Analysis and intervention of heatwave related economic loss: Comprehensive insights from supply, demand, and public expenditure into the relationship between the influencing factors

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Abstract: Increasing extreme temperatures are producing a serious impact on the economies of cities. However, the importance of social factors is typically neglected by the existing research. In this work, we first establish a supply demand-public expenditure (SDP) framework for assessing and forecasting heat-related economic loss. Compared with the previous framework, SDP possesses a more comprehensive index system and functions that apply to all types of cities. We selected different economic development and geographical locations (Nanjing, Suzhou, and Yancheng) as case studies to verify the wide applicability of the SDP framework. A qualitative analysis and quantitative prediction of heatwaves and socioeconomic factors on losses were conducted for different cities. The results showed that different loss types displayed obvious regional heterogeneity among the cities. The labor value loss was the most significant type, and health loss was the most vulnerable type. In addition, public expenditure played a neglected critical regulatory role. Apart from these, the current level of public expenditure for heat prevention and control remains insufficient. Based on an assessment of the effects of interventions, policymakers need to make more efforts to increase the proportion of heat-related public spending and ensure stable socio-economic development by utilizing pathways with positive intervention potentials.

Keywords: Heatwave, Economic loss, Exposure assessment, Evaluation framework, Influence path, Intervention

1. Introduction

Global warming and associated climate change are already increasingly causing climate events and extreme weather (Zhang et al., 2021). Since the 1950s, extreme temperature events have increased in frequency and intensity in most areas of the world, as reported by the International Panel on Climate Change 6 (IPCC6). Many cities even face the interact effect of urban heat challenges, such as heatwaves and urban heat island (He et al., 2021). The entire economy, agriculture, and tourism are affected by weather events (Campbell and Spencer, 2021).Particularly, heatwaves have a huge impact on the economy(Oppermann et al., 2021). The increasing heatwave events have significant adverse impact on human health, ecosystems, crop yield and public infrastructure (Wu et al., 2021; H. H. Wang et al., 2021). Climate change will cause direct economic losses to the industrial sector (Zhang et al., 2021). Heatwaves can lead to increased morbidity and mortality from stroke, cardiovascular disease, and respiratory disease than air pollution (Chen et al., 2015). And the mortality rate of heat-related diseases in summer will increase in the future due to the higher temperature (Chen et al., 2017). As a result of the large numbers of people dying from extreme heat, this will cause significant economic losses in terms of health (Yan et al., 2022).

Considering the enormous damage caused by heatwaves and the more severe problems of heat-related economic losses and greater risk we will face in the future (Stott et al., 2004). It is necessary to analyze heat-related economic loss and propose effective mitigation measures to lessen these losses. But the current frameworks and subjects of heatwave- related economic loss lack comprehensive consideration. A vast majority of the studies have only assessed the loss due to a single event for a social sector. A survey from Nanjing defined heat-related economic loss as the loss of the accompanying delay and medical expenses (Xia et al., 2018). An assessment which was focused on impacts caused by the heatwave event in 2017 measured the economic damage by heat-related mortality and its interrelated economic indicators (Yan et al., 2022). A model-based analysis from European focused on the stress of high temperatures in agriculture and subsequent events (Mechler et al., 2010). However, the factors that were rarely mentioned may play important roles under a high-temperature circumstance. Climate investment as a public expenditure can be translated into higher resilience to heatwaves which means a less negative impact due to temperature on economic and productivity growth (Adom and Amoani, 2021). Investments in society and public expenditures from the government are key factors that regulate heatwave events, while the relationship between them and economic losses remains unclear. Chinese cities should pay more attention to the study of the economy-related losses of labor, goods, and services caused by heatwaves (He et al., 2022). Correctly assessing the economic loss can help to propose specific interventions.

In the context of climate change, the temperature is projected to continue to rise globally and heatwaves are also increasing in frequency, intensity and duration (P. C. Wang et al., 2022). Few studies have made predictions of future heatwave losses and proposed effective interventions. The relationship between health loss and temperature is complex (Campbell et al., 2018), and understanding their relationship with economic loss is challenging. In addition, few effective intervention measures have been proposed for the interaction of factors of the society and environment (Campbell et al., 2018). The existing literature has centered on the calculation of economic benefits using input-output models that are only useful for the analysis of the current year, and they lack the forecasting ability of a regression model and other tools (Liang et al., 2016).

Therefore, a more comprehensive and forward-looking assessment framework is urgently required to improve our understanding of the hazards of heatwave events. This study aims to propose a new framework to clarify the regional heterogeneity of the heatwave effect and the impact mechanism of loss. In this manner, we can find the neglected important factors and the future trends. This study is intended to compensate for deficiencies in the existing studies, suggest effective intervention measures according to the different intervention effects to reduce the social losses, and relieve the burden on residents caused by high temperatures. Finally, this study contributes to the sustainable development of cities.

2. Materials and methods

2.1. Definition of a heatwave

Different studies have defined heatwave events differently and have drawn different conclusions (Chen et al., 2015), we define a heatwave day as a day when the maximum temperature exceeds 35 °C, and the heatwave index (HI) is the total number of days exceeding 35 °C in the current year.

This setting helps us to clearly see how the frequency of high temperatures will change from now into the future. After data sorting, we decided to use the dates from May to September, the primary occurrence period of heatwaves.

2.2. SDP evaluation framework

This study proposed a comprehensive framework to evaluate the extra economic loss related to heatwave from three dimensions: supply, demand and public expenditure. Supply and demand side factors are the primary and significant economic analysis tools (Yang et al., 2020). The evaluation framework that reflects the supply and demand relationship has been proposed already (Leith et al., 2018). Supply and demand perspectives are also widely used to assess social issues (Wang et al., 2021, 2022; P. Wang et al., 2022). In addition, "public expenditure" also plays an important role in climate change issues as a means of government macro-control apart from the market economic elements.

For details, "Supply" is a set of factors that provide goods and services in a national economy and includes labor, land, and capital. Heatwave caused serious economic loss to supply side factors. Exposure to extreme heat will reduce working hours and productivity of workers (Creemers et al., 2015). Heatwave will affect the photosynthetic rate of vegetable crops during growth and development, resulting in lower yield and quality (Bisbis et al., 2018; Lizaso et al., 2018). During heatwave days, the increase of residential electricity consumption may greatly increase the load of power grid (Zhipeng, 2016), and increase the damage risk of power equipment in regional power grid. "Demand" is a set of factors required in a national economy and includes investment, consumption, and exports. Heatwave causes a host of additional economic costs for residents. Heatwave leads to a range of heat-related health and disease problems among residents, resulting in health losses (Liu et al., 2019). As the same time, people will adopt adaptive measures to cope with extreme heat events such as purchasing air conditioning equipment. The domestic water and electricity consumption increased significantly during heatwave days (Toth et al., 2018; Liu and Zhang, 2020). And residents tend to pay more to improve their transportation way due to the heatwave (Vanky et al., 2017; Creemers et al., 2015). In addition, "public expenditure" also plays an important role in climate change issues as a means of government macro-control apart from the market economic elements. The government will spend extra expenditure to deal with the heatwave. Public expenditure related to extreme heat obtained from government budget reports consists of "Medical and health expenditure", "Energy conservation and environmental protection expenditure", "Agriculture, forestry and water expenditure" and "Land, marine and meteorology expenditure". As the government financial tool, public expenditure can effectively help to mitigate climate change and ameliorate climate problems (Yuelan et al., 2021).

We screened and summarized eight indicators of loss types from the level of the production sector and the consumption structure included three supply-side indicators and five demand-side indicators from the studies mentioned above. In the general public budget, we chose four expenditure indicators which were highly related to climate change (CAFS, 2017). Accordingly, we proposed the SDP evaluation framework (Fig. 1), a comprehensive evaluation method for the socio-economic losses related to heatwaves that includes three dimensions (supply, demand and public expenditure) and twelve indicators ("labor value loss", "crop value loss", "equipment loss", "health loss", "adaption expenditure", "water bills", "electricity bills", "transportation spending", "medical and health", "energy conservation and environmental protection", "agriculture, forestry and water" and "land, marine and meteorology") (Table S2).

The definition and source of the index are provided in the supporting information (Table S2). The detailed explanation and calculation process of the indicators of the SDP framework are also provided (**Text S1**).

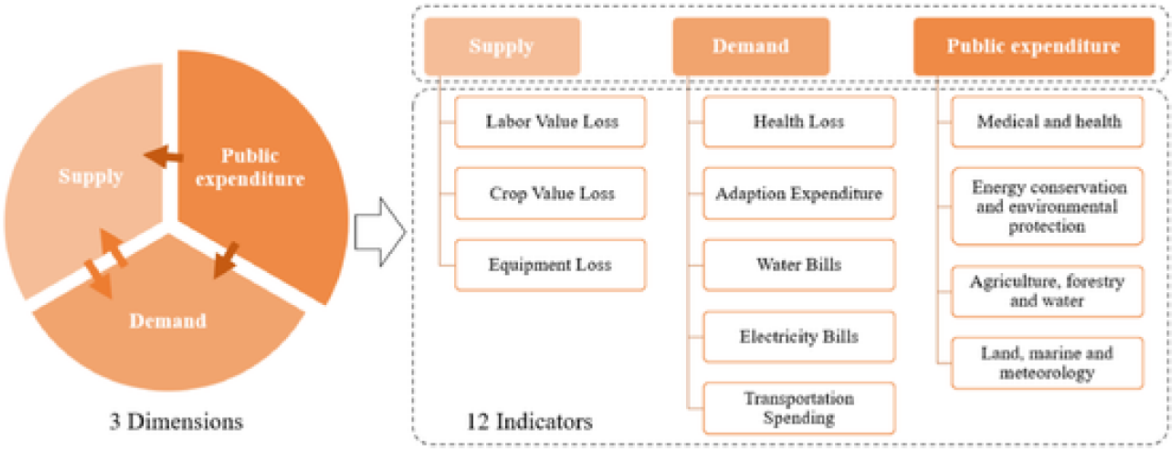

Fig. 1. SDP evaluation framework.

Fig. 2. Case areas.

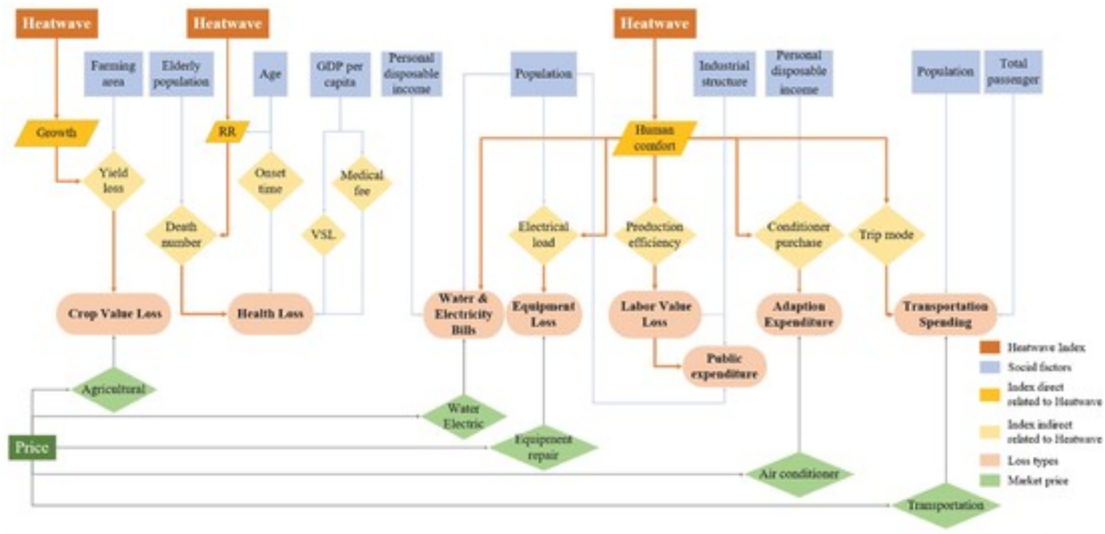

Fig. 3. Influence paths of heatwave related social losses.

2.3. Case city selections

To verify the features and utility value of the SDP framework, we selected representative cities for the analysis. As the largest developing country, the surface temperatures of China are rising rapidly due to rapid urbanization during the past decades (Chen et al., 2022).

Jiangsu Province is one of the most developed provinces of China and is the most densely populated provinces in China (C. X. Wang et al., 2022; Chen et al., 2017). Three cities (Nanjing, Suzhou, and Yancheng) in Jiangsu Province were considered. Because they are located in different latitudes, with two different types of climates (Fig. 2a). In addition, they represent different levels of economic development. Nanjing and Suzhou are two cities that have good economies, and Yancheng has a poorer economy (Fig. 2b). The structure of heatwave-related economic losses in these three cities may be potentially heterogeneous. Taking these three cities as object of study will help to accurately analyze the economic loss related to heatwave and the influence path, then put forward targeted suggestions.
Nanjing is located in the southwest of Jiangsu Province, one of the major cities in eastern China, and it has a resident population of over 9.3 million. Suzhou is located in the southeast of Jiangsu Province and is one of the major cities in the Yangtze River Delta. It has a resident population of over 12.7 million. Yancheng is located in the middle of Jiangsu Province near the coast, and it has a resident population of over 6.7 million.
The study period of this study was from 2007 to 2019 and 2030 for the predictions. The daily meteorological data of Jiangsu Province from 2007 to 2019 was acquired by the National Meteorological Information Center. Based on this, we evaluated the long-term heat-related economic losses without intervention using the method and information in Text S1.

2.4. Loss prediction

2.4.1. Influence path analysis

The influence factors of social-economic losses are not only related to heatwaves but also include a variety of social factors. The vegetable yield is affected by the cultivated area, the multiple cropping index, and the vegetable planting ratio (Wang et al., 2018). For health, income, and the living environment, individual differences are also important factors (Campbell et al., 2018). For the industrial output, the industrial structure, tax revenue, regional gross domestic product (GDP), production efficiency, and other factors also play key roles (Huang et al., 2022). For the consumption expenditure, income, policies, and commodity prices may influence the consumption behavior of residents. In addition, even mood, family relationships, and the cultural environment may play a role (Ding et al., 2018). In light of the above, the following question is posed: how do social factors cooperate with heatwaves to affect social economics? In this study, several widely concerned factors were discovered, and a multiple linear regression (MLR) model was used for the comprehensive analysis (Eq. (1)). The MLR is a reliable and widely used prediction model that is often used to predict climate change (Bera et al., 2021). By eliminating insignificant or high collinearity factors and changing the combination of different factors, the impact path and model of each heatwaverelated loss type were determined under the SDP framework using SPSS.

$$Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_i X_i. \tag{1}$$

2.4.2. Heatwave index prediction

We predicted the future climate combined with social factors using the SSP scenario proposed by Phase 6 of the Coupled Model Intercomparison Project (CMIP6). This study adopted the Shared Socioeconomic Pathway scenarios 2 (SSP2) scenarios that represent a medium development path for analysis that aims to reveal the general development trend. The NorESM2--MM output model was used in this study. We downloaded the temperature data for the future (2030) from the SSP-RCP. We then obtained the city grid data of the temperature and the heatwave index (HI) using ArcGIS.

2.4.3. Social factor predictions

Different social factors have different characteristics and development rules that need to be analyzed using different prediction models. ARIMA, high precision and common stationary time series fitting model (Mills, 2019), was used to predict the economic social factors (e.g., GDP, per capita disposable income, and market prices) in this study. A linear regression model was used to predict the non-economic social factors (e.g., passenger trips and crop sown area).

2.4.4. Population prediction

Given the prediction of the future resident and the aging population, this study utilized the cohort element method to make a scenario prediction with the help of PADIS-INT. The future fertility, death, migration, and other parameters were established using the SSP2 scenario in the IPCC6 for China. The migration level was set to zero, and the sex ratio at birth and willingness to raise were set according to the historical data of each city.

3. Results and discussion

3.1. Influence path

For the three case cities, the influence path charts of heatwaverelated social economic losses (Fig. 3) were obtained by collating and analyzing the results of the MLR model. In Fig. 3, "Heatwave" in the orange box was our main research object; "Farming area", "Elderly population" and other social factors in the blue box played vital roles out of the model; "Price" in green was also an indispensable role in the social factors and we put them separately below to match the form of loss prediction formulas; All of them interacted and indirectly determined losses ultimately by affecting intermediate variables in parallelograms and rhomboids. Heatwave has an impact on crop growth, and then crop growth and the farming area jointly determine the crop yield loss.

Heatwave causes premature deaths and extra health care costs, causing economic losses. The health loss is determined by death number, onset time, value of a statistical life and medical fee. Age and GDP per capita, as important socioeconomic variables, were included in the economic loss of health. We also found that heatwave has a direct effect on human comfort, and a change in human comfort has a common effect with other social factors by indirectly affecting the water and electricity expenditure, equipment loss, labor value loss, adaptive expenditures, and transportation spending. During the heatwave, extreme heat will affect the human comfort, then increase the water bills and electricity bills. Extreme high temperature will stimulate electricity consumption behavior of residents, increase electrical load and cause equipment loss. And it will reduce the production efficiency of workers, then causes labor value loss and public expenditure. In order to cope with the changes in human comfort brought by extreme heat events, people will choose to purchase conditioners and change the trip mode, resulting in extra expenditure. We have considered personal disposable income, population, industrial structure and total passenger as control variables in the model. And the price of agricultural products, water, electric, equipment repair, air conditioner and transportation ultimately affect the economic loss.

In addition to the qualitative path analysis, this study quantitatively described the relationship among a heatwave, various social factors, and various loss types using multivariate equations. The positive and negative coefficients of each variable reflect the promoting or inhibitory relationship between the variable and losses. A positive coefficient means aggravation, and a negative coefficient is a deceleration. The magnitude of the absolute value of reflects the influence degree of the variable on the economic loss.

$$LL_{\text{primary},Nan} = 1.069 \times HI_{Nan} + 0.794 \times IS_{Nan} - 31.372$$
$$Beta(HI_{Nan} = 0.81, IS_{Nan} = 0.37)$$
$$P(HI_{Nan} = 0.00, IS_{Nan} = 0.00) \ R^2 = 0.91. \tag{2}$$

For the labor value loss of primary industry in Nanjing (Eq. (2)), everyone changes in the changes the economic loss by 106.9 million CNY. The industrial structure index (IS) equals the proportion of the tertiary industry, and a one-percent change in the ratio changes the economic loss by 79.4 million CNY. is higher than the industrial structure index, indicating that for the primary industry in Nanjing, the impact of high temperatures on the output loss is significantly greater than that of the industrial structure. We further used such equations to predict future economic losses.

A significance test was used to verify the significance of each factor. In Equation (2), the significance levels ( ) of the and were under 0.01, showing the excellent significance of heatwaves and the industrial structure to the labor value loss of the primary industry in Nanjing. The goodness of fit test proves that the MLR model has a good fitting performance for this study. The value of in Equation (2) was 0.91, which is near one. This indicates good predictive performance and goodness of fit.

Other equations for the different cities and loss types and the corresponding values of , and are provided in the appendix (Text S2).

3.2. Long-term developmental outcomes of loss without intervention

We adopted the SDP framework to analyze the long-term developmental outcomes of the heatwave-related loss of the three case cities in a situation without intervention. The losses of the different types of cities from 2007 to 2019 were obtained, and the future loss in 2030 was further predicted. We found a regional heterogeneity of the different loss types and some of the important factors and threats were ignored.

3.2.1. Total loss

From a horizontal perspective, the adverse impacts of a heatwave in Nanjing were much higher than that in Suzhou and Yancheng. For the values (Figs. S1–3a, Figs. S1–3b), the total loss due to a heatwave in Nanjing was significantly higher than that in Suzhou and Yancheng. The same conclusion was drawn by considering the proportion of total loss in the GDP (Figs. S1–3c, Figs. S1–3d). Using 2030 and 2019 as references, the total loss of a heatwave in Nanjing accounted for 11% and 9% of the GDP, respectively. The proportions for Suzhou for these two years were 5% and 4%, respectively, and that of Yancheng was 4% and 2%, respectively, demonstrating a significant gap.

It was found by examining the change in the total annual losses (Figs. S1–3a) that the losses varied sharply in 2013, 2014, and 2015. The losses spiked in 2013 and dropped considerably in 2014 and 2015. This unusual phenomenon may have been related to the global El Nino event that occurred near 2014 (Xie and Fang, 2020).

The growth rate of the total loss in Yancheng was significantly higher than that in Nanjing and Suzhou. In terms of the numerical value, the ratio of Yancheng 2030) to 2019 was 464% (Figs. S1–3b), and the ratio of 2019 to 2007 was 250%, while the two values were 206% and 228% for Nanjing, respectively, and 193% and 295% for Suzhou, respectively. This indicates that in the context of climate change, the vulnerability of Yancheng to high temperatures is higher than that of Nanjing, indicating Suzhou and Yancheng will be more affected by heatwaves in the future. This is related to the coupling effect between the increasing frequency of heatwaves and various social covariables.

3.2.2. Regional heterogeneity of the different loss types

The heat map (Figs. S4–6) reflects a comparison and of the various degrees among the different loss types annually. The different losses reflect a sufficient heterogeneity to varying degrees. Therefore, it is necessary to classify the loss types by city according to their different status to evaluate the various loss types intuitively (Table S4).

Some loss types played a similar role in the three cities. In general, health loss deserves our primary concern, and it belongs to Class A in every city (Table S4). The health losses in Nanjing and Suzhou were similar in value and significantly greater than that in Yancheng (Table S3). Between the two heat-related diseases, the loss of value of a statistical life (VSL, Text S1) accounted for the largest proportion, and this was followed by the loss of the accompanying delay and medical expenses. For example, in 2019 and 2030, the loss of VSL accounted for 87.23% and 87.20% of the total health loss in Nanjing, respectively; 86.63% and 87.49% in Suzhou, respectively; and 93.49% and 93.11% in Yancheng, respectively, all of which were dominant. It can be seen that the potential loss risk caused by heat-related diseases is much greater than the direct loss risk, indicating that heatwaves pose a huge but often overlooked health threat to residents.

In addition, circulatory diseases cause a bigger loss than respiratory diseases. For example, in 2019 and 2030, the proportion of heat-related circulatory system disease loss in the total health loss was 77.6% and 81.8%, respectively, in Nanjing; 83.1% and 86.7%, respectively, in Suzhou; and 77.8% and 77.6%, respectively, in Yancheng.

The overall growth rate of the health loss was the highest (Figs. S4–6). The potential threat and vulnerability of health loss when facing a heatwave are far greater than the other social loss types, and the level of health care and cooling measures are facing more serious challenges. Among all the cities, high-temperature days in the future and the surge of elderly people bring great potential risks to Yancheng, whose loss growth rate is the highest.

Second, in general, the labor value loss in Class C accounted for the highest proportion of the total loss and caused the greatest impact on the entire social-economic development. Every year, the labor value loss in Nanjing was much higher than that of Suzhou and Yancheng (Table S3). This result indicates that the loss of labor value in Nanjing would be most significantly affected by a heatwave. Such a conclusion is the same as the situation expressed by predecessors, but much higher than that found in previous studies (Xia et al., 2018).

Compared with the other two major industries, primary industry workers have the highest direct exposure to high temperatures, but the results are different from those expected. In Nanjing and Suzhou, the negative impact of high temperature on the output value of the primary industry was much less than that of the secondary and tertiary industries. The losses of the three industries in Yancheng fluctuated greatly under the influence of temperature, and the loss gap between the three industries was not as obvious as that of the other cities. (Figs. S4–6; Table 1).

In the future, the adverse impact and vulnerability of a heatwave in Yancheng is far more than that in Nanjing and Suzhou, and the industrial loss rate has increased 8.2 times in ten years. The explanation for this phenomenon is that under SSP2, the number of high-temperature days in the future will rise obviously, but effective cooling measures for working environments would not have been adopted in our hypothesis (**Text S1**).

The adaption expenditure in Class C of all the cities reaches an interesting conclusion. According to the search index, the search volume of air conditioners in summer is significantly higher than that in winter. This indicates that heat is more likely to drive the attention of residents to ultimately pay for air conditioners. Currently, the adaptive expenditure of Suzhou is higher than that of Nanjing and Yancheng (Table S3). However, the increasing frequency of heatwaves and the per capita disposable income will result in a narrowing of the gap between cities, and the adaption expenditure of Yancheng will surpass that of Suzhou in 2030.

Some loss types played different roles in different cities. For Nanjing, significantly higher transportation costs and higher amounts of daily traffic trips than the other two cities will lead to a larger expenditure of heat-related transportation expenses. However, Yancheng will see the biggest increase in future transportation expenditures due to the daily frequency of heatwaves and a surge in the total population and number of passengers. In addition, we found that Nanjing's public expenditure was much higher than Yancheng's every year.

For Suzhou, the loss of equipment was prominent, and this was primarily related to the total population. The Suzhou power grid will face more severe challenges under the scenario of high-temperature stress and population growth in the future.

For Yancheng, the loss of crop value in all years was much higher than that in Nanjing and Suzhou due to the significantly larger acreage (Table S3). The impacts of high temperatures were different for different crops. The largest one was vegetables, followed by rice and corn. The residential heat-related additional expenditure on electricity will be significantly higher than the water in the three cities, but the growth will be similar (Table S3). This means that the urban water and electricity expenditure losses in Yancheng are more vulnerable to high temperatures than in Nanjing and Suzhou.

Table 1

Loss in the different industrial sectors, *100 million CNY*.

City	Year	Primary industry	Secondary industry	Tertiary industry
Nanjing	2030	73.42	996.94	1324.05
	2019	38.62	514.01	646.32
	2007	20.48	307.04	211.23
Suzhou	2030	24.64	684.73	524.57
	2019	12.44	403.23	284.99
	2007	8.81	177.48	68.97
Yancheng	2030	48.34	114.10	68.81
	2019	5.90	9.56	7.27
	2007	5.50	8.74	4.20

3.2.3. Relatedness and implications

From a deeper perspective, public expenditure can make a big difference and with low associated costs, as described below. Heat-related government expenditure is highly correlated with urban population and economic factors. The public expenditure of Nanjing and Suzhou with higher development levels is much higher than that of Yancheng with a lower development level (Table S3). In addition, we found that the amount of government public spending seems to be inversely proportional to the extent to which the urban economy is affected by a heatwave. Despite the fact of economic volume, the economic losses of Nanjing and Suzhou were found to be much higher than that of Yancheng. However, under the scenario of SSP2, the growth rate of economic losses on both sides of “supply” and “demand” in Yancheng was much higher than those in Nanjing and Suzhou.

The results suggested that the loss as a percentage of the GDP in cities with high public expenditures (Nanjing and Suzhou) will be significantly lower than that in cities with low public expenditures (Yancheng). The changes in the individual loss types are the same. Although the loss of cities with low public expenditures was lower than that of cities with high public expenditures. However, this was attributed to the much higher loss growth rate, and some loss types even will tend to surpass the corresponding loss of cities with high public expenditures in the future.

Cities with low levels of economic development are already at great risk from high temperatures and still receive no adequate protection from public expenditure, making them even more vulnerable to future high temperatures. The effect would also act on the social market, affecting capital operation, financial operations, and personal consumption more broadly, thus possibly causing more severe economic loss. This is why Yancheng and similar "sensitive" cities will face a mortal "heatwave" threat in the future.

As shown in the SDP framework, governmental public expenditure plays a regulatory role in economic loss and further improves the social environment of "supply" and "demand" when facing climatic variation. However, the current expenditure degree and ability of cities to withstand heatwaves remain weak, and this can be seen in an increase in the ratio of heat-related losses to the GDP in the future for all cities. Decision- makers in cities of all types should take a long-term sustainability perspective and further increase climate-related public spending.

3.3. Loss intervention and effect

The SDP framework and the results of the typical case studies suggested that government regulation played a vital role in the prevention and control of heat damage. To guide the practices, we further discovered the beginning points where government spending can invest and reach beneficial effects. Furthermore, using the result of the influence path analysis, we developed the intervention effect assessment for two scenarios.

3.3.1. For the different social factors

The following assumptions were made: 1) the heatwave index (HI) and heatwave-related health risk (RR) stayed the same; 2) the individual social factor variable changed by 1%, and the rest remained unchanged in 2030 in scenario 1.

For the different loss types, the observation of the results (Fig. 4) shows that the adjustment of the industrial structure alleviates the loss for most of the tertiary industry in Nanjing, and the mitigation value of the equipment loss by controlling the population number is the largest for Suzhou. However, the farming area, industrial structure, and population all played an important role in Yancheng. It is worth mentioning that alleviating the proportion of the elderly population will play a positive role in alleviating the health loss of Yancheng, but the equipment loss will be exacerbated by a decline in the population number.

For the reduction rate of a single social factor (Fig. S7), we can conclude that the population had the most significant mitigation effect on the equipment losses for Nanjing and Suzhou. For Yancheng, reducing the farming area had the most significant effect on the crop value loss.

In addition, the degree and efficiency of mitigation to the total losses by changing a single influencing factor clearly indicated which intervention paths would be the most effective (Table S5). We used the influence of governmental regulation to intervene in some specific social factors, and this resulted in a better effect of heatwave events.

3.3.2. For the heatwave index

The following assumptions were made: 1) all social and other factors stayed the same; 2) the heatwave index decreased by 1 in 2030 in scenario 2.

The results (Fig. 5) expressed the reduction values and corresponding ratios of the different loss types for each daily reduction in the heatwave days in 2030 under the condition that the high-temperature degree remained unchanged. It was found that for the three cities, controlling the high temperatures had the largest reduction value on the loss of secondary industry. For the reduction rate, the mitigation effect of the maize value loss was the most significant for Nanjing. Suzhou had the most significant relieving effect on the loss of the secondary industry, and the most significant one in Yancheng was the transportation expenditure.

For the total economic loss caused by heatwaves (Table S5), if we could shorten the one heatwave day in the future (2030), we would avoid 1.337% of the heat-related losses in

Nanjing, 1.829% in Suzhou, and 2.107% in Yancheng. This illustrates the extent of benefits due to extreme heatwave prevention measures for the different cities.

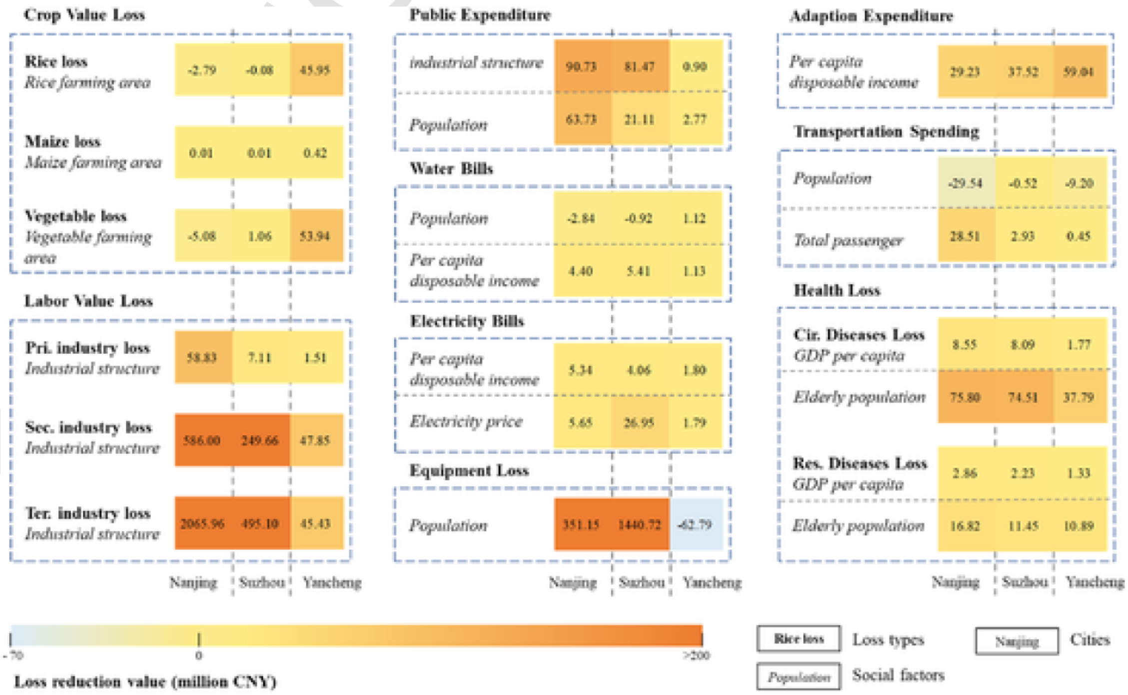

Fig. 4. The reduction value of the different loss types when the different influencing factors decrease by 1%. The color depth of each grid represents the relative extent of the loss mitigation for that city. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.4. Policy suggestions

By combining the discussion of the influence factors' relatedness and the intervention effect of the different paths, policymakers can make optimal choices and macroscopic decisions. However, not all the influence factors can be affected intuitively by policy tools. Therefore, we chose some factors that were closely relevant to the policy impact for further analysis, such as the farming area, industrial structure, electricity price, and elderly population. It is necessary to provide the corresponding policy recommendations to improve the situation of heatwave damage:

Targeting the cities with high development levels, we found that health loss is the largest loss type of vulnerability. Policymakers should focus on enhancing high-temperature protection publicity. Creation of green spaces, providing rooftop garden, and using more optimized building materials in the city can reduce the intensity of extreme heat (Sharma et al., 2018). Improving heat early warning systems and emergency response planning can help residents prepare for extreme heat in advance (Arifwidodo and Chandrasiri, 2020).

Because the industrial output loss was the largest loss type in amount, it will be necessary to increase the number of hightemperature holidays and coordinate with enterprises to install cooling equipment to improve the job security of workers in heatwave events to reduce the loss of secondary industry. In addition, we should try to adjust the industrial structure appropriately to reduce the loss of tertiary industry and encourage more companies to participate in carbon trading activities (Jin et al., 2020).

Targeting the cities with low development, we found that public expenditure is a priority for policymakers. More public expenditure should be allocated and it will demonstrate a greater inhibition ability on losses. On this basis, the social economy will obtain a more suitable development environment, and the loss situation will be correspondingly improved. The government could invest more in "Medical and health expenditure", "Energy conservation and environmental protection expenditure", "Agriculture, forestry and water expenditure" and "Land, marine and meteorology expenditure" to cope with extreme heat and prevent greater economic loss damage caused by heatwave in the future. For example, government can create more outpatient departments and beds in the hospitals to better cope with the pressure of outpatient visits and hospital admission under the heat wave. And it is necessary to increase the protection of nature such as woodlands and wetlands.

Additionally, by optimizing the crop farming area and industrial structure—which are effective ways to reduce losses—crop and industrial losses would be mitigated. Measures should be taken to alleviate the problem of an aging population, and this is even more urgent for these cities because of the vital position of health loss in their social economy. Policy makers should pay more attention to the effects of social- economic factors like per capita GHI, urbanization rate and life expectancy which have positive influence on aging problems (Wang, 2020).

Furthermore, it is showed in our results that the current public expenditure of all cities is still insufficient and their economic positions are still facing great heat stress. Obviously, the government should formulate further and reasonable public finance plans to ensure the orderly progression and development of the market economy. Government should increase the proportion of heat prevention expenditures in public expenditures, improve the efficiency of government regulation and control, and optimize the heat resistance capacity of society. In this way, future heat trends can be mitigated and social-economic losses can be reduced by reducing the number of heatwave days efficaciously.

Fig. 5. The reduction value and rate of different loss types when the HI decreased by 1. The color depth of each grid represents the relative extent of the loss mitigation for that city. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.5. Limitations and future work

This study has some limitations that should be noted. First, it is not clear that to what extent has public expenditure contributed to mitigating heatwave-related losses in this study. And we didn't consider whether extreme temperatures affect the market economy, government policies, and further affect household consumption or not.

In future studies, it will be fruitful to explore these questions and provide an in-depth understanding how related factors interact and influence heat-related economic losses.

4. Conclusion

In this study, SDP, a more comprehensive framework for assessing economic losses related to heatwaves, was proposed. This framework helped to clarify the influence path, summarize the heterogeneity of the regional economic loss, comprehensively predict the loss, propose effective intervention measures, and finally promote the urban sustainable development strategy.

SDP could be utilized in every city and had perfect performance. We confirmed the features of SDP using three case cities with different economic development and regions and then analyzed the results. We found the influence path of loss using the MLR and a series of fitting and prediction models under the guidance of the SDP. Results showed that heatwaves affect urban economics from all aspects, and the degree is huge and inevitable. The total social loss caused by a heatwave accounted for approximately 1%–10% of the city's GDP every year, showing a prominent annual increasing trend. Cities with high levels of economic development, such as Nanjing and Suzhou, face high heat-related economic losses every year. However, cities with low levels of economic development, such as Yancheng, face higher vulnerability and risks in the future.

Heat-related economic losses displayed an obvious heterogeneity in the different cities. What requires more attention is a public expenditure, a dimension of loss that is often overlooked by the existing research. Public expenditure is a part of the heat-related economic losses and expenditures as well as a social factor that plays a moderating role in the loss of "supply" and "demand."

The SDP framework assisted in the discovery that cities with high economic development levels would need to have higher public spending plans to prevent and resist climate events. Cities that do so could significantly slow down the growth of economic losses, such as labor value loss and health loss. However, even if the current government public expenditure reflects some loss mitigation capacity, extreme heatwave events could still be dangerous in the future because the current public spending is not sufficient.

Fortunately, the proposed SDP framework had a practical use for the analysis and proposal of optimal intervention strategies for cities facing the economic threat mentioned above. Through the analysis of the loss path and the prediction of mitigation benefits, we could find the optimal intervention strategy. More expenditure and policy tools for effective social factors are required to improve the current social environment and prevent future heat stress.

Credit authorship contribution statement

Peng Wang: Methodology, Writing – original draft. **Wendi Zhang**: Investigation. **Jiawen Liu**: Writing – review & editing. **Pan He**: Writing – review & editing. **Jiaming Wang**: Data curation. **Lei Huang**: Conceptualization. **Bing Zhang**: Supervision. **Declaration of competing interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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