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ORIGINAL RESEARCH

# Including Health System Capacities into the Assessment Framework of a Temperature-Resilience Health System

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**Introduction:** This study includes health system capacities into the assessment framework of a temperature-resilience health system while accounting for system interactions.

**Methods:** In accordance with the guidelines provided by the World Health Organization, the conceptual framework of a climate-resilient health system has been adopted. The International Health Regulations are utilized to assess the health system capacities in 171 countries from year 2011 to 2019. Exploratory factor analysis and reliability tests have been conducted to confirm the validity and reliability of the framework. Moreover, a data-driven decision-making trial and evaluation laboratory method is employed to quantify the interactions among the structured aspects.

**Results:** The assessment framework consists of five aspects, namely high temperature-sensitive risks, low temperature-sensitive risks, low-temperature exposure, vulnerability factors and health system capacities. Globally, the mean (standard deviation) for addressing the first four aspects are 0.77 (0.14), 0.87 (0.13), 0.88 (0.21), 0.72 (0.17), respectively, and health system capacities reach 0.67 (0.17). This study identifies health system capacities as the main driving forces. Interactions between it and other aspects call for multisectoral and coordinated actions. On a global scope, low-temperature exposure and its health risks, with the strongest dependence, should be prioritized to enhance temperature resilience, especially in high-income countries. In order to mitigate these risks, it might be necessary to disrupt the cascade effects resulting from low-temperature exposure by leveraging the capacities of coordination and multisectoral communication. Notably, low-income countries are more affected by high-temperature exposure, thus requiring flexible ways to strengthen temperature resilience.

**Discussion:** Our study underscores the significance of health system capacities in strengthening a temperature-resilient health system. Undoubtedly, the development of the temperature-resilient health system ought to follow a coordinated and flexible approach, giving priority to dealing with low-temperature exposure.

**Keywords:** temperature resilient, health system capacities, interactions, decision making trial and evaluation laboratory method

## Introduction

Under the circumstances of global warming, ambient non-optimal temperature exposure has become a major health threat facing humanity.[1,2] A series of studies have presented solid evidence that global warming has caused a substantial increase in non-optimal temperature exposure, manifested by an increase in mean climate warming, the frequency, duration, and intensity of extreme temperatures, and a widening of temperature variability.[3,4] This in turn has considerable health implications in direct (eg, heat-related morbidity and mortality) and indirect ways (eg, increased malnutrition risk due to reduced food production).[5] According to conservative estimations by the World Health Organization (WHO), increasing non-optimal temperature exposure may result in approximately 250,000 additional deaths annually due to heat

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stress, malaria, diarrhea and malnutrition alone from 2030 to 2050.[6] Without additional policies and actions, sustainable increases in disease burden attributed to global warming are expected in the coming decades.[7] This points to the need for nations worldwide to build climate-resilient health systems.[8,9]

According to the WHO, a climate-resilient health system is one that is able to predict, recognize, manage and adapt to climate-related health shocks and finally sustainably improve population health.[10] The WHO has proposed a conceptual framework covering vulnerability factors, health system capacities, exposure pathways and health risks.[10] The development of the climate-resilient health system follows enhancing specific system capacities as its principal step.[11] However, health system capacities have often been neglected in quantitative studies and practices. Zhu et al[12] Yu et al[13] and Wang et al[14] encompassed health sensitivity, exposure and vulnerability factors while assessing vulnerability to temperature-sensitive health outcomes in Guangdong Province, China, British Columbia, Canada and Australia. Nevertheless, they did not take health system capacities into consideration. Tran et al[15] and Grigorescu et al[16] included health staff, health service quality and a number of pharmacies to measure health system capacities. Kamal et al[17] also covered access to health care while assessing health vulnerability to extreme heat. However, such studies have yet to systematically take the health system into account. Moreover, in current practice among multiple nations worldwide (such as South Africa,[18] United States,[19] Ireland,[20] and Ghana[21]), health capacities to respond to climate change have also been largely absent from the public health sector. Martinez et al[22] figure out that preparedness of the health system is the least often implemented action in a comprehensive strategy for reducing heat exposure. Thus, vulnerable populations (eg, children, pregnant women, older populations, with a larger percentage of those with chronic diseases, as well as poor people) are often placed at risk. These people are more sensitive to health risks that are triggered by temperature exposure, either due to their poor physical conditions or the shortage of resources at their disposal. The phenomenon has been repeatedly witnessed in South Africa,[18] the Mediterranean Basin,[23] Ireland,[20] and Peru.[24] Taken together, a systematic approach to examine the role of health system capacities for enhancing climate-resilient health systems is needed.

More importantly, interactions among the socioeconomic network and the ecosystem further complicate the issue.[9,25] Temperature risk has a “cascade” effect transmitting from the ecosystem to the socioeconomic network.[7,26] The WHO has identified the complex interactions[10] and calls for the development of the climate resilient health system in the “health national adaptation plan” (NAP).[27,28] Previous studies have attempted to quantify the possible interactions between environmental exposure, vulnerable factor and health risks using multi-criteria decision-making models, such as the analytic hierarchy process[12,15] or principal component analysis method.[13,17] These models calculate the relative contribution of aspects but are unable to account for the complex interactions among different aspects. Without addressing these complex interactions, the development of temperature-resilient health system may encounter difficulty in formulating policies and actions to address temperature risks.

Therefore, the objectives of this study are to assess the role of health system capacities that supports the basis of coordinated temperature-resilient health system development. Based on the conceptual framework of the temperature-resilient health system proposed by the WHO, possible indicators and aspects, including health system capacities, have been covered. Then, a data-driven decision-making trial and evaluation laboratory (DEMATEL) method is utilized to explore the possible interactions among aspects to provide precise guidelines to enhance health system capacities for facing temperature changes. A conceptual framework diagram is shown in Figure 1. This study contributes by (1) enhancing the understanding of the conceptual framework to achieve climate-resilient health systems by providing credible aspects and rules to bridge the gaps between theory and practice; (2) including health system capacities into the assessment framework of a temperature-resilience health system and quantifying the interrelationship between health system capacities and socioeconomic and ecosystem aspects, which extends the qualitative conceptual framework into quantitative relationships; and (3) offering strategies to enhance health system capacities and guide the operation of temperature-resilient health systems.

# Methods

Using a panel data set of 171 countries from 2010 to 2019, the study employed quantitative and qualitative methods (exploratory factor analysis (EFA) and reliability tests (RT), data-driven DEMATEL method) to address these three

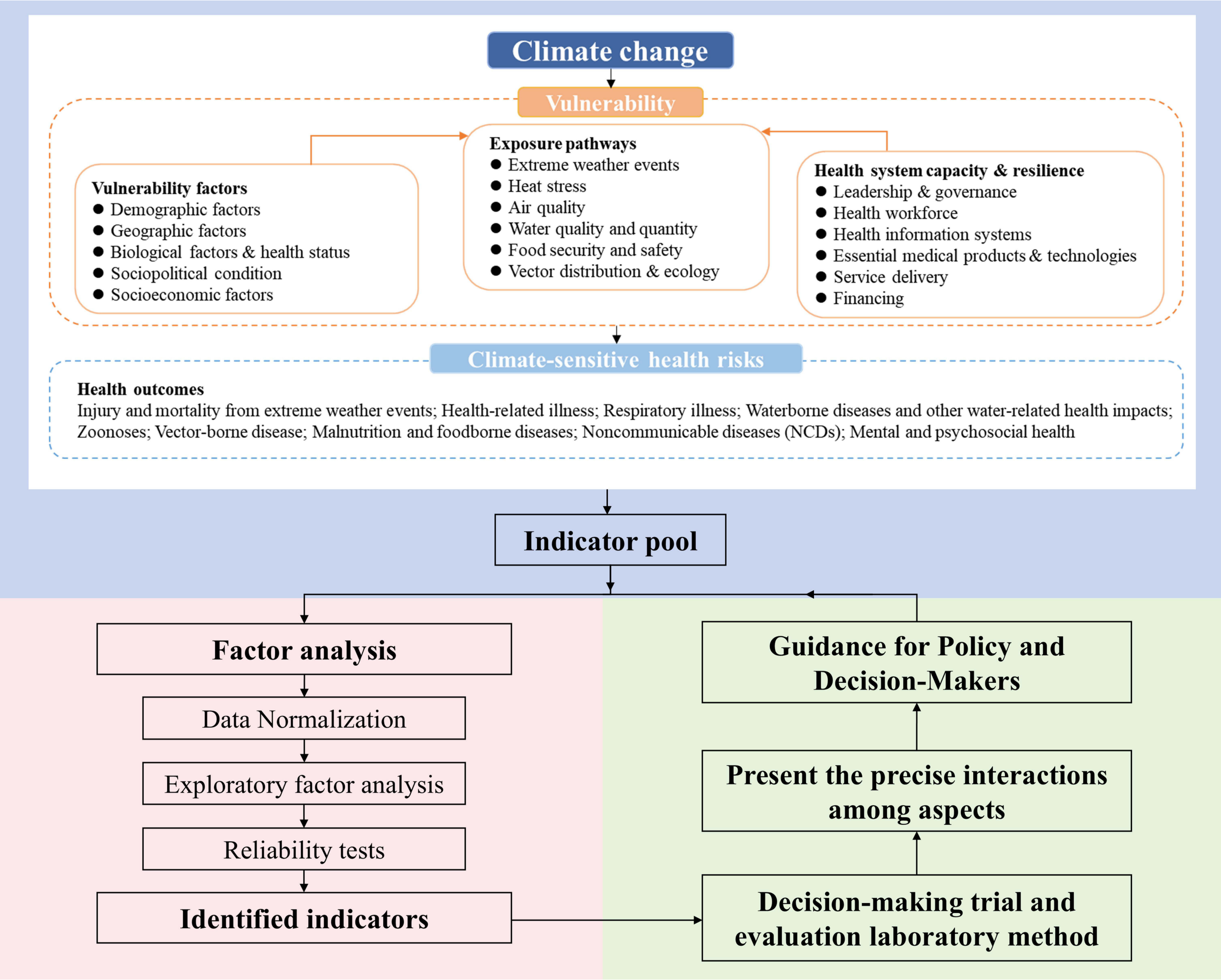

**Figure 1** Conceptual framework for study design and analysis.

dimensions: 1) indicator pool of temperature-resilient health systems, 2) the structured indicators and aspects, and 3) the possible interactions among aspects.

## Proposed Measures

Based on WHO conceptual framework,[10] temperature-sensitive health risks, exposure pathways and vulnerability factors have been included as proposed measures. Temperature-sensitive health risks refer to a wide range of health outcomes associated with temperature exposure, including disease burden attributed to non-optimal temperature exposure (I29 - I40). To be specific, burdens of disease attributable to high temperature include cardiovascular diseases mortality (I29), cardiovascular diseases years of life lost (YLL) (I30), all-cause mortality (I31), all-cause YLL (I32), chronic respiratory diseases YLL (I33), chronic respiratory diseases mortality (I34). Burdens of disease attributable to low temperature also cover all-cause YLL (I35), all-cause mortality (I36), cardiovascular diseases YLL (I37), cardiovascular diseases mortality (I38), chronic respiratory diseases YLL (I39), chronic respiratory diseases mortality (I40). Additional temperature-sensitive risks include the diarrheal diseases death rate (I43), all-cause mortality attributable to air pollution (I44), malaria death rate (I45), dengue death rate (I46), Zika virus death rate (I47), and yellow fever death rate (I48).[29]

Temperature exposure shall be considered the nature and degree to which a system is exposed to temperature. The former section included annual temperature and extreme temperature, manifested as average maximum temperature (I5), average mean temperature (I6), average minimum temperature (I7), relative humidity (I8), cold spell duration index (I9), warm spell duration index (I10), number of very hot days (I11) number of frost days (I12), maximum length of consecutive dry spell (I13) and maximum length of consecutive wet spell (I14).[15] This study also adds the population exposure to extreme heat and cold (I1–I4)[30] to represent annual extreme temperature exposure conditions of vulnerable populations. For the purpose of capturing the significance of wind speed and relative humidity in the process of assessing temperature-related impacts, the universal thermal climate index is adopted to measure the population's exposure to extreme heat and cold.[31]

Health system capacities relate to the capacities to predict, recognize and manage health risks in a way that the essential structure, infrastructure, and functions of health systems could sustain.[11] WHO has proposed International Health Regulation capacities for measuring the health system capacities.[11,25] It covers national health emergency framework, response and preparedness capacities, health service provision, risk communication, laboratory, surveillance, coordination and NAP communications, zoonotic events, national legislation, policy and financing, human resource capacities, chemical events, food safety, points of entry and radiation emergencies (I15 - I26).

For the vulnerability factors, it involves to demographic factors, socioeconomic factors, biological factors, and health resources and statuses that can reduce or expand the impact of temperature. Socioeconomic factors contain urbanization (proportion of urban population) (I60),[15] gross domestic product per capita (I61),[12] proportion of older population (aged 65+) (I68),[13] proportion of unemployment (I73),[16] particularly using government expenditure on education (I70) for education development. Health financing is measured by risk of impoverishing expenditure for surgical care (% of people at risk) (I56), domestic general government health expenditure (% of current health expenditure) (I59), current health expenditure (% of GDP) (I71), and out-of-pocket expenditure (% of current health expenditure) (I72). Prevalence of anemia among children (I75), all-cause mortality rate in 60+ people (I76), age-standardized NCD mortality rate (I77), and age-standardized suicide rates (I78) are used to measure overall health status. In total, 78 indicators have been included. Appendix Table S1 presents detailed information on the selected 78 indicators.

## Data Source

The data of the included 78 indicators are collected from eight databases, namely, the ERA5-HEAT, the Socioeconomic Data and Applications Center Gridded Population of the World version 4, the United Nations World Population Prospects, the Global Burden of Disease Study 2019, the Global Health Observatory data repository of the WHO, the World Development Indicators and the Climate Change Knowledge Portal of the World Bank, and the World Bank Country and Lending Groups. The extent of the population exposure to extreme heat and cold is obtained from the study of Du et al.[30] After eliminating countries with huge numbers of missing data, the final confirmed data include 171 countries from 2010 to 2019, then missing data are adopted multiple imputations to make up for it. Details for the data source are presented in Appendix (Table S1).

## Quantitative Normalization

In this study, the data normalization for the values of indicators $a = 1, 2, \cdots 78$ utilizes the maximum and minimum method to consider the positive and negative indicators.[32,33] The following formulas are adopted for normalization:

For positive indicators,

$$r_{ac}^{y} = \frac{x_{ac}^{y} - min\left(x_{ac}^{y}\right)}{max\left(x_{ac}^{y}\right) - min\left(x_{ac}^{y}\right)}, r_{ac}^{y} \in [0, 1] \tag{1}$$

Where $r_{ac}^{y}$ represents the normalized values for indicators $a$'s value $x_{ac}^{y}$ at year $y$ for country $c$; $max\left(x_{ac}^{y}\right)$ and $min\left(x_{ac}^{y}\right)$ represents the maximum and minimum value of indicator $a$.

For negative indicators,

$$r_{ac}^{y} = \frac{max\left(x_{ac}^{y}\right) - x_{ac}^{y}}{max\left(x_{ac}^{y}\right) - min\left(x_{ac}^{y}\right)}, r_{ac}^{y} \in [0, 1] \tag{2}$$

Otherwise, there are several indicators belonging to the interval data. And the normalization method of the interval data is shown in the following formula:

$$M = \max\left\{m - min\left\{x_{ac}^{y}\right\},\, max\left\{x_{ac}^{y}\right\} - n\right\} \tag{3}$$

$$r_{ac}^{y} = \begin{cases} 1 - \frac{m - x_{ac}^{y}}{M},\, x_{ac}^{y} < m \\ 1, m \le x_{ac}^{y} \le n,\, r_{ac}^{y} \in [0, 1] \\ 1 - \frac{x_{ac}^{y} - n}{M},\, x_{ac}^{y} > n \end{cases} \tag{4}$$

Where [m, n] could be seen as an ideal interval for the indicator *a*.

## EFA and RT

The discovered indicators and aspects rely on EFA and RT to confirm the validity and reliability of the structuring aspects *i*. The validity must check the Kaiser-Meyer-Olkin value if it is greater than 0.7 and Bartlett's spherical test (*p*-value <0.05), as well as all the factor loadings, also needs to be greater than 0.5. Then, the RT is employed to confirm the reliability by checking Cronbach's alpha (greater than 0.7), average variance extraction value (higher than 0.36), and composite reliability respectively (greater than 0.7).[33–35]

## Data-Driven Integration with DEMATEL

Data-driven integration is used to measure performances for each aspect, and then DEMATEL method is applied to explore the interactions among aspects.[32,36] After obtaining the normalized values $r_{ac}^{y}$ of indicators *a* with each aspect *i*, the degrees of aspect *i* at a given country *c* in study year *y* refers to $k_{ic}^{y}$, is calculated through the arithmetic average as follows:

$$k_{ic}^{y} = \frac{1}{u}\left(r_{1c}^{y} + r_{2c}^{y} + \cdots + r_{uc}^{y}\right),\, y = 2010,\, 2011, \cdots 2019 \tag{5}$$

where $u$ represents the number of indicators of each aspect $i$.

The ten-year average of $k_{ic}^{y}$ is calculated as follows:

$$k_{ic} = \frac{1}{10}\left(k_{ic}^{2010} + k_{ic}^{2011} + \cdots + k_{ic}^{2019}\right) \tag{6}$$

Afterward, aspect interactions are identified using the DEMATEL method. First, the continuous aspect performance $k_{ic}(i = 1, 2, \cdots \varepsilon)$ is converted to qualitative values $d_{ic}$ according to the quartile and 90th percentile of $k_{ic}$. The resulting $d_{ic}$ values are then assigned values of $1, 2, \cdots \varepsilon$, respectively.

Second, using the arithmetic average, qualitative values of $d_{ic}$ are aggregated for each country group *j* and arranged into a direct relation matrix by using the following equation:

$$E = \left[e_{ij}\right]_{\varepsilon \times \varepsilon} \tag{7}$$

$$e_{ij} = \frac{\sum_{c=1}^{h} d_{ic}}{h} \tag{8}$$

where $d_{ic}$ represents the qualitative values of aspects with countries arranged by the groups *j*, and *h* is the relevant number of countries in each group.

The study countries are classified into groups *j* according to economic development and aging society. The number of country groups *j* is similar to that of aspects. Classifications are shown in Appendix Table S2. By doing so, the study could assess the role of health system capacities accounting for country distribution of economic and demographic characteristics. Then, this direct relation matrix needs to be normalized and then generate the total relation matrix using the following equations.

$$\tilde{E} = \frac{e_{ij}}{\max_{1 \le i \le \varepsilon} \sum_{i=1}^{\varepsilon} e_{i}} \tag{9}$$

$$T = \tilde{E} \times \left(I - \tilde{E}\right)^{-1} = \left[t_{ij}\right]_{\varepsilon \times \varepsilon} \tag{10}$$

where $I$ is the identify matrix.

Thirdly, the following equation can conduct to gather the driving and dependence powers.

$$D = \left[\sum_{i=1}^{\varepsilon} t_{ij}\right] = \left[t_i\right]_{\varepsilon \times 1} \tag{11}$$

$$R = \left[\sum_{j=1}^{\varepsilon} t_{ij}\right] = \left[t_j\right]_{1 \times \varepsilon} \tag{12}$$

Using the coordinates maps the aspects to the cause and effect diagram, and then $(D + R)$ and $(D - R)$ are the $x$ and $y$ axis separately. Thereinto, $(D + R)$ represents the importance of aspects, $(D - R) \geq 0$ means the casual feature and $(D - R) < 0$ is the effect feature. Finally, applying the following equation generates the threshold for identifying the interactions among the aspects.

$$\theta = \frac{t_{ij}}{\varepsilon^2} \tag{13}$$

If $t_{ij} > \theta$, then a strong (TOP 30%) and medium interaction exists between the $i^{th}$ and $j^{th}$ aspects; otherwise, weak interaction exists.

# Results

## Geographic Comparison

### Striking Geographical Imbalance

The 53 indicators passing the test are grouped into five aspects (Table 1), namely, high temperature-sensitive risks, low-temperature exposure and low temperature-sensitive risks, health system capacities, and vulnerability factors. Judging from the factor loadings of the above five aspects (greater than 0.5), the Cronbach's alpha and composite reliability values (greater than 0.6), and the average variance extracted value (above 0.36), the aspects are valid to structure the enforced coordinated conceptual framework. On a global scale, the degrees to which high temperature-sensitive risks, low temperature exposure, low temperature-sensitive risks, and vulnerability factors are addressed are measured in terms of the mean (Standard deviation (SD)). Their respective values globally are 0.77 (0.14), 0.88 (0.21), 0.87 (0.13), 0.72 (0.17); as for health system capacities, they are 0.67 (0.17) (as presented in Table 2). Thus, a lot can be done when it comes to health system capacities. With respect to individual capacity, in the context of extreme temperature conditions, responding to health risks related to entry ports (points of entry) turns out to be the most arduous event (the mean (SD) being 50.72% (33.90%), and it calls for special attention.

Figure 2 presents geographic comparisons for health system capacities, and the other aspects are included in the Appendix (Figures S1–S3). The comparison reveals a dramatic geographical imbalance in the five aspects. Contrasting Figures 2 and S1–S4, low-temperature exposure exhibits the greatest regional differences, and the range between the maximum and minimum value reaches a 7.52-fold difference. Health system capacities rank second, with a multiple of 4.53 difference. As a result, enhancing health system capacities may contribute to narrow the cross-national difference in the health system's resilience to temperature changes (Table 2). With regard to individual capacity, points of entry, radiation emergency and national health emergency framework specifically, they demonstrate significant variance, with the SD of 33.90%, 37.38%, and 34.13%, respectively.

The study further compares the characteristics of the five aspects across countries with varying levels of socioeconomic development. Figures S5–S6 demonstrate that countries with different levels of economic development and aging exhibit different character in health system capacities and temperature exposure, which may influence their temperature resilience. To be specific, the degrees to which high temperature-sensitive risks, low-temperature exposure, low temperature-sensitive risks, and vulnerability factors are addressed, as well as health system capacities in high-income countries, with mean (SD) values of 0.81 (0.15), 0.75 (0.25), 0.88 (0.06), 0.88 (0.04) and 0.80 (0.10); while these values in low-income countries are 0.67 (0.16), 0.94 (0.17), 0.83 (0.20), 0.48 (0.12) and 0.49 (0.10) (as presented in Table 2). Even though high-income countries have a significant proportion of older populations with a mean (SD) of 13.9% (6.09%), they still maintain an advantage in health system capacities and vulnerability factors, which might potentially mitigate the risks that are highly sensitive to high

**Table 1** Exploratory Factor Analysis Results

| Aspects | Cronbach's Alpha | Average Variance Extracted | Composite Reliability | Indicators | | Factor Loading |
|---|---|---|---|---|---|---|
| High temperature-sensitive risks (HTR) | 0.942 | 0.6821 | 0.9549 | I29 | Cardiovascular diseases mortality attributable to high temperature | 0.920 |
| | | | | I30 | Cardiovascular diseases YLL attributable to high temperature | 0.915 |
| | | | | I31 | All-cause mortality attributable to high temperature | 0.907 |
| | | | | I11 | Number of hot days | 0.890 |
| | | | | I32 | All-cause YLL attributable to high temperature | 0.847 |
| | | | | I33 | Chronic respiratory diseases YLL attributable to high temperature | 0.819 |
| | | | | I34 | Chronic respiratory diseases mortality attributable to high temperature | 0.817 |
| | | | | I13 | Max number of consecutive dry days | 0.780 |
| | | | | I27 | Ambient particulate matter pollution | 0.673 |
| | | | | I49 | $PM_{2.5}$ air pollution, mean annual exposure | 0.637 |
| Low temperature-sensitive risks (LTR) | 0.946 | 0.7323 | 0.9419 | I35 | All-cause YLL attributable to low temperature | 0.942 |
| | | | | I36 | All-cause mortality attributable to low temperature | 0.940 |
| | | | | I37 | Cardiovascular diseases YLL attributable to low temperature | 0.896 |
| | | | | I38 | Cardiovascular diseases mortality attributable to low temperature | 0.873 |
| | | | | I39 | Chronic respiratory diseases YLL attributable to low temperature | 0.745 |
| | | | | I40 | Chronic respiratory diseases mortality attributable to low temperature | 0.709 |
| Low temperature exposure (LTE) | 0.967 | 0.6865 | 0.9161 | I1 | Children exposure to extreme cold | 0.865 |
| | | | | I2 | Older population exposure to extreme cold | 0.864 |
| | | | | I6 | Average mean temperature | 0.848 |
| | | | | I12 | Number of frost days | 0.787 |
| | | | | I7 | Average minimum-temperature | 0.774 |
| Health system capacities (HSC) | 0.911 | 0.447 | 0.9054 | I15 | National health emergency framework | 0.826 |
| | | | | I16 | Risk communication | 0.746 |
| | | | | I17 | Laboratory | 0.722 |
| | | | | I18 | Surveillance | 0.707 |
| | | | | I19 | Coordination and NAP communications | 0.694 |
| | | | | I20 | Zoonotic events | 0.669 |
| | | | | I21 | National legislation, policy and financing | 0.654 |
| | | | | I22 | Human resource capacity | 0.643 |
| | | | | I23 | Chemical events | 0.615 |
| | | | | I24 | Food safety | 0.594 |
| | | | | I25 | Points of entry | 0.555 |
| | | | | I26 | Radiation emergencies | 0.543 |

(*Continued*)

**Table 1** (Continued).

| Aspects | Cronbach's Alpha | Average Variance Extracted | Composite Reliability | Indicators | | Factor Loading |
|---|---|---|---|---|---|---|
| Vulnerability factors (VF) | 0.969 | 0.5978 | 0.9666 | I51 | Mortality rate, under-5 | 0.897 |
| | | | | I52 | People using at least basic sanitation services | 0.894 |
| | | | | I53 | Life expectancy at birth, total | 0.886 |
| | | | | I41 | All-cause mortality attributable to unsafe water, sanitation and handwashing | 0.884 |
| | | | | I54 | People using at least basic drinking water services | 0.881 |
| | | | | I42 | All-cause mortality attributable to child growth failure | 0.874 |
| | | | | I43 | Diarrheal diseases death rate | 0.861 |
| | | | | I55 | Maternal mortality ratio | 0.846 |
| | | | | I56 | Risk of impoverishing expenditure for surgical care | 0.837 |
| | | | | I75 | Prevalence of anemia among children | 0.828 |
| | | | | I57 | Adolescent fertility rate | 0.778 |
| | | | | I44 | All-cause mortality attributable to air pollution | 0.775 |
| | | | | I58 | Prevalence of undernourishment | 0.709 |
| | | | | I59 | Domestic general government health expenditure | 0.705 |
| | | | | I45 | Malaria death rate | 0.690 |
| | | | | I76 | All-cause mortality rate in 60+ people | 0.640 |
| | | | | I60 | Urban population | 0.631 |
| | | | | I61 | Gross domestic product per capita | 0.608 |
| | | | | I77 | Age-standardized NCD mortality rate | 0.537 |
| | | | | I3 | Older population exposure to extreme heat | 0.505 |

**Note**: Kaiser-Meyer-Olkin test reach 0.902 under significant level p<0.001.

**Abbreviations**: NCD, Noncommunicable diseases; PM, particulate matter; YLL, years of life lost; NAP, National Adaptation Plans.

**Table 2** Characteristics of Health System Capacities and Performance of Building a Temperature-Resilience Health System

| | Mean (SD) | | | | |
|---|---|---|---|---|---|
| | **Total** | **High-Income and Very High-Income Country** | **Upper Middle-Income Country** | **Lower Middle-Income Country** | **Low-income Country** |
| **Health system capacities** | | | | | |
| National health emergency framework (%) | 69.72 (34.13) | 83.79 (26.15) | 75.37 (29.98) | 61.78 (35.59) | 48.93 (36.81) |
| Risk communication (%) | 73.32 (25.33) | 84.41 (18.90) | 76.16 (24.50) | 69.34 (25.20) | 55.83 (25.80) |
| Laboratory (%) | 78.55 (19.80) | 84.56 (17.65) | 78.37 (19.70) | 75.49 (21.18) | 73.44 (18.55) |
| Surveillance (%) | 69.16 (24.39) | 83.33 (17.78) | 71.41 (22.90) | 61.51 (24.43) | 53.41 (22.25) |
| Coordination and NFP communications (%) | 68.76 (28.01) | 80.68 (22.50) | 71.45 (26.72) | 61.55 (28.82) | 55.48 (28.23) |
| Zoonotic events (%) | 57.10 (32.94) | 58.67 (34.20) | 64.05 (32.39) | 53.50 (32.37) | 48.74 (29.90) |
| National legislation, policy and financing (%) | 75.92 (22.36) | 85.39 (18.21) | 78.78 (20.79) | 68.82 (22.96) | 66.46 (22.88) |
| Human resource capacity (%) | 55.74 (32.09) | 72.24 (27.29) | 60.60 (32.33) | 48.20 (29.85) | 31.38 (23.19) |
| Chemical events (%) | 78.25 (25.80) | 88.47 (19.62) | 80.66 (25.07) | 73.26 (26.39) | 64.71 (27.52) |
| Food safety (%) | 69.20 (28.89) | 90.11 (16.22) | 74.12 (24.16) | 60.00 (26.41) | 39.79 (26.02) |
| Points of entry (%) | 50.72 (33.90) | 74.14 (27.10) | 54.68 (31.84) | 39.67 (30.22) | 21.65 (21.66) |
| Radiation emergencies (%) | 54.64 (37.38) | 78.80 (28.01) | 58.38 (35.56) | 43.39 (35.90) | 24.99 (27.37) |

(*Continued*)

**Table 2** (Continued).

| | Mean (SD) | | | | |
|---|---|---|---|---|---|
| | **Total** | **High-Income and Very High-Income Country** | **Upper Middle-Income Country** | **Lower Middle-Income Country** | **Low-income Country** |
| **Aspect performance/characteristics** | | | | | |
| Health system capacities | 0.67 (0.17) | 0.80 (0.10) | 0.70 (0.15) | 0.60 (0.15) | 0.49 (0.10) |
| Vulnerability factors | 0.72 (0.17) | 0.88 (0.04) | 0.79 (0.07) | 0.64 (0.11) | 0.48 (0.12) |
| High temperature-sensitive risks | 0.77 (0.14) | 0.81 (0.15) | 0.82 (0.06) | 0.74 (0.12) | 0.67 (0.16) |
| Low temperature-sensitive risks | 0.87 (0.13) | 0.88 (0.06) | 0.86 (0.14) | 0.88 (0.13) | 0.83 (0.20) |
| Low temperature exposure | 0.88 (0.21) | 0.75 (0.25) | 0.90 (0.18) | 0.96 (0.14) | 0.94 (0.17) |
| **Performance of building a temperature-resilience system** | 0.78 (0.08) | 0.82 (0.05) | 0.81 (0.06) | 0.76 (0.06) | 0.68 (0.06) |

temperatures. Conversely, exposure to low temperatures and the associated health risks continue to pose challenges to the temperature-resilience system in these countries, higher than those in low-income countries. Among low-income countries, which are more likely to be located in low-latitude regions, high temperature-sensitive risks continue to be the predominant risks. Moreover, the disadvantages in health system capacities as well as the presence of vulnerable factors might further exacerbate these risks.

Regarding health system capacities, capacity to address zoonotic events (mean (SD): 58.67% (34.20%)) and human resource capacity (mean (SD): 72.24% (27.29%)) in high-income countries are among the lowest compared to other capacities and thus should be the focus of attention. In contrast, human resource capacity (mean (SD): 31.38% (23.19%)) and response to points of entry (mean (SD): 21.65% (21.66%)) and radiation emergencies (mean (SD): 24.99% (27.37%)) in low-income countries should be particularly strengthened.

To gain insights into how health system capacities can be included to enhance temperature resilience, a data-driven DEMATEL model has been employed to investigate the potential interactions among the various aspects.

## Aspect Interactions

Figure 3 shows the influential diagram describing aspect interactions accounting for characteristics of economic development and aging trend, respectively. Health system capacities rank second in terms of the degree of cause and importance. Regardless

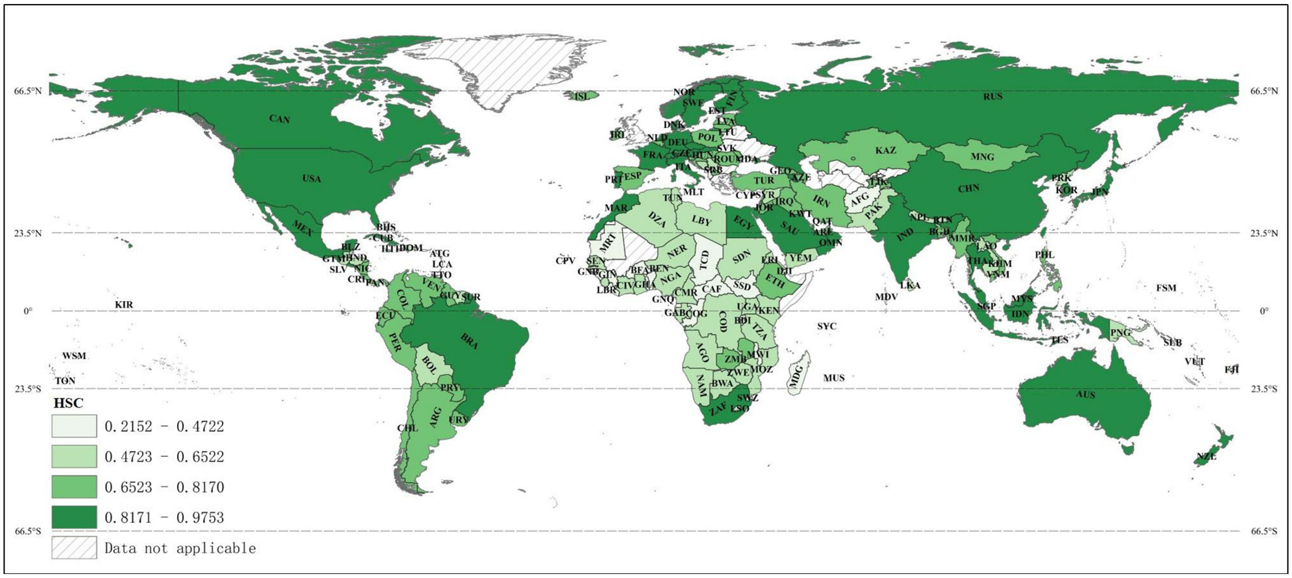

**Figure 2** Geographic comparison diagram of health system capacities (HSC) aspect.

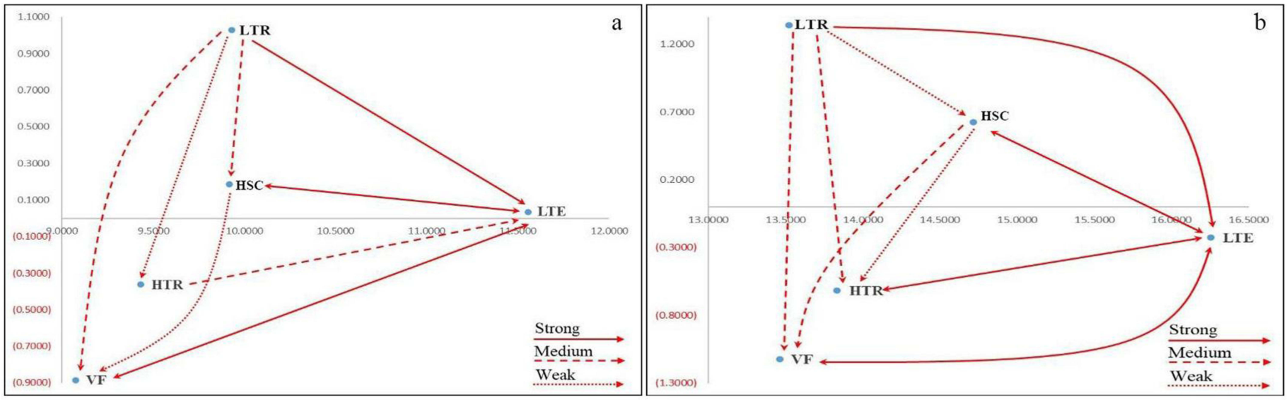

**Figure 3** Data-driven influential diagram comparison for building a coordinated temperature resilient health system. (**a**) Accounting for Economic Development (2010–2019). (**b**) Accounting for Social Aging (2010–2019).
**Abbreviations**: VF, vulnerability factors; HTR, high temperature-sensitive risks; HSC, health system capacities; LTR, low temperature-sensitive risks; LTE, low temperature exposure.

of the level of economic development and demographic characteristics, health system capacities are directly linked to the reduction of vulnerability, exposure to temperature variations, and temperature-sensitive health risks. It determines health system capacities as a causal aspect and driving force. Moreover, health system capacities play an integrating role through their interactions with temperature exposure, temperature-sensitive health risks, and vulnerable factors. This implies that building a temperature-resilient health system cannot be solely the responsibility of health departments; instead, such a process must be coordinated among multiple sectors. However, up to now, health system capacities have yet to fulfill their full potential. Health system capacities exert a small or even insignificant direct effect on the performance of addressing risks that are highly sensitive to high temperatures. This may be partly due to the immediate effects of high-temperature exposure on health outcomes, with a special need for health system instant response capacities in low-income countries.[37]

In contrast, low-temperature exposure is affected by multiple aspects such as health system capacities and vulnerable factors, determining the aspect with the strongest dependence power. Its importance is 1.10 to 1.15 times as much as that of health system capacities. The latter holds the second position in terms of importance. Low-temperature exposure has a long-term health impact, enabling the influence to be transmitted across aspects.[38] In addition, low temperature-sensitive health risks could further affect the development of health system capacities and reduction of vulnerable factors, thus giving rise to cascade effects. Consequently, it demands coordinated strategies to deal with low temperatures and the associated risks.

# Discussion

In the context of global warming, the current study includes health system capacities into the assessment framework of a temperature-resilience health system and reveals an influential model that explores the precise interactions among aspects. Based on worldwide data of 73 indicators covering 171 countries, the indicator system for the temperature-resilient health system is categorized into five validated aspects: high temperature-sensitive risks, low-temperature exposure and low temperature-sensitive risks, health system capacities, and vulnerability factors. Low- and high-temperature exposure and their associated health risks are separated to identify different strategies. Furthermore, based on the interactions among aspects, the study presents guides to support the development of a coordinated temperature-resilient health system.

## Enhance Health System Capacities to Build a Temperature-Resilient Health System

Three features should be attributed to the development of a temperature-resilient health system. First, health system capacities are consistently identified as a major driver, highlighting the crucial importance of strengthening them to address temperature-sensitive health risks. Our results suggest that health system capacities can have an impact on temperature-sensitive health risks not only directly but also indirectly (for instance, through influencing vulnerable factors). Consequently, enhancing health system capacities might help to mitigate temperature-sensitive health risks. These findings are in line with the proposals put forward by the WHO, which state that developing specific system capacities constitutes a principal approach to constructing climate-resilient health systems.[11] Second, developing temperature-resilient health systems needs to consider maximizing synergies across aspects. Strengthening health system capacities is not the sole responsibility of health departments. Instead, the interactions among various aspects highlight the necessity that this task should be coordinated. The WHO also advocates that temperature-resilient health systems should be integrated into the "health NAP".[10] Third, when developing a coordinated temperature-resilient health system, low-temperature exposure and the associated health risks that are sensitive to it should be given top priority. Our influential model shows that low-temperature exposure and its corresponding sensitive health risks are of great importance. Exposure to low temperature can have a much greater accumulative impact on health, which directly calls for the response of the health system.[39,40] Moreover, low-temperature exposure tends to trigger a stronger cascade of socioeconomic impacts.[41–44] Consequently, in order to mitigate the health risks that are sensitive to low temperature, health system capacities need to be strengthened to disrupt the cascade effect caused by low-temperature exposure.

For relevant global agencies such as the WHO, they could advocate for the establishment of a coordinated temperature-resilience health system by incorporating relevant capacities into their Health NAP. Particular attention should be paid to the deficiencies on a global scale, such as those in points of entry, radiation emergencies, and the national health emergency framework. Also, using this framework, they can follow set procedures to monitor and report on the progress of the temperature-resilience health system. Currently, they might alert governments to be cautious about low-temperature exposure and its related health risks. Early warning of health risks in low temperature has not received enough attention.

### Flexible Process to Build a Temperature-Resilient Health System

Temperature exposure and the associated health risks that are sensitive to it vary across countries, which suggests that the development of a temperature-resilient health system capacity should be a highly flexible process. Among high-income nations, especially those located in high-latitude zones, low temperature-sensitive health risks pose the predominant challenge with regard to temperature resilience.[30] In contrast, low-income countries are usually located in low-latitude regions, and health risks that are highly sensitive to high temperature continue to be their main challenges.

This study extracts differential practical recommendations for the development of climate-resilient health systems. High-income countries might strengthen their actions to interrupt the cascade effects set off by low-temperature exposure through multi-sectoral cooperations, with a particular focus on response to zoonotic events. The capacity is the one that has the poorest performance. Conversely, low-income countries may need to develop immediate response mechanisms and build capacities to deal with high temperature-sensitive health risks. To date, our influential model reveals that the health system has had a limited impact on health risks associated with high temperature. The less-developed capacities, like human resources, the points of entry and radiation emergencies related to high-temperature exposure, deserve special attention. Moreover, prevalent vulnerable factors (such as poverty and low health coverage) and malfunctioning health systems further intensify these challenges.[45,46] Hence, along with socioeconomic development, the sustainable development of health system capacities should be emphasized.

## Limitations

There are several limitations. (1) Although data of 78 indicators among 171 countries are included in the current study, some important indicators (such as solar radiation) are excluded due to data limitation. Due to the uncertainties of data sources, many indicators are not recorded by the second-hand authentic agencies, especially in the developing countries. (2) Because of method shortcomings, the study can only provide a static analysis of aspect interactions. A dynamic one needs to be proposed to capture the dynamic interactions among indicators across periods. (3) The data used in our study range across a span of ten years, which may not be generalizable to the long-term practice of temperature-resilient health systems. Overall, future studies can be undertaken to continuously collect as many data sets as possible to generate a more comprehensive and dynamic framework. Moreover, by utilizing this framework, future studies can further follow the same procedures to gather data at the city level and apply it to comprehensively reveal the lessons learned and existing gaps concerning multiple environmental health problems.

## Conclusions

For the first time, this study systematically integrates health system capacities into the assessment framework of a temperature-resilient health system and explores the interactions among different aspects. This study validates the framework of climate-resilient health systems and enriches it by categorizing temperature-sensitive risks into low-risk and high-risk categories. This study uncovers the driving and integrating role of health system capacities as well as the prioritized role of low-temperature exposure and its related health risks in the development of a temperature-resilient health system. Based on the research findings, the study emphasizes the significance of constructing a coordinated temperature-resilient health system, with a focus on the health system capacities for multisectoral cooperation to interrupt the cascade effects of low-temperature exposure. Given that low-income countries are more likely to be affected by high temperature-sensitive health risks, flexible approaches are necessary. Overall, this study can provide valuable assistance to decision-makers and international organizations in building more effective temperature-resilient health systems.

## Abbreviations

WHO, World Health Organization; NAP, National Adaptation Plans; EFA, exploratory factor analysis; RT, reliability tests; DEMATEL, decision-making trial and evaluation laboratory; YLL, years of life lost; SD: standard deviation; HTR, high temperature-sensitive risks; LTR, low temperature-sensitive risks; LTE, low temperature exposure; HSC, health system capacities; VF, vulnerability factors; PM, particulate matter.

## Data Sharing Statement

The datasets used and analyzed during the current study are available at the following links:

https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.553b7518?tab=overview.
https://beta.sedac.ciesin.columbia.edu/data/collection/gpw-v4.
https://population.un.org/wpp/Download/Standard/Population/.
https://climateknowledgeportal.worldbank.org/download-data.
https://extranet.who.int/e-spar#capacity-score.
https://ghdx.healthdata.org/record/global-burden-disease-study-2019-gbd-2019-air-pollution-exposure-estimates-1990-2019.
https://vizhub.healthdata.org/gbd-results/.
https://databank.worldbank.org/source/world-development-indicators.
https://apps.who.int/gho/data/node.main.

## Ethics Approval and Informed Consent

The study was approved by the Institutional Review Board of the School of Public Health, Shandong University (approval number: LL2303021).

## Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

## Disclosure

The authors declare no competing interests.

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