authors contributed to interpreting the results and revised the draft critically. TL had final responsibility for the decision to submit for publication.

Data sharing statement

The meteorological data, population data and the air quality data (daily concentrations of $PM_{2.5}$ and O_3) in the 323 counties and a data dictionary defining each field in the set, may be provided upon reasonable request via email to the corresponding author after this article is published. Statistical data on mortality may be provided upon reasonable request via email to the corresponding author and application through compliant means.

Editor note

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Declaration of interests

The authors declare that there is no conflict of interest for the publication of this manuscript.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.lanwpc.2024.101266.

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