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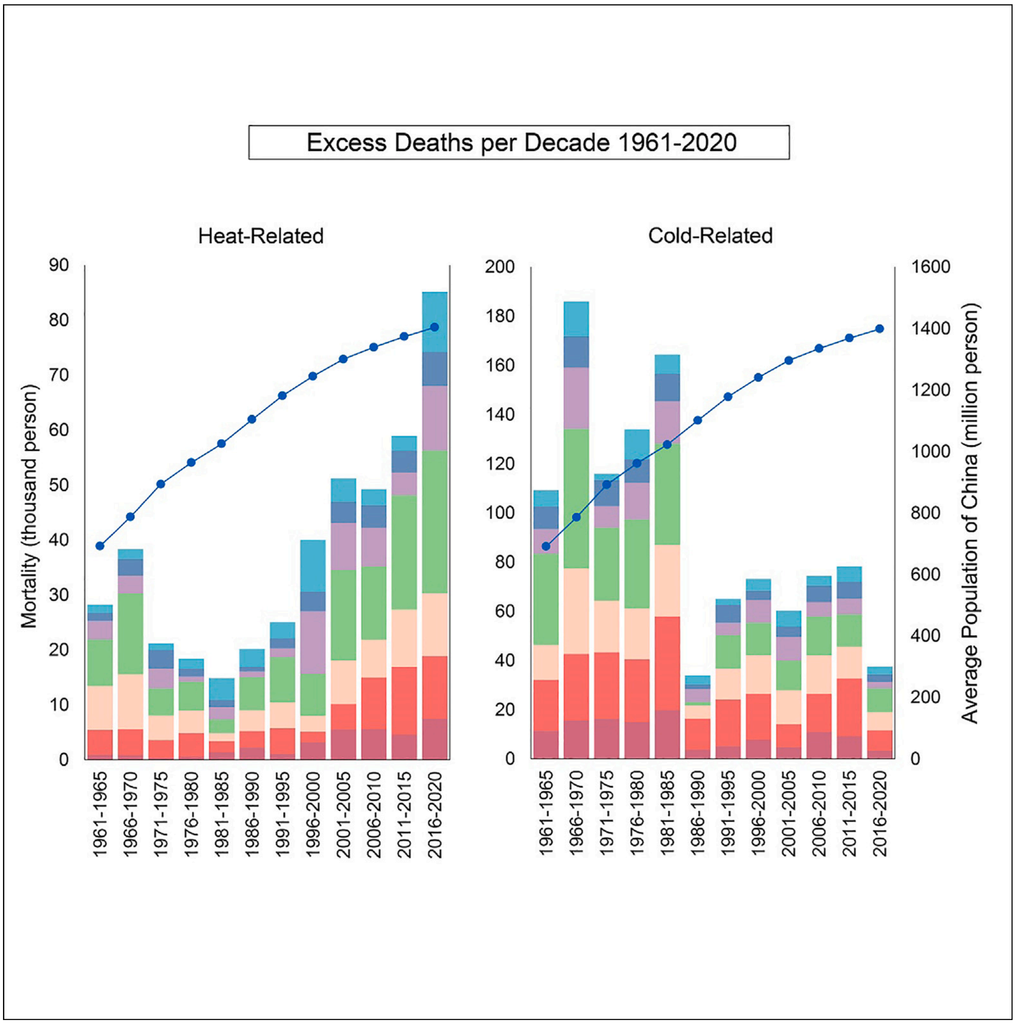

Yang Xie, Ziqiao Zhou, Qinghua Sun, ..., Yue Sun, Hancheng Dai, Tiantian Li

hancheng.dai@pku.edu.cn (H.D.)
litiantian@nieh.chinacdc.cn (T.L.)

Highlights

This study estimates heat- and cold-related excess deaths over 60 years in China

Heat-related mortality has increased sharply during the last two decades

Spatial heterogeneity is apparent in heat- and cold-related mortality

Social-economic development contributes to adaptability

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Social-economic transitions and vulnerability to extreme temperature events from 1960 to 2020 in Chinese cities

Yang Xie,[1,4] Ziqiao Zhou,[2,4] Qinghua Sun,[3] Mengdan Zhao,[1] Jinlu Pu,[1] Qiutong Li,[3] Yue Sun,[3] Hancheng Dai,[2,5,*] and Tiantian Li[3,*]

SUMMARY

Climate change leads to more frequent and intense extreme temperature events, causing a significant number of excess deaths. Using an epidemiological approach, we analyze all-cause deaths related to heatwaves and cold spells in 2,852 Chinese counties from 1960 to 2020. Economic losses associated with these events are determined through the value of statistical life. Findings reveal that cold-related cumulative excess deaths (1,133 thousand) are approximately 2.5 times higher than heat-related deaths, despite an increase in heat-related fatalities in recent decades. Monetized mortality due to heat-related events is estimated at 1,284 billion CNY, while cold-related economic loss is 1,510 billion CNY. Notably, cities located in colder regions experience more heat-related excess deaths, and vice versa. Economic development does not significantly reduce mortality risks to heatwaves across China. This study provides insights into the spatial-temporal heterogeneity of heatwaves and cold spells mortality, essential for policymakers ensuring long-term climate adaptation and sustainability.

INTRODUCTION

Climate change is an inevitable reality. Extreme temperature events such as heatwaves and cold spells are increasing globally in both frequency and intensity due to human activities.[1,2] Extensive studies have focused on the health outcomes, including morbidity and mortality arising from heatwaves and cold spells.[3–6] Research confirms that prolonged exposure to excessive heat and cold is detrimental to public health, contributing to various diseases like respiratory disease,[7,8] cardiovascular disease,[9,10] and even death.[11–13] Furthermore, some studies have been conducted on the additional influence of heatwave and cold spells on specifically vulnerable individuals, such as newborns, pregnant women,[14,15] and the elderly.[16] Apart from causing health damage, extreme temperatures also lead to substantial economic losses, which can be typically divided into medical expenditures,[17,18] productivity loss,[19,20] and excess mortality losses[21] according to the previous researches.

China has experienced more heatwaves and fewer cold spells but with higher intensity over the past five decades.[22–24] Extreme temperature events have caused substantial health risks in China. For example, Yan et al. estimated that 16,299 all-cause deaths are attributable to the exceptional heatwave in 2017.[25] Sun et al. found that 57,783 non-accidental deaths occurred due to the cold spell in 2018.[26] However, most studies mainly focus on the health and economic impacts in particular years, while few studies have quantified the long-term impacts caused by both heatwaves and cold spells in China. An extended time frame allows researchers to capture potential long-term changes, contributing to identify potential cyclical trends, shifts in vulnerability, or the influence of broader environmental and societal factors in China. Notably, there are significant spatial disparities in the intensity of heatwaves and cold spells and their effects in China, considering the geography, climatic characteristics, and economic development differences.[27–29] Some studies observe that cities located in southern China receives a more significant health burden from cold spells[26] while the those located in eastern and southern China are more severely affected by heatwaves.[30] Therefore, it is imperative to examine the spatial and temporal distribution of the health economic impacts associated with heatwaves and extreme cold in China stemming from the uneven economic development of different regions.

Here, we examine the non-accidental excess deaths caused by heatwaves and cold spells in China from 1960 to 2020 with an epidemiological approach. We further evaluate the economic losses associated with these events through the willingness-to-pay (WTP) method. The

[1]School of Economics and Management, Beihang University, Beijing, China
[2]College of Environmental Sciences and Engineering, Peking University, Beijing 100871, China
[3]China CDC Key Laboratory of Environment and Population Health, National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, Beijing, China
[4]These authors contributed equally
[5]Lead contact
*Correspondence: hancheng.dai@pku.edu.cn (H.D.), litiantian@nieh.chinacdc.cn (T.L.)
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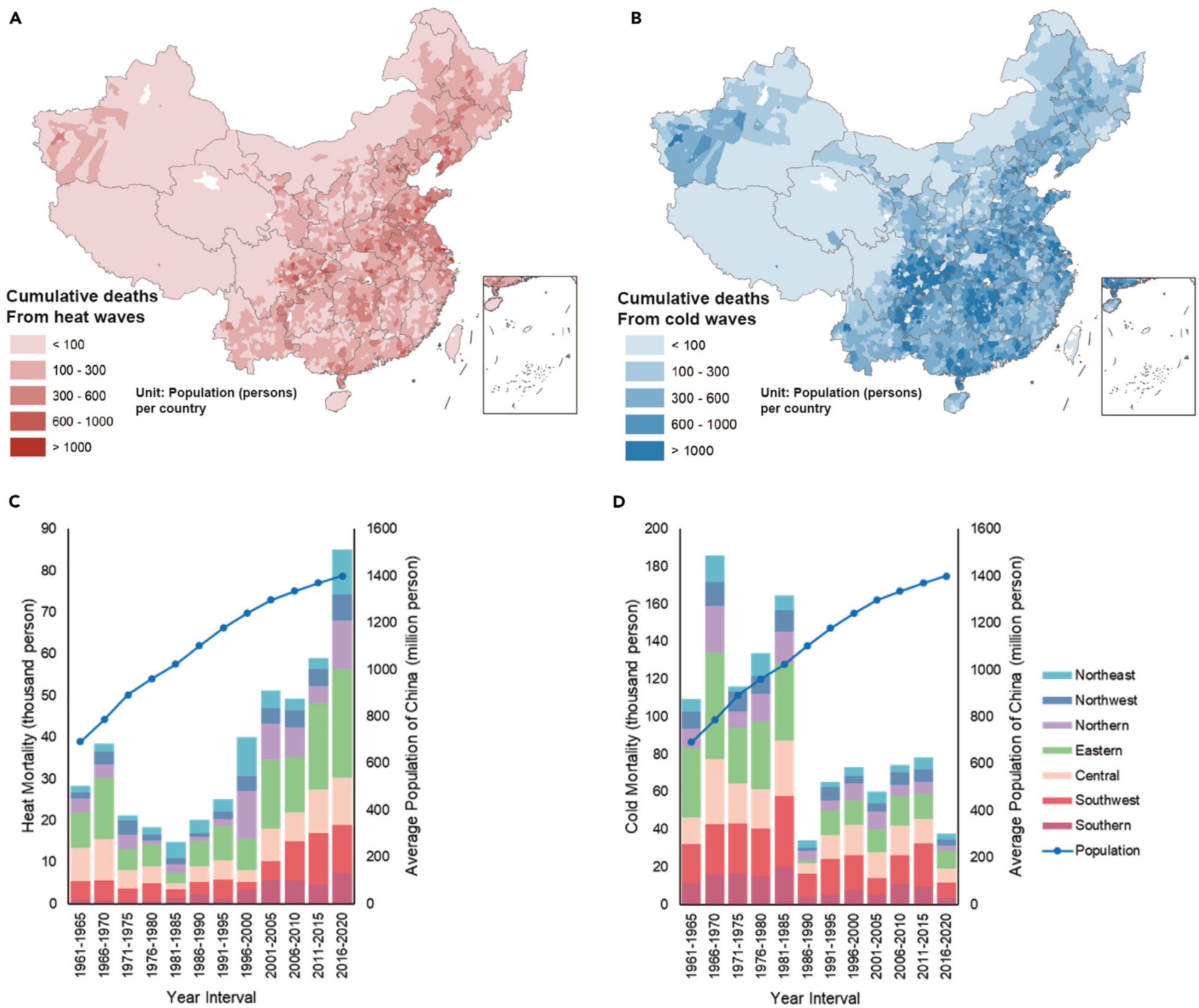

Figure 1. Cumulative cold- and heat-related excess deaths (1961–2020)

(A) Cumulative cold-related excess deaths; (B) cumulative heat-related excess deaths; (C) heat-related excess deaths per decade; (D) cold-related excess deaths per decade.

results are characterized by a long period and a high spatial accuracy, reaching down to the county level. This paper contributes to a deeper understanding of the impacts of extreme temperatures on human health and the economy. More importantly, our findings offer valuable insights into the spatial and temporal heterogeneity of heatwaves and cold spells, which are important considerations for policymakers seeking to ensure long-term sustainability and adaptation in the face of a changing climate.

RESULTS

Total deaths

China is frequently influenced by heatwaves and cold spells. A number of extreme temperature event studies has been examined that there is a discernible increasing trend of heatwaves and extreme cold spells, especially after the year 2000.[27,31] Both heatwaves and cold spells have devastating health impacts. Our results indicate that cumulative excess deaths are predominantly concentrated in areas other than the northwest region, regardless of the types of the two temperature events (Figures 1A and 1B). From 1961 to 2020, 450 thousand cumulative excess deaths were attributable to heatwaves, and the deaths were primarily observed in counties located in northern, southwestern, and southern China. Nevertheless, the cumulative number of deaths caused by cold spells is 1.133 million, 2.5 times higher than that caused by heatwaves. Cold spell-induced deaths were primarily concentrated in counties located in central and southwestern China.

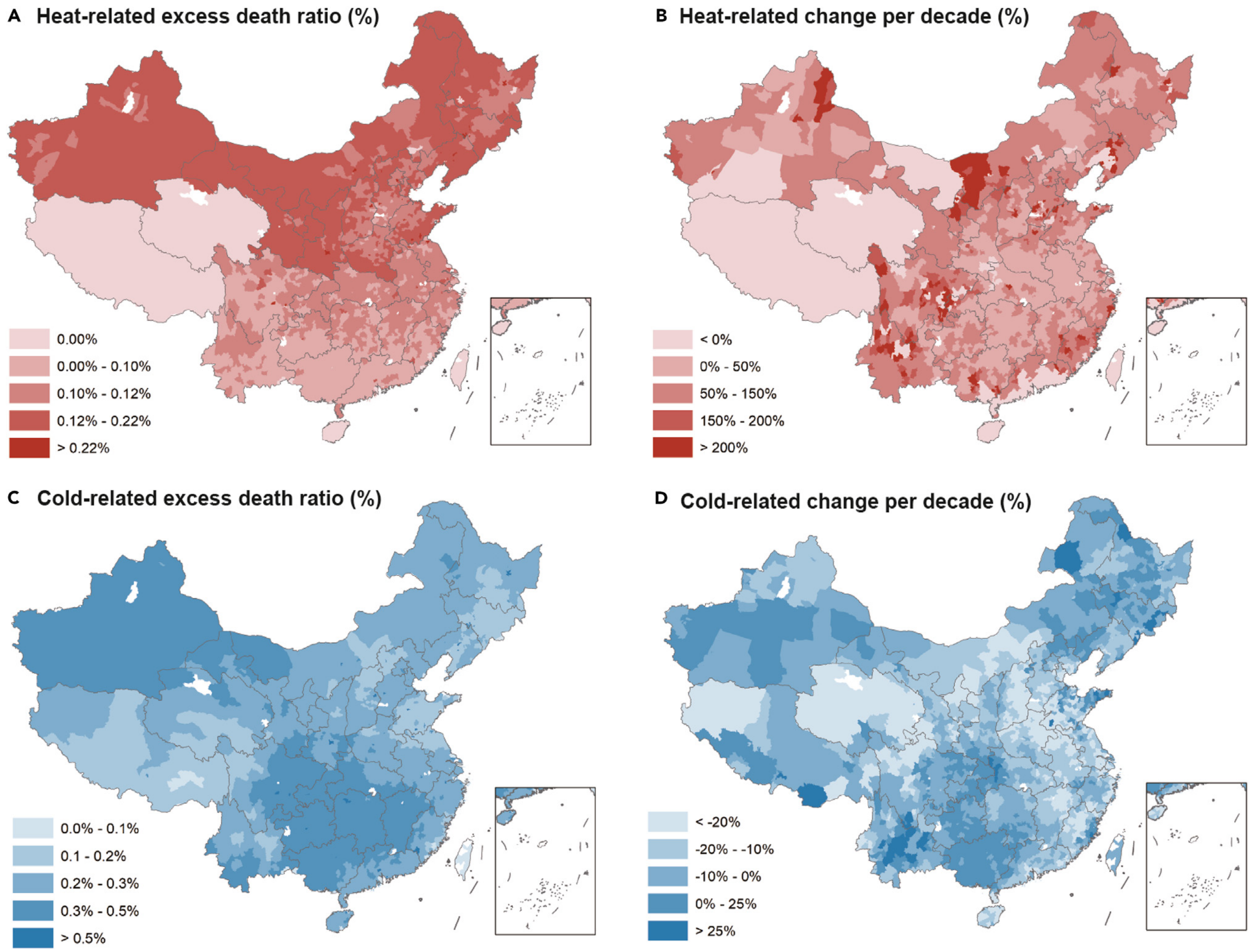

Figure 2. Total excess death ratio and average change per decade (1961–2020)

Excess death ratio is defined as the number of annual excess death upon all deaths of that year.

(A) The total heat-related excess death ratio during 1961–2020 and (B) its average change per decade; (C) the total cold-related excess death ratio during 1961–2020 and (D) its average change per decade.

Excess deaths show discernible temporal and spatial patterns for heatwaves and cold spells, and this phenomenon is more evident when the counties are aggregated into regional level. Figures 1C and 1D provide a detailed overview of the deaths in seven regions induced by the two extreme temperature events every five years to minimize the short-term climate fluctuation. The findings show that 5-year heat mortality exhibits a V-shaped pattern, decreasing in the early period and reaching the lowest number of 15 thousand deaths during 1981–1985, before rebounding after 1985. The rebound may be the consequence of both increasing intensity and frequency of heatwaves. The uptrend of population growth rate in 1980s may also led to a larger number of heat-related deaths since 1980. The historical peak years for heatwave-induced deaths were 2010, 2012, and 2017, with the toll becoming increasingly severe in 2016–2020, when the total number of excess deaths caused by heatwaves increased to 85 thousand.

Excess deaths attributable to cold spells increased in the early time frames but dropped substantially since the 1980s. From 1961 to 1985, the number of cold-related excess deaths increased, reaching its peak in 1966–1970, with 186 thousand of excess deaths, which is more harmful than heatwaves. This was primarily attributed to an extreme cold event in 1969, resulting in 66 thousand excess deaths in one year. The introduction of district heating in the 1980s may be conducive to reducing the toll, with cold-related deaths dropping from 165 thousand during 1981–1985 to 34 thousand during 1986–1990. Cold-related excess deaths have remained relatively constant in the subsequent 25 years.

The overall cold spell-induced excess death ratios are much higher than the heatwaves-induced. For the 2,852 counties, the overall excess death ratios for heat waves range from 0% to 0.45% (Figure 2A), while the cold-related ones range from 0% to 1.22% (Figure 2C). However, the heat-related ratios are increasing among almost all counties across China during the observed time frames, when most cold-related ratios show decreasing trends. In the first recorded decade (1961–1970), the average heat-related ratios heatwaves were only 0.01%. During the same period, the average cold-related ratios were 0.07%, indicating that cold spells were responsible for most of the extreme-temperature-induced excess deaths in China. In the most recent decade (2011–2020), both heat-related and cold-related excess death ratios reach an average of 0.03%.

Heat-related and cold-related excess deaths have significant regional disparities in China. The numbers of both heat-related and cold-related excess deaths are the highest in eastern China. However, excess death ratios show distinct spatial signatures. Generally, the excess death ratio caused by extreme heat is typically higher in counties located in northern, northeastern, and northwestern China, while the ratio due to extreme cold is more server in counties located in central, southern, and southwestern China. Furthermore, nearly all counties across China have increasing heat-related ratios, with only 8 out of 2,852 counties of which the ratio is decreasing. The change of excess death ratio per decade is the highest in counties in Inner Mongolia and some in southern and southwestern China (Figure 2B), with percentage changes per decade exceeding 200%. On the other hand, counties with growing cold-related ratios account for approximately a quarter of the all, and they are mostly located in southwestern, northeastern, and eastern China (Figure 2D).

Economic loss due to heatwaves and cold spells

The economic losses of heatwaves and cold spells from 1961 to 2020 are evaluated based on the monetized mortality, and the results indicate that heatwaves and cold spells have resulted in substantial economic losses in China with distinct regional differences. Given that economic losses are confined to a single county, we opted to aggregate the monetary impacts at the regional level to magnify the observed effects. Generally, the total valuation of mortality induced by heatwaves is estimated at approximately 1,284 billion CNY, and the cold-related economic loss is 1,510 billion CNY over the observed years. Among the different regions, the eastern region stands out with a total heat-related monetized mortality of 446 billion CNY, making it the highest in China. Specifically, Shandong bears the brunt of these losses, experiencing cumulative economic losses of 129 billion CNY due to heatwaves. In contrast, the heat-related losses in northwestern China are just a fraction of those in the eastern region, amounting to less than one-fifth. However, it's important to note that cold spells inflict even more severe economic losses. The southwestern region, except for eastern China, is particularly susceptible to cold spells, with economic losses nearing 300 billion CNY. In contrast, the cold-related economic losses in northeastern and northwestern China are relatively lower, standing at 117 billion and 111 billion CNY, respectively, for the period from 1961 to 2020.

Measurement of economic losses resulting from extreme temperature events considers location-specific economic development. However, it is essential to note that severer economic losses do not necessarily equate to a heavier economic burden on the affected area. Therefore, we further calculate the value of statistical life (VSL) in terms of the corresponding gross domestic product (GDP) from 1961 to 2020 to avoid bias evaluation (Figure 3). Our results reveal that the heat-related economic loss ratio has been increasing for all regions during the observed period. The average yearly economic loss ratio for all regions was 0.03% before 2000, but rose to 0.08% between 2001 and 2020. The heat-related economic losses reached its peak in China in 2018, with heatwaves causing an estimated 0.18% of GDP loss. At the regional level, the heatwave-induced economic loss is relatively severer on northern, northwestern, and northeastern China. Northeastern China experienced the largest economic loss ratio, reaching 0.57% of the regional GDP due to heatwaves in 2018. In contrast, the economic loss ratio of heatwaves was relatively lower in southern China, which is 0.09% during 2016 through 2020.

The average yearly cold-related economic loss on GDP ratio was higher than that of heat-related. Cold spells led to approximately 0.12% of GDP loss annually for all provinces. However, unlike heatwaves, the cold-related ratio has decreased in recent years, with a ratio of approximately 0.09% after 2000 and 0.14% before 2000. The national maximum cold-related economic burden ratio was 0.53%. The economic burden induced by cold spells was relatively more severe in southwestern, central, and southern China, with the historical maximum ratio occurring in 1985 and accounting for 0.80%, 0.75%, and 0.70% of the GDP in these regions, respectively. Conversely, cold spells barely resulted in GDP losses in northeastern and northern China.

The regional population plays a significant role in explaining the disparity in the number of excess deaths. A larger population increases vulnerability due to the higher number of exposed individuals. Consequently, we analyzed the mortality rate in 7 regions with varying levels of economic development over different decades, as shown in Figure 4. Our findings suggest that economic development alone cannot address the rising mortality induced by increasing frequency and intensity of heatwaves. On the other hand, for cold spells, the mortality rate decreases as the per capita GDP increases (Figures S1 and S2). Furthermore, experience over time may help individuals become more resilient to cold spells.

DISCUSSION

Heatwaves and cold spells have substantial health and economic consequences. Our results show that the cumulative excess deaths attributable to cold spells are more detrimental to human health compared with heatwaves, which is approximately 2.5 times that induced by heatwaves from 1961 to 2020. Nevertheless, heat and cold-related excess deaths show distinct temporal and spatial signatures. Generally, 5-year heat mortality exhibits a V-shaped pattern, while 5-year cold mortality increased before its sharp drops in 1986–1990. Furthermore, excess death ratios attributable to heatwaves are higher in counties located in northern, northeastern, and northwestern China, while those caused by cold spells are more severe in counties located in central, southern, and southwestern China. From the aspect of monetized mortality, economic losses increase as per capita GDP grows. Therefore, although cold-related excess deaths significantly exceed heat-related, but the difference in their corresponding total economic losses is relatively small. The total valuation of mortality induced by heatwaves is

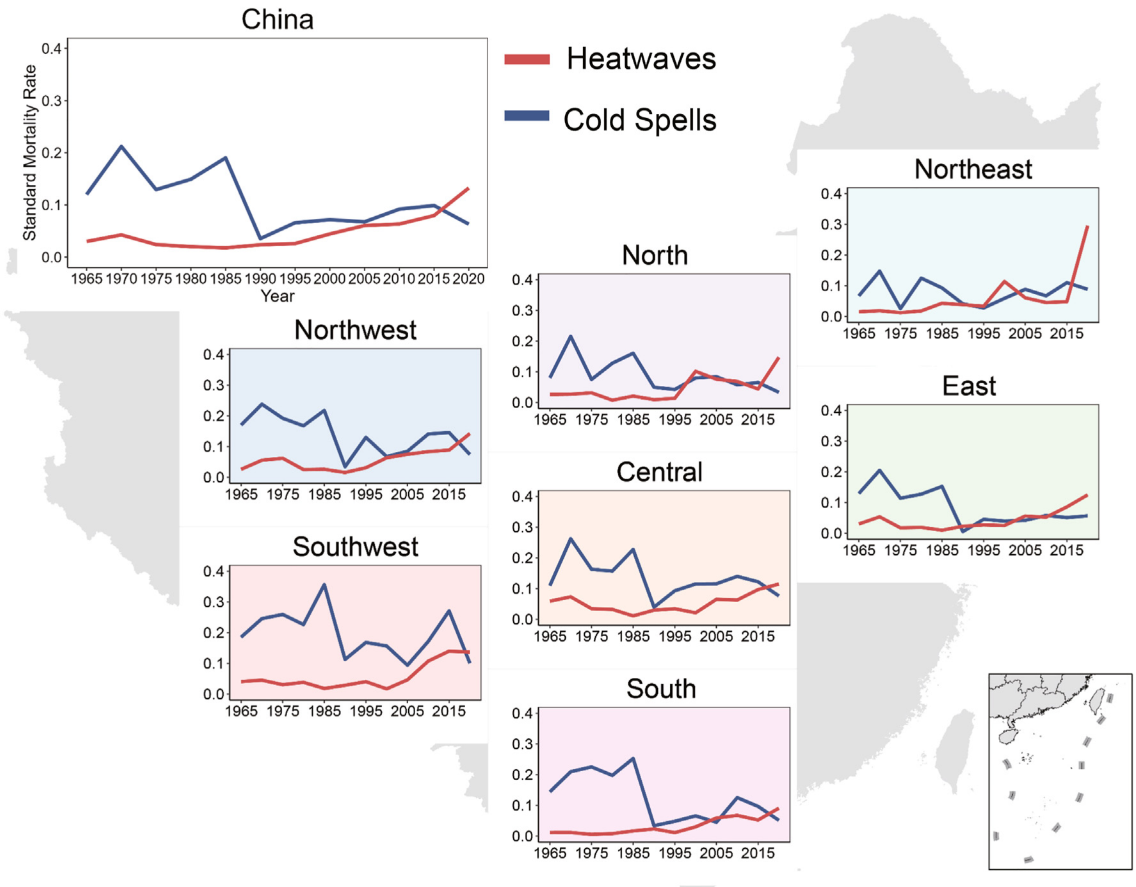

Figure 3. Economic losses from heatwaves and cold spell exposure per 5 years in China and 7 regions

Economic losses from heatwave (red lines) and cold spell (blue lines) exposure in China and 7 regions, respectively. The economic losses are calculated every 5 years to avoid short-term climate fluctuations.

estimated at approximately 1,284 billion CNY, and the cold-related one is 1,510 billion CNY over the observed years. After controlling the influence of uneven population distribution, we found that economic development could help reduce the mortality rate attributable to cold spells, but had little influence on heat-related mortality.

This paper complements the previous investigation of health consequences of extreme temperatures, but surpasses it by covering 60 years of mortality analysis and enriching the analysis with monetized valuation. Two results should be highlighted. First, our study found that the turning points for excess deaths induced by two extreme temperature events all occurred around 1980s, after which excess deaths induced by heatwaves increased while those attributable to cold spells decreased. The heat-related finding aligns with Chen et al.,[32] who identified a rising trend in heat-related excess deaths over the past four decades. Regarding the decrease in cold-related deaths, we posit that the initiation of Chinese economic reform in the 1980s enable the government to introduce district heating, potentially contributing to the reduction in cold spell-related fatalities. However, our results also suggest that economic development does not appear to mitigate the increasing mortality rate associated with heatwaves since 1980s. This finding is against the traditional view that higher income increases individual resilience under extreme temperature,[33] and one possible explanation is that global warming increases the intensity and frequency of heatwaves, most of which are record-breaking. Energy supply systems may not be well-prepared for peak times, resulting in break-outs. For example, some cities in Sichuan, a major hydropower province, experienced severe heatwave and drought in the summer of 2022. The power shortage leaves millions of people exposed to extreme temperatures. Furthermore, certain heatwaves and cold spells occur unexpectedly, leading to a lack of responsiveness and insufficient consideration in existing planning and response mechanisms.[34]

The distribution of excess deaths induced by both extreme temperature events is mainly located in crowded cities; however, the distribution shows discernible regional heterogeneity after controlling the population effects. The spatial signature of the excess death ratio supports the hypothesis that a lack of preparedness of extreme temperature events may result in severe negative health impacts. Our findings show that from the excess death ratio, northern cities, which are normally regarded as colder areas in China, suffer more from heat than cold. On the contrary, southern cities, which should be relatively hotter, are more vulnerable to cold spells. Furthermore, national analysis suggests that

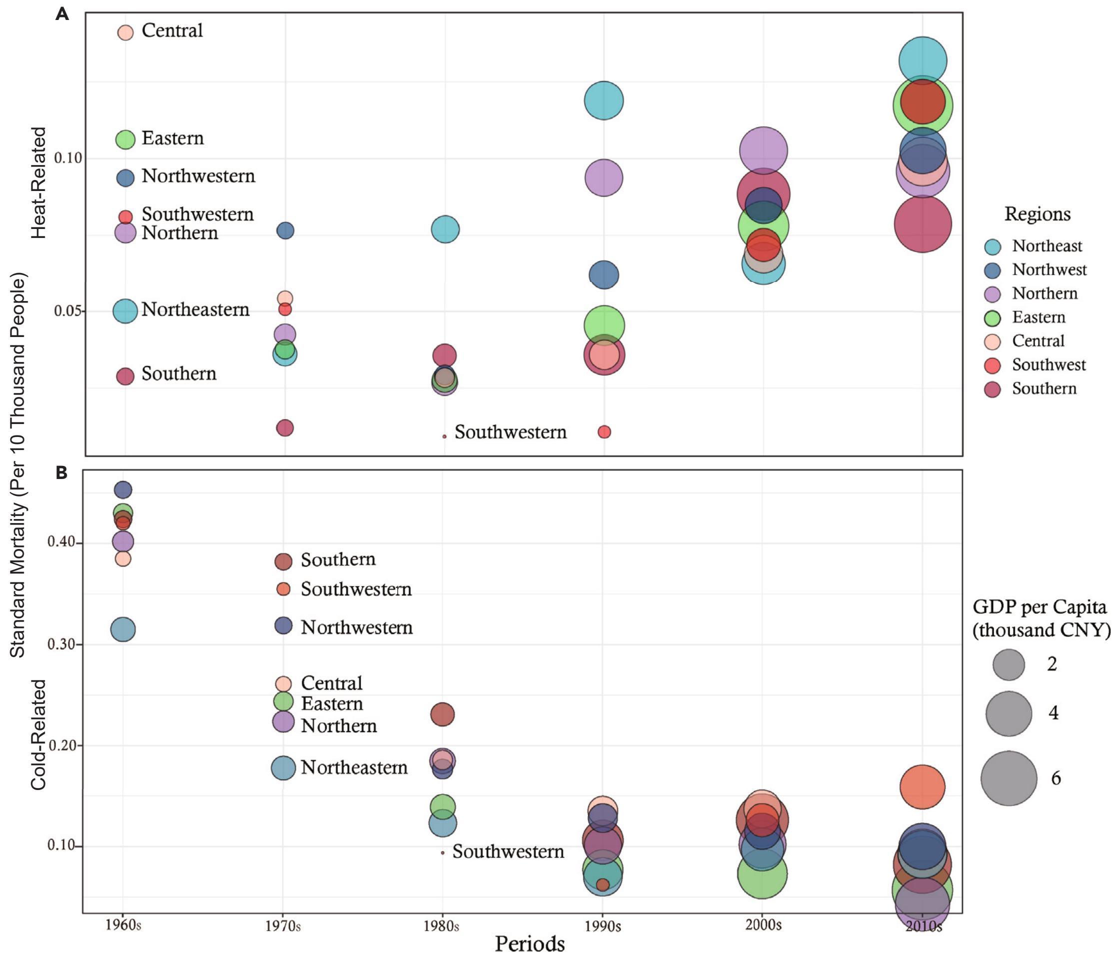

Figure 4. Standard mortality rate per 10 years in 7 regions

(A) Heat-related mortality; (B) cold-related mortality.

economic development may partly increase the residents' resilience to cold spells, which may explain the cold-related excess death ratios are relatively lower in well-developed provinces and municipalities.

In summary, instead of focusing on specific diseases, we provide a more comprehensive health impact evaluation on heatwaves and cold spells in China from 1961 to 2020, and estimate the economic loss attributable to the two extreme temperature events. Based on our findings, we suggest that (1) because of the inevitability of climate change, an early warning system against extreme temperature is essential for preventing loss of life and assets. Notably, the identified regional disparities in the impacts of two extreme weather events underscore the importance of tailoring early warning systems to different geographical areas in China. More specifically, the early warning system should take into account the distinct risks posed by heatwaves in the northern, northwestern, and northeastern regions, and cold spells in the central, southern, and southwestern areas. An early warning system may result in the temporary closure of businesses, construction sites, and other outdoor activities leading to short-term labor productivity losses. However, despite short-term disruptions, the implementation of an effective early warning system can contribute to long-term economic resilience by reducing the health risks associated with extreme heat[35,36]; (2) The government should shoulder the needs of vulnerable populations. Our results show that heat-related mortality soars, especially after the year 2000. Furthermore, heatwaves scorched across China, and even growing GDP per capita cannot significantly help reduce mortality rates. Under such circumstances, high-intensity work groups, including the agriculture and construction sector, low-income households, and the aging population, are most sensitive to heatwaves as they are either have less accessibility to cooling places and devices or are physiologically more vulnerable than the young. Therefore, the government should provide working allowance and sign-up public cooling for anyone in need. In addition, the local community should recommend the elderly to stay indoors in the air conditioning; (3) Policymakers in southwestern China should pay more attention to cold spells and guarantee the availability of local power systems during cold spells. Although cold-related mortality shows an obvious decreasing trend in most cities in China, we find a rebound in southwestern China since 2000 after controlling population change. Since residents in southwestern China normally use air conditioning for heating, the government should ensure the local power system is available during cold spells. More importantly, cold spell alert is important to inform the residents of hazards.

Limitations of the study

Some limitations must be acknowledged. Firstly, we do not account for mortality displacement, which refers to deaths that would have happened even in the absence of exposure to extreme temperatures.[37] Therefore, our estimated number of excess deaths induced by heat-waves and cold spells may be overstated. Secondly, the excess non-accidental mortality rates used for calculating came from a subset of counties in China within a limited time frame. This limitation arises from the lack of a long-term nationwide exposure-response relationship in previous studies, which may have led to bias. In addition, the income elasticity is predicated on China being a developing country. However, given that some provinces are relatively well-developed, their income elasticity may be higher and should be adjusted accordingly. Finally, our analysis mainly incorporates the VSL when estimating economic losses. Impacts on labor productivity and medical expenses are not taken into account in this paper.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.109066.

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AUTHOR CONTRIBUTIONS

Y.X. designed the research. Y.X., Z.Z., and T.L. collected data and conducted the analysis. Y.X., Z.Z., and Q.S. led the drafting of the manuscript and analyzed the results. M.Z., J.P., and Y.S. provided visualization. H.D., T.L., Y.S. and C.G. provided suggestion to the article.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Population	National Bureau of Statistics of China	https://www.stats.gov.cn/
Daily Meteorological Data	China Meteorological Data Sharing Service System	https://data.cma.cn/
Per capita GDP	China City Statistical Yearbook	https://www.stats.gov.cn/
Software and algorithms		
R-4.0.0	R	https://www.r-project.org/; RRID: SCR_001905

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Hancheng Dai (hancheng.dai@pku.edu.cn).

Materials availability

The study did not generate new materials.

Data and code availability

Data: All data reported in this paper will be shared by the lead contact upon request.

Code: All custom codes can be available on request from the lead contact.

Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

We have defined heatwaves as a period of at least two consecutive day temperature exceeding the 99th percentile of the recorded during the period.[38] Cold spells refer to a period of seven or more consecutive days with temperatures lower than the 5th percentile for the given periods.[39,40]

We collected population data and baseline mortality rates from the 6th National Population Census. The cause of death was classified according to the 10th Revision of the International Classification of Diseases (ICD-10), with non-accidental mortality considered the primary health consequence. Furthermore, 102 counties located in 31 provinces and covered multiple climate zones were included to measure the influences of heatwaves and cold spells. Locations at Hong Kong, Macau and Taiwan are not included due to data unavailability. Daily meteorological data were gathered from the China Meteorological Data Sharing Service System. Per capita GDP was obtained from the China City Statistical Yearbook.

Statistical analysis

We identified heat wave days and cold spell days for each county from 1960 to 2020 based on the definitions of heat wave and cold spells. The excess risk (ER) refers to previous national multi-center studies that represented the impact of heatwaves and cold spells on a small subset of counties within a more recent time frame in China.[26,41] We extrapolated the ER into 2,852 counties, which had a total residential population of 13.3 billion. Heat-related ER is 18.17% for middle temperate zone, 17.61% for warm temperate zone and 13.55% for subtropical zone. Cold-related ER is 17.4% for the south while 13.0% for the north. The distinction reflects the acclimatization heterogeneity to extreme temperature exposures in different climate regions.

Excess mortality, a concept frequently employed in epidemiology and public health, refers to the number of deaths across all causes during a crisis that surpasses what would be expected under normal circumstances.[42] In the second stage, we calculated the excess non-accidental mortality attributable to the two extreme temperature events by applying Equation 1 [37]:

$$ED_{ET}^{c} = N^{c} \times ER \times L_{ET}^{c} \quad \text{(Equation 1)}$$

where, ED_{ET}^{c} is the estimated number of excess deaths induced by extreme temperature events for county c. N^{C} represents the average daily non-accidental mortality counts in specific year, while L_{ET}^{C} is the number of days for a given extreme temperature event. The annual mortality attributable to heatwaves or cold spells is computed by summing the excess deaths of each extreme temperature event period. The annual mortality is aggregated to be 5-year or 10-year ones to avoid short-term climate fluctuations.[20,43] Furthermore, as sensitivity analyses, we grouped 2,852 counties into city, provincial and regional level, respectively.

Mortality valuation

VSL can be described as quantification of the worth that individuals place on marginal changes in mortality risks in monetary terms.[44] We adopted the most up-to-date estimate of VSL from a 2016 field survey in China.[45] VSL is then adjusted for the individual city based on the city's economic development[46,47] and income elasticity,[48] as Equation 2 shows.

$$VSL_{ET}^{i,y} = ED_{ET}^{i,y} \times \left(VSL \times \frac{GDP_y^i}{GDP_{2016}} \right)^{0.5} \quad \text{(Equation 2)}$$

where VSL_{ET}^{i} is the estimated VSL for city i attributable to an extreme temperature event in year y, while $ED_{ET}^{i,y}$ is the estimated number of excess deaths. GDP_y^i is the per capita GDP for city i in year y and GDP_{2016} is the national average per capita GDP in 2016. China is a developing country and income elasticity is set as 0.5.[48] All values are in constant 2016 CNY to ensure the economic losses from different time periods are comparable.