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Article

Combined effect of climate change and labor relation on optimally managing labor productivity under uncertainty

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Abstract: Heat stress amplified by climate change causes excessive reductions in labor capacity, work injuries, and socio-economic losses. Yet studies of corresponding impact assessments and adaptation developments are insufficient and incapable of effectively dealing with uncertain information. This gap is caused by the inability to resolve complex channels involving climate change, labor relations, and labor productivity. In this paper, an optimization-based productivity restoration modeling framework is developed to bridge the gap and support decision-makers in making informed adaptation plans. The framework integrates a multiple-climate-model ensemble, an empirical relationship between heat stress and labor capacity, and an inexact system costs model to investigate underlying uncertainties associated with climate and management systems. Optimal and reliable decision alternatives can be obtained by communicating uncertain information into the optimization processes and resolving multiple channels. Results show that the increased heat stress will lead to a potential reduction in labor productivity in China. By solving the objective function of the framework, total system costs to restore the reduction are estimated to be up to 248,700 million dollars under a Representative Concentration Pathway of 2.6 (RCP2.6) and 697,073 million dollars under RCP8.5 for standard employment, while less costs found for non-standard employment. However, non-standard employment tends to restore productivity reduction with the minimum system cost by implementing active measures rather than passive measures due to the low labor costs resulting from ambiguities among employment statuses. The situation could result in more heat-related work injuries because employers in non-standard employment can avoid the obligation of providing a safe working environment. Urgent actions are needed to uphold labor productivity with climate change, especially to ensure that employers from non-standard employment fulfill their statutory obligations.

Keywords: heat stress; labor relations; labor productivity; optimization; uncertainty

1. Introduction

Ongoing climate change has been and will continue to pose threats to human life and outdoor activities by exceeding the limits of human thermoregulatory (Borg et al., 2021; Liu et al., 2018; Yan et al., 2022; Zhao et al., 2016; Zhu et al., 2021). Such climatic conditions could directly decrease labor productivity and increase the chance of work injuries (Foley, 2017; Ma et al., 2019; Yu et al., 2017). Assessing the impact of climate change on labor productivity is complex, diverse, and fragmented considering labor demand, supply, relation, and legislation (Matsumoto, 2019; Zhu et al., 2021). A growing trend in the world of work is the rise in non-standard employment such as delivery riders, online platform postmen, and drivers (Gao et al., 2018; Lan et al., 2022). Workers from non-standard employment are more likely exposed to outdoor heat stress due to a lack of occupational protection rights caused by ambiguous employment status. An increasing concern is that global warming would increase inequity in the work environment between standard employment and non-standard employment (Day et al., 2019; Nunfam et al., 2018). A rising number of studies have been focused on the change in labor capacity and the related economic consequences (Borg et al., 2021; Ma et al., 2019; Matsumoto, 2019; Yan et al., 2022; Zhao et al., 2016). It is still rare to see research addressing the impacts of labor relations and climate change on labor productivity by resolving multiple complex channels. The challenge linked to developing adaptation strategies is how to effectively treat uncertainty from climate projections and labor relations. Optimized programming is proven to be an effective tool for exploring feasible decision alternatives with the lowest cost and reducing system complexity (Borba et al., 2019; Gao et al., 2018; Nunfam et al., 2018; Nunfam et al., 2019). The development of optimal adaptation for dealing with climate-change-induced labor productivity reduction is crucial for preventing inequity from being amplified and building resilient economies.

Previous studies have been carried out to optimally manage labor productivity through various means such as labor planning and scheduling. Descriptive (or exploratory) models and normative models are widely used as analytical or optimizing tools in labor planning and scheduling (Bastian et al., 2020; Borba et al., 2019; Day et al., 2019; De Feyter et al., 2017; Di Francesco et al., 2016; Zhu et al., 2021). For instance, the labor stream responding to various conditions is predicted by descriptive models such as Markov (cross-sectional) models (De Feyter et al., 2017), renewal models (Di Francesco et al., 2016), and semi-Markov models (Chen et al., 2010; Dimitriou and Georgiou, 2021). Besides, dynamic programming within a Markov framework is also applied to allocate the workforce, generate optimal labor streams, and recruit to meet dynamic needs at various service levels. Normative models are developed to achieve a certain degree of satisfaction for an objective function under given criteria (Bastian et al., 2020; Borba et al., 2019; Fischereit and Schlünzen, 2018). Policies are then prescribed for a labor management system to obtain an ideal balance with optimizing personnel flow, labor size, and related costs. However, these models are intended to facilitate decision-makers to determine schedule patterns and assign the workforce to various tasks for balancing the short-term and low-level labor demand and supply. Even though non-standard employment becoming more widespread across economic sectors and occupations, few models attempt to include the potential impact of different labor relations on labor productivity management in their model schemes.

The long-term climate change impacts and labor relations' complexities on labor productivity are not studied sufficiently and are based on some weak methodologies. Since information related to environmental situations and socio-economic developments is imprecise, uncertainties inherently exist in climate and management systems and are presented as intervals in real-world planning problems. This non-deterministic information cannot be processed in previous studies and hence failed to integrate the climate and management system effectively. To address this issue, an optimization-based productivity restoration modeling framework is developed to cost-effectively manage the long-term labor productivity affected by climate change and labor relations. To our best knowledge, we, for the first time, developed a framework to facilitate decision-makers to restore productivity reduction with the minimum system cost under an uncertain environment. The proposed framework considers the evolution of uncertainties within the integrated system from three perspectives. First, plausible ranges of future changes in heat stress are investigated by an ensemble of Global Climate Models (GCMs) projections under different Representative Concentration Pathways (RCPs). Second, intervals of productive working time are estimated based on the empirical relationship between heat stress and labor capacity. Third, incomplete and sparse data on system costs and capacity limits are incorporated into an interval programming model to determine the optimal alternative with the minimum system costs.

The rest of the paper proceeds as follows: the methods and datasets used to obtain the climate projections, labor productivity changes, and interval programming model formulations are presented in Section 2. A thorough comprehension of the impacts of heat stress and labor relations on the labor management system provides the basis to develop the optimization-based productivity restoration modeling framework. The main findings of the case study in heat stress, labor productivity, optimal solutions, and system costs are exhibited in Section 3. The practical significance of the novel framework assessing the impacts of climate change and labor relations on labor productivity and adaptation plans to minimize the system cost is discussed in Section 4. The novelty of this study, highlighted findings, associated implications, and limitations are concluded in Section 5.

2. Methods and data

2.1. Climate models, heat stress indices, and labor productivity calculations

Simulations and projections of hourly mean surface air temperature and relative humidity from five GCMs, including HadGEM2-ES, MIROC5, CSIRO-MK3.6.0, CanESM2, and IPSLCM5A-MR are used to derive heat stress over China (please refer to **Table 1** in the supplementary information for the details of GCMs). Applying hourly average values can typically avoid the underestimation of peak value resulting from the daily average value. Changes in heat stress are calculated by subtracting projections over the period from 2076 to 2100 from simulations over the reference period from 1981 to 2005. To explore the range of possible outcomes under different climate warming scenarios, the largest and least warming scenarios are chosen (Hatvani-Kovacs et al., 2016; Kjellstrom et al., 2018; Zhu et al., 2022). The largest warming scenario (RCP8.5) is constructed with CO_2 concentrations keeping increasing through 2100. The least warming scenario (RCP2.6) can be realized by aggressive mitigation by limiting warming to below 2 ℃.

Table 1. A list of five CMIP5 models used in this study. Hourly outputs of air temperature and relative humidity at 2 m above the surface are used in the historical, RCP2.6, and RCP8.5 simulations.

GCMs	**Climate Modelling Groups**	**Resolution (Longitude × Latitude)**
CanESM2	Canadian Centre for Climate Modelling and Analysis	128 × 64
IPSL-CM5A-MR	Institute Pierre-Simon Laplace Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	144 × 143
MIROC5	Institute Pierre-Simon Laplace Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology Meteorological Research Institute	256 × 128
HadGEM2-ES	Met Office Hadley Centre	192 × 144
CSIRO-MK3.6.0	Commonwealth Scientific and Industrial Research Organisation	192 × 97

The Bureau of Labor Statistics commonly divides the nature of labor relations into two categories, namely standard employment and non-standard employment (China National Bureau of Statistics, 2021). Outdoor workers (i.e., street sweepers, track maintainers, electrical field technicians, construction workers, gardeners, and steeplejacks) are engaged on the basis of a contract of service that falls into the categories of standard employment. Under the employment contract, the employer normally controls when, where, and how the work gets done. In contrast, workers in non-standard employment are involved in a service contract where they are responsible for their own jobs. Self-employed delivery riders, online platform postmen, and drivers are supposed to own their businesses and are contracted to provide services for payment over a fixed term. We focus on how heat stress reduces the working hours of two different employment statuses and assess the impact of labor relations on managing labor productivity reduction. A large number of thermal indices that consider the combined effect of air temperature and relative humidity were developed to address heat stress posing on the human body (Fischereit and Schlünzen, 2018; Wang and Zhu, 2020; Zhu et al., 2019). The Wet-Bulb Globe Temperature (WBGT) is adopted for measuring heat stress across all available indices for its well validation and high usability (Budd, 2008; Willett and Sherwood, 2012). It should be noted that a low limit of heat stress in the outdoor working environment is explored by shading the sunlight in the WBGT.

$$e_{sat} = \exp\Big(18.8764 - \frac{2991.2729}{T^2} - \frac{6017.0128}{T} - 0.0285 \times T + 1.7838 \times 10^{-5} \times T^2 - 8.4150 \times 10^{-10} \times T^3 + 4.4413 \times 10^{-13} \times T^4 + 2.8585 \times 10^{-2} \times \ln(T)\Big)/100 \tag{1}$$

$$e = \mathrm{RH} \times e_{sat} \tag{2}$$

$$\mathrm{WBGT} = 0.567 \times T + 0.393 \times e + 3.94 \tag{3}$$

where e_{sat} is the saturation vapor pressure (hPa), T is the hourly surface air temperature with a valid range from 0 °C to 100 °C, e is the simultaneous vapor pressure (hPa), and RH is the hourly relative humidity (%).

The relationship between WBGT and labor capacity can be estimated by an empirical metric that is widely applied (Fischereit and Schlünzen, 2018; Lohrey et al., 2021; Shakerian et al., 2021). In the metric, the 100% labor capacity can only be reached for continuous work being carried out by a healthy and acclimatized worker in a safe and comfortable working environment. A 50% labor capacity situation means that the worker needs to take a 30-minute break for every 1-hour work. Three different types of labor work namely light, moderate, and heavy labor are considered. Moreover, heavy labor is assumed to be equivalent to two times moderate labor and four times light labor. The unhealthy and unacclimatized workers are excluded for data limitation and the purpose of model simplification. The empirical relationship for heavy work is estimated as

$$\mathrm{LC} = 100\%, \mathrm{WBGT} \le 25℃ \tag{4}$$

$$\mathrm{LC} = \left[1 - 0.25 \times \max(0, \mathrm{WBGT} - 25)^{\frac{2}{3}}\right] \times 100\%, 25℃ < \mathrm{WBGT} < 33℃ \tag{5}$$

$$\mathrm{LC} = 0\%, \mathrm{WBGT} \ge 33℃ \tag{6}$$

where LC is the labor capacity (%), and WBGT is the Wet-Bulb Globe Temperature (℃).

Based on the data collected from 2011 to 2021, 6.7% and 0.8% of workers were involved in heavy and very heavy-level activities; 30.1% of workers carried out moderate-level activities; 62.4% of civilian workers performed light-level labor (Yu et al., 2017; Zhang et al., 2018; Zhao et al., 2016). To be consistent, we combined the values of 6.7% and 0.8% to represent the total percentage of civilian workers involved in heavy-level activities. The temporal resolution is three hours due to the CMIP5 models' limitation. The daily labor capacity reduction is accumulated by counting exposure to heat stress in working hours from 9 am to 5 pm. We define the annual productivity loss/working hour loss as the multiyear averaged labor capacity reduction multiplied by the population of workers involved in a given labor type. We can then obtain the change in working hour loss induced by climate change by subtracting the accumulated labor productivity reduction for the baseline period from the reduction for the future period.

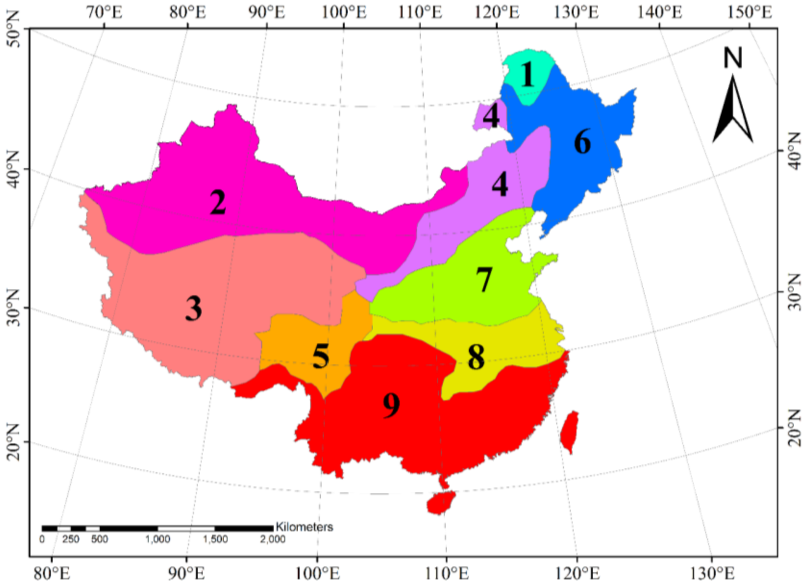

Figure 1. Nine climate regions are delineated according to temperature and moisture characteristics.

The WBGT could vary to a large extent across different regions for their unique climate. Local contexts and geographical complexities could also influence how entities adapt to the labor productivity loss caused by the rising WBGT. Due to China's large and complex territory, the study area is divided into nine divisions based on their unique temperature and moisture characteristics (as shown in **Figure 1**). The nine divisions are 1) Cold and humid region; 2) Warm and arid region; 3) Plateau and arid region; 4) Warm and semi-arid region; 5) Plateau and semi-humid region; 6) Cool and humid region; 7) Warm and humid region; 8) Hot and humid region; 9) Subtropical and humid region.

2.2. Novel framework for productivity restoration

Various adaptation options are available to cope with the labor capacity reduction induced by heat stress (Ma et al., 2019; Yan et al., 2022; Yu et al., 2017; Zhao et al., 2016). The most common measures used to deal with labor productivity loss are working time shifts, work practice programs, education programs, air conditioning, and outdoor portable cooling devices (Bastian et al., 2020; Dimitriou and Georgiou, 2021; Zhang et al., 2018; Zhu et al., 2021). Among various measures, the implementation of air conditioning and shifting/extending working hours stands out as more economical and practical for industries across the board (Xiang et al., 2018). Nevertheless, each adaptation option faces limitations due to processing efficiencies and national safety regulations. The heightened occurrence of elevated nighttime temperatures may diminish the efficacy of adaptation strategies such as overtime work or shift adjustments to compensate for lost working hours. On days when nighttime temperatures surpass the threshold for labor capacity reduction, resorting to passive cooling mechanisms becomes imperative, despite incurring operational expenses and capital investments for nighttime operations. Notably, commonly employed passive cooling measures, such as air conditioning and cooling fans, are resource-intensive solutions with significant energy consumption and carbon emissions. In comparison, working overtime emerges as an adaptation measure with a smaller carbon footprint and reduced energy costs.

Significant uncertainty surrounds the expenses associated with the implementation of each adaptation measure, encompassing both direct capital investments/payments and indirect costs, such as those related to operations, maintenance, and management. Systematic planning to prevent labor productivity from reducing is complicated at a national level. It is imperative to effectively integrate uncertain information into the systematic planning of labor productivity restoration to identify cost-optimal adaptation measures. Within the scientific community, there exists a consensus on specific cost-effective adaptation options for restoring lost working hours, guided by established principles (Pogačar et al., 2018). These adaptation options fall into two categories: passive measures (such as air conditioning, outdoor shades, and personal cooling devices) and active measures (including working overtime, occupational choices, and work practice programs). Optimizing the application of both active and passive measures is suggested to have the most significant systematic impact on restoring lost working hours on a regional scale. Economic cost data for active and passive measures are gathered in intervals, except for divisions 3 and 5, where passive measures are scarcely applied over the 25-year planning horizons. These intervals account for the uncertainty in implementing adaptation measures, incorporating variations in population weight, economic development, and air-conditioning penetration rate. The study utilizes provincial-level air-conditioning penetration rates, average market values of air conditioners, energy consumption for passive cooling mechanisms, and socio-economic scenarios to estimate future running costs and capital investments for applying passive measures (supplementary information **Table 2**). Yearly provincial population projections in China under Shared Socioeconomic Pathways (2010–2100) provide the provincial-scale long-term forecasting database for national regulations, population, and GDP. The China Population and Employment Statistics Yearbooks (1981–2005) are employed to calculate population changes and estimate managing costs and payments for overtime work.

Table 2. Area-averaged air conditioning penetration rate in each province of China for the period 1985–2004.

Province	Air Conditioning Penetration Rate (%)
Guangdong	[119.3, 121.5]
Shanghai	[109.7, 110.8]
Chongqing	[103, 104.0]
Beijing	[89.4, 91.3]
Zhejiang	[87.9, 90.1]
Tianjin	[76.6, 80.5]
Fujian	[73.9, 75.4]
Jiangsu	[69.6, 73.4]
Hubei	[59.2, 61.5]
Henan	[58.2, 59.6]
Anhui	[48.9, 49.0]
Hunan	[50.9, 53.6]
Hebei	[48, 51.4]
Shaanxi	[45.8, 46.3]
Shandong	[46.3, 49.0]
Guangxi	[44.9, 45.1]
Jiangxi	[37.1, 40.6]
Sichuan	[37.4, 40.9]
Hainan	[25.4, 27.3]
Shanxi	[14.2, 16.8]
Liaoning	[7.5, 11.1]
Guizhou	[5.4, 7.7]
Xinjiang	[4.6, 7.3]
InnerMongol	[3.9, 5.1]
Heilongjiang	[3.4, 6.5]
Ningxia	[3, 6.3]
Jilin	[2.7, 4.4]
Tibet	[2.7, 4.2]
Gansu	[1.7, 2.2]
Yunnan	[0.5, 3.1]
Qinghai	[0.3, 0.5]

The provinces are sorted by the air conditioning penetration rate. In this study, we utilize the province-level air conditioning penetration rate, the electricity consumption rate, and electricity price to estimate future air conditioning application costs. The future air conditioning application consists of increased use of installed air conditioning units in workspaces that already have air conditioning installed and increased prevalence of air conditioning units to expand the number of workplaces that can reduce internal temperatures. Considering research and development in reducing the costs of producing an air conditioner and reducing the energy consumption of air conditioning, the flow use of this adaptation measure can be greater at the end of the 21st century than before. It also adds uncertain information into estimating the costs of applying the air conditioning in the future. With a comprehensively understanding of all factors, the costs of applying air conditioning are calculated and presented as intervals. Our study used the yearly provincial population projections in China (Chen et al., 2020). with considering the changes in national fertility policies and population ceiling policies under shared socioeconomic pathways from 2010 to 2100. We then analyze socioeconomic scenario drivers and quantify scenario assumptions following the shared socioeconomic pathways to obtain the provincial-scale long-term forecasting database of socio-economic driving factors for calculating future overtime costs in China. Regarding overtime payment regulations in China, there are mainly three categories of employee systems, namely the standard work hour system, the comprehensive work hour system, and the non-fixed work hour system.

Within the framework of this study, the productivity restoration process is treated as an interval system for both non-standard and standard employment situations. The productivity restoration management system employs interval decision variables representing the number of working hour losses across different divisions with various adaptation options under each RCP scenario. The objective is to minimize the system cost for labor productivity restoration by optimally allocating the number of working hour losses to adaptation options. Constraints account for the inherent relationships between decision variables and restoration restrictions. The detailed interval programming model is formulated as follows:

a. Standard employment situation

Objective function:

$$\begin{aligned}\mathrm{Min}G^{\pm} = {} & \sum_{i=1}^{u}\sum_{j=1}^{v}\sum_{k=1}^{w} y_{ijk}^{\pm} \times (IV_{ijk}^{\pm} + MO_{ijk}^{\pm} + SU_{ik}^{\pm}) + \sum_{i=1}^{u}\sum_{k=1}^{w}[(\sum_{j=1}^{n} RA_{ik}^{\pm} \times y_{ijk}^{\pm}) \times (\sum_{j=n+1}^{v} OP_{ijk}^{\pm})] \\ & - \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} y_{ijk}^{\pm} \times (EB_{ijk}^{\pm} - RI_{ijk}^{\pm} \times PN_{i}^{\pm}\end{aligned} \tag{7}$$

Constraint on active methods capacity:

$$\sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} y_{ijk}^{\pm} \leq CA^{\pm} \tag{8}$$

Constraint on passive methods capacity:

$$\sum_{i=1}^{u}\sum_{j=n+1}^{v}\sum_{k=1}^{w} y_{ijk}^{\pm} + \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} RA_{ik}^{\pm} \times y_{ijk}^{\pm} \leq CP^{\pm} \tag{9}$$

Constraints on the allocation of workforce capacity:

$$\sum_{j=1}^{v} y_{ijk}^{\pm} = AW_{ik}^{\pm}, \forall i, k. \tag{10}$$

$$y_{ijk}^{\pm} \geq 0, \forall i, j, k. \tag{11}$$

b. Non-Standard employment situation

Objective function 1:

$$\text{Min}H_1^{\pm} = \sum_{i=1}^{u}\sum_{j=1}^{v}\sum_{k=1}^{w} z_{ijk}^{\pm} \times (IV_{ijk}^{\pm} + MO_{ijk}^{\pm}) + \sum_{i=1}^{u}\sum_{k=1}^{w}[(\sum_{j=1}^{n} RA_{ik}^{\pm} \times z_{ijk}^{\pm}) \times (\sum_{j=n+1}^{v} OP_{ijk}^{\pm})] - \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} z_{ijk}^{\pm} \times EB_{ijk}^{\pm} \quad (12)$$

Constraint on active methods capacity:

$$\sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} z_{ijk}^{\pm} < CA^{\pm} \quad (13)$$

Constraint on passive methods capacity:

$$\sum_{i=1}^{u}\sum_{j=n+1}^{v}\sum_{k=1}^{w} z_{ijk}^{\pm} + \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} RA_{ik}^{\pm} \times z_{ijk}^{\pm} < CP^{\pm} \quad (14)$$

Constraints on the allocation of workforce capacity:

$$\sum_{j=1}^{v} z_{ijk}^{\pm} < AW_{ik}^{\pm}, \forall i, k. \quad (15)$$

$$z_{ijk}^{\pm} \geq 0, \forall i, j, k. \quad (16)$$

The optimal solution for the objective function is $z_{ijk_{opt}}^{\pm}$.

Objective function 2:

$$\text{Min}H_2^{\pm} = \sum_{i=1}^{u}\sum_{j=1}^{v}\sum_{k=1}^{w} u_{ijk}^{\pm} \times (IV_{ijk}^{\pm} + MO_{ijk}^{\pm}) + \sum_{i=1}^{u}\sum_{k=1}^{w}[(\sum_{j=1}^{n} RA_{ik}^{\pm} \times u_{ijk}^{\pm}) \times \sum_{j=n+1}^{v} \text{OP}_{ijk}^{\pm})] - \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} u_{ijk}^{\pm} \times AR_{ijk}^{\pm} + \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} (u_{ijk}^{\pm} + z_{ijk_{opt}}^{\pm}) \times \text{RI}_{ijk}^{\pm} \times \text{LS}_{ik}^{\pm} \quad (17)$$

Constraint on active methods capacity:

$$\sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} (u_{ijk}^{\pm} + z_{ijk_{opt}}^{\pm}) \leq CA^{\pm} \quad (18)$$

Constraint on passive methods capacity:

$$\sum_{i=1}^{u}\sum_{j=n+1}^{v}\sum_{k=1}^{w} (u_{ijk}^{\pm} + z_{ijk_{opt}}^{\pm}) + \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} RA_{ik}^{\pm} \times (u_{ijk}^{\pm} + z_{ijk_{opt}}^{\pm}) \leq CP^{\pm} \quad (19)$$

Constraints on the allocation of workforce capacity:

$$\sum_{j=1}^{v} u_{ijk}^{\pm} = AW_{ik}^{\pm} - z_{ijk_{opt}}^{\pm}, \forall i, k \quad (20)$$

$$u_{ijk}^{\pm} \geq 0, \forall i, j, k. \quad (21)$$

where:

$G^{\pm}$ is the total system cost for the standard employment (unit: \$);

$y_{ijk}^{\pm}$ is the number of working hour loss in the region *i* allocated to the adaptation option *j* (Options from 1 to *n* are the active measures; Options from *n* + 1 to *v* are the passive ones) for the labor type *k* (unit: hr) for the standard employment;

$SU_{ik}^{\pm}$ is the subsidy of working on extremely hot days for the labor type *k* in the region *i* (unit: \$/hr);

$RI_{ijk}^{\pm}$ is the ratio of work injuries resulting from using the active measure *j* for the labor type *k* in the region *i* (unit: %);

$PN_{i}^{\pm}$ is the capital investment for the prevention of work injuries in the region *i* (unit: \$/hr);

$LS_{ik}^{\pm}$ is the lawsuit settlement for work injuries resulting from the labor type *k* in the region *i* (unit: \$/hr);

$IV_{ijk}^{\pm}$ is the investment for implementing the adaptation option *j* for the labor type *k* in the region *i* (unit: \$/hr);

$MO_{ijk}^{\pm}$ is the managing cost for implementing the adaptation option *j* (penalties and/or injuries compensations for active measures and budgets for passive ones) for the labor type *k* in the region *i* (unit: \$/hr);

$RA_{ik}^{\pm}$ is the rate of tropical nights when the nighttime temperature is high enough for using passive cooling methods in the region *i* for the labor type *k* (unit: %);

$OP_{ijk}^{\pm}$ is the cost for passive measures for the labor type k in the region *i* for tropical nights (unit: $/hr);

$EB_{ijk}^{\pm}$ is the health benefit/medical savings from using the passive cooling mechanism *j* for the labor type *k* in the region *i* (unit: $/hr);

$AR_{ijk}^{\pm}$ is the achievement reward from using the active measure *j* for the labor type *k* in the region *i* (unit: $/hr);

$CA^{\pm}$ is the total inherent capacity of implementing active methods for compensating the working hour loss (unit: hr);

$CP^{\pm}$ is the total capacity of implementing passive methods for restoring labor productivity (unit: hr);

$AW_{ik}^{\pm}$ is the accumulated working hour loss for the labor type k in the region *i* (unit: hr);

$H_1^{\pm}$ is the total system cost for the self-employed sectors or independent contractors in the non-standard employment (unit: $);

$H_2^{\pm}$ is the total system cost for the employer sectors in the non-standard employment (unit: $);

$z_{ijk}^{\pm}$ is the number of working hours losses in the region *i* allocated to the adaptation option *j* for the labor type *k* (unit: hr) in the self-employed sectors or independent contractors in the non-standard employment;

$u_{ijk}^{\pm}$ is the number of working hour losses in the region *i* allocated to the adaptation option *j* for the labor type *k* (unit: hr) in the self-employed sectors or independent contractors in the non-standard employment.

The following is the interval programming model applied to the study area, together with the solving procedure for productivity restoration:

c. Standard employment situation in China

Objective function:

$$\begin{aligned}\text{Min}G^{\pm} = {} & \textstyle\sum_{i=1}^{7}\sum_{j=1}^{2}\sum_{k=1}^{3} y_{ijk}^{\pm} \times (IV_{ijk}^{\pm} + MO_{ijk}^{\pm} + SU_{ik}^{\pm}) + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{\pm} \times y_{i1k}^{\pm} \times OP_{i2k}^{\pm} \\ & - \textstyle\sum_{i=1}^{7}\sum_{k=1}^{3} y_{i1k}^{\pm} \times (EB_{i1k}^{\pm} - RI_{i1k}^{\pm} \times PN_i^{\pm}\end{aligned} \tag{22}$$

Constraint on active methods capacity:

$$\textstyle\sum_{i=1}^{7}\sum_{k=1}^{3} y_{i1k}^{\pm} \leq CA^{\pm} \tag{23}$$

Constraint on passive methods capacity:

$$\textstyle\sum_{i=1}^{7}\sum_{k=1}^{3} y_{i2k}^{\pm} + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{\pm} \times y_{i1k}^{\pm} \leq CP^{\pm} \tag{24}$$

Constraints on the allocation of workforce capacity:

$$\textstyle\sum_{j=1}^{2} y_{ijk}^{\pm} = AW_{ik}^{\pm}, \forall i, k. \tag{25}$$

$$y_{ijk}^{\pm} \geq 0, \forall i, j, k. \tag{26}$$

d. Upper bound of standard employment

Objective function:

$$\begin{aligned}\text{Min}G^{+} = {} & \textstyle\sum_{i=1}^{7}\sum_{j=1}^{2}\sum_{k=1}^{3} y_{ijk}^{+} \times (IV_{ijk}^{+} + MO_{ijk}^{+} + SU_{ik}^{+}) + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{+} \times y_{i1k}^{+} \times OP_{i2k}^{+} \\ & - \textstyle\sum_{i=1}^{7}\sum_{k=1}^{3} y_{i1k}^{+} \times (EB_{i1k}^{-} - RI_{i1k}^{-} \times PN_i^{+}\end{aligned} \tag{27}$$

Constraint on active methods capacity:

$$\sum_{i=1}^{7}\sum_{k=1}^{3} y_{i1k}^{+} \leq CA^{-} \tag{28}$$

Constraint on passive methods capacity:

$$\sum_{i=1}^{7}\sum_{k=1}^{3} y_{i2k}^{+} + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{+} \times y_{i1k}^{+} \leq CP^{-} \tag{29}$$

Constraints on the allocation of workforce capacity:

$$\sum_{j=1}^{2} y_{ijk}^{+} = AW_{ik}^{+}, \forall i, k. \tag{30}$$

$$y_{ijk}^{+} \geq 0, \forall i, j, k. \tag{31}$$

Let $y_{ijk_{opt}}^{+}$ be the optimal solution of the model given in function (6a)–(6e).

e. Lower bound of standard employment

Objective function:

$$\begin{aligned}\text{Min}G^{-} = {} & \sum_{i=1}^{7}\sum_{j=1}^{2}\sum_{k=1}^{3} y_{ijk}^{-} \times (IV_{ijk}^{-} + MO_{ijk}^{-} + SU_{ik}^{-}) + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{-} \times y_{i1k}^{-} \times OP_{i2k}^{-} \\ & - \sum_{i=1}^{7}\sum_{k=1}^{3} y_{i1k}^{-} \times (EB_{i1k}^{+} - RI_{i1k}^{-} \times PN_{i}^{-}\end{aligned} \tag{32}$$

Constraint on active methods capacity:

$$\sum_{i=1}^{7}\sum_{k=1}^{3} y_{i1k}^{-} \leq CA^{+} \tag{33}$$

Constraint on passive methods capacity:

$$\sum_{i=1}^{7}\sum_{k=1}^{3} y_{i2k}^{-} + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{-} \times y_{i1k}^{-} \leq CP^{+} \tag{34}$$

Constraints on the allocation of workforce capacity:

$$\sum_{j=1}^{2} y_{ijk}^{-} = AW_{ik}^{-}, \forall i, k. \tag{35}$$

$$0 \leq y_{ijk}^{-} \leq y_{ijk_{opt}}^{+}, \forall i, j, k. \tag{36}$$

f. Non-Standard employment situation in China

Objective function 1:

$$\begin{aligned}\text{Min}H_{1}^{\pm} = {} & \sum_{i=1}^{7}\sum_{j=1}^{2}\sum_{k=1}^{3} z_{ijk}^{\pm} \times (IV_{ijk}^{\pm} + MO_{ijk}^{\pm}) + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{\pm} \times z_{i1k}^{\pm} \times OP_{i2k}^{\pm} \\ & - \sum_{i=1}^{7}\sum_{k=1}^{3} z_{i2k}^{\pm} \times EB_{i1k}^{\pm} \text{Min}G^{-} \\ & = \sum_{i=1}^{7}\sum_{j=1}^{2}\sum_{k=1}^{3} y_{ijk}^{-} \times (IV_{ijk}^{-} + MO_{ijk}^{-} + SU_{ik}^{-}) + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{-} \times y_{i1k}^{-} \times OP_{i2k}^{-} \\ & - \sum_{i=1}^{7}\sum_{k=1}^{3} y_{i1k}^{-} \times (EB_{i1k}^{+} - RI_{i1k}^{-} \times PN_{i}^{-}\end{aligned} \tag{37}$$

Constraint on active methods capacity:

$$\sum_{i=1}^{7}\sum_{j=1}^{2}\sum_{k=1}^{3} z_{ijk}^{\pm} < CA^{\pm} \tag{38}$$

Constraint on passive methods capacity:

$$\sum_{i=1}^{7}\sum_{j=1}^{2}\sum_{k=1}^{3} z_{ijk}^{\pm} < CA^{\pm} \tag{39}$$

Constraints on the allocation of workforce capacity:

$$\sum_{j=1}^{2} z_{ijk}^{\pm} \pm AW_{ij}^{\pm}, \forall i, k. \tag{40}$$

$$z_{ijk}^{\pm} \geq 0, \forall i, j, k. \tag{41}$$

The optimal solution for objective function 1 is $z_{ijk_{opt}}^{\pm}$.

Objective function 2:

$$\begin{aligned}\text{Min}H_{2}^{\pm} = {} & \sum_{i=1}^{7}\sum_{j=1}^{2}\sum_{k=1}^{3} u_{ijk}^{\pm} \times (IV_{ijk}^{\pm} + MO_{ijk}^{\pm}) + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{\pm} \times u_{i1k}^{\pm} \times OP_{i2k}^{\pm} - \sum_{i=1}^{7}\sum_{k=1}^{3} u_{i2k}^{\pm} \times AR_{i1k}^{\pm} \\ & + \sum_{i=1}^{7}\sum_{k=1}^{3} (u_{i1k}^{\pm} + z_{i1k_{opt}}^{\pm}) \times RI_{i1k}^{\pm} \times LS_{ik}^{\pm}\end{aligned} \tag{42}$$

Constraint on active methods capacity:

$$\sum_{i=1}^{7}\sum_{k=1}^{3} (u_{i1k}^{\pm} + z_{i1k_{opt}}^{\pm}) \leq CA^{\pm} \tag{43}$$

Constraint on passive methods capacity:

$$\sum_{i=1}^{7}\sum_{k=1}^{3} (u_{i2k}^{\pm} + z_{i2k_{opt}}^{\pm}) + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{\pm} \times (u_{i1k}^{\pm} + z_{i1k_{opt}}^{\pm}) \leq CP^{\pm} \tag{44}$$

Constraints on the allocation of workforce capacity:

$$\sum_{j=1}^{2} u_{ijk}^{\pm} = AW_{ik}^{\pm} - z_{ijk_{opt}}^{\pm}, \forall i, k. \tag{45}$$

$$0 \le u_{ijk}^{\pm} \le z_{ijk_{opt}}^{\pm}, \forall i, j, k. \tag{46}$$

g. Upper bound of non-standard employment

Objective function 1:

$$\text{Min} H_1^{+} = \sum_{i=1}^{7}\sum_{j=1}^{2}\sum_{k=1}^{3} z_{ijk}^{+} \times (IV_{ijk}^{+} + MO_{ijk}^{+}) + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{+} \times z_{i1k}^{+} \times OP_{i2k}^{+} - \sum_{i=1}^{7}\sum_{k=1}^{3} z_{i2k}^{+} \times EB_{i1k}^{-} \tag{47}$$

Constraint on active methods capacity:

$$\sum_{i=1}^{7}\sum_{j=1}^{2}\sum_{k=1}^{3} z_{ijk}^{+} < CA^{-} \tag{48}$$

Constraint on passive methods capacity:

$$\sum_{i=1}^{7}\sum_{k=1}^{3} z_{i2k}^{+} + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{+} \times z_{i1k}^{+} < CP^{-} \tag{49}$$

Constraints on the allocation of workforce capacity:

$$\sum_{j=1}^{2} z_{ijk}^{+} < AW_{ik}^{+}, \forall i, k. \tag{50}$$

$$z_{ijk}^{+} \ge 0, \forall i, j, k. \tag{51}$$

The optimal solution for objective function 1 is $z_{ijk_{opt}}^{+}$

Objective function 2:

$$\text{Min} H_2^{+} = \sum_{i=1}^{7}\sum_{j=1}^{2}\sum_{k=1}^{3} u_{ijk}^{+} \times (IV_{ijk}^{+} + MO_{ijk}^{+}) + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{+} \times u_{i1k}^{+} \times OP_{i2k}^{+} - \sum_{i=1}^{7}\sum_{k=1}^{3} u_{i2k}^{+} \times AR_{i1k}^{-} + \sum_{i=1}^{7}\sum_{k=1}^{3} (u_{i1k}^{+} + z_{i1k_{opt}}^{+}) \times RI_{i1k}^{+} \times LS_{ik}^{+} \tag{52}$$

Constraint on active methods capacity:

$$\sum_{i=1}^{7}\sum_{k=1}^{3} (u_{i1k}^{+} + z_{i1k_{opt}}^{+}) \le CA^{-} \tag{53}$$

Constraint on passive methods capacity:

$$\sum_{i=1}^{7}\sum_{k=1}^{3} (u_{i2k}^{+} + z_{i2k_{opt}}^{+}) + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{+} \times (u_{i1k}^{+} + z_{i1k_{opt}}^{+}) \le CP^{-} \tag{54}$$

Constraints on the allocation of workforce capacity:

$$\sum_{j=1}^{2} u_{ijk}^{+} = AW_{ik}^{+} - z_{ijk_{opt}}^{+}, \forall i, k. \tag{55}$$

$$0 \le u_{ijk}^{+} \le z_{ijk_{opt}}^{+}, \forall i, j, k. \tag{56}$$

h. Lower bound of non-standard employment

Objective function 1:

$$\text{Min} H_1^{-} = \sum_{i=1}^{7}\sum_{j=1}^{2}\sum_{k=1}^{3} z_{ijk}^{-} \times (IV_{ijk}^{-} + MO_{ijk}^{-}) + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{-} \times z_{i1k}^{-} \times OP_{i2k}^{-} - \sum_{i=1}^{7}\sum_{k=1}^{3} z_{i2k}^{-} \times EB_{i1k}^{+} \tag{57}$$

Constraint on active methods capacity:

$$\sum_{i=1}^{7}\sum_{j=1}^{2}\sum_{k=1}^{3} z_{ijk}^{-} < CA^{+} \tag{58}$$

Constraint on passive methods capacity:

$$\sum_{i=1}^{7}\sum_{k=1}^{3} z_{i2k}^{-} + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{-} \times z_{i1k}^{-} < CP^{+} \tag{59}$$

Constraints on the allocation of workforce capacity:

$$\sum_{j=1}^{2} z_{ijk}^{-} > AW_{ik}^{-}, \forall i, k. \tag{60}$$

$$z_{ijk}^{-} \ge 0, \forall i, j, k. \tag{61}$$

The optimal solution for objective function 1 is $z_{ijk_{opt}}^{+}$.

Objective function 2:

$$\text{Min} H_2^{-} = \sum_{i=1}^{7}\sum_{j=1}^{2}\sum_{k=1}^{3} u_{ijk}^{-} \times (IV_{ijk}^{-} + MO_{ijk}^{-}) + \sum_{i=1}^{7}\sum_{k=1}^{3} RA_{ik}^{-} \times u_{i1k}^{-} \times OP_{i2k}^{-} - \sum_{i=1}^{7}\sum_{k=1}^{3} u_{i2k}^{-} \times AR_{i1k}^{+} + \sum_{i=1}^{7}\sum_{k=1}^{3} (u_{i1k}^{-} + z_{i1k_{opt}}^{-}) \times RI_{i1k}^{-} \times LS_{ik}^{-} \tag{62}$$

Constraint on active methods capacity:

$$\sum_{i=1}^{7}\sum_{k=1}^{3} (u_{i1k}^{-} + z_{i1k_{opt}}^{-}) \le CA^{+} \tag{63}$$

Constraint on passive methods capacity:

$$\sum_{i=1}^{7}\sum_{k=1}^{3}(u_{i2k}^{-} + z_{i2k_{opt}}^{-}) + \sum_{i=1}^{7}\sum_{k=1}^{3}RA_{ik}^{-} \times (u_{i1k}^{-} + z_{i1k_{opt}}^{-}) \leq CP^{+} \tag{64}$$

Constraints on the allocation of workforce capacity:

$$\sum_{j=1}^{2}u_{ijk}^{-} = AW_{ik}^{-} - z_{ijk_{opt}}^{-}, \forall i,k. \tag{65}$$

$$0 \leq u_{ijk}^{-} \leq z_{ijk_{opt}}^{-}, \forall i,j,k. \tag{66}$$

As depicted in **Figure 2**, the crafted framework aimed at efficiently reinstating labor productivity amidst climate change encompasses four key components. These include the collection of socio-economic data, ensemble projections for future climate warming, computation of labor capacity reduction, and the formulation of optimal strategies for restoring labor productivity. The primary goal of this framework is to derive the most economically viable solution for mitigating the loss of working hours, and minimizing overall system costs across various climate change scenarios. Initially, an ensemble of projections from five GCMs under two RCP scenarios is amalgamated to examine climate modeling uncertainties and generate hourly time series data for heat stress. Subsequently, the empirical correlation between heat stress and labor capacity for each labor category is utilized to estimate potential future working hour losses. To formulate optimal adaptation strategies for productivity restoration, an interval programming model is employed. This model takes into account the distinctive features of both standard and non-standard employment. The study delves into the exploration of working overtime, a commonly employed active measure, and air conditioning, the prevalent passive adaptation option, within the context of a case study conducted in China. Notably, using more active measures like working overtime and expanding recruitment rather than air conditioners could result in more work injuries and related penalties or lawsuits (Schwatka et al., 2017). In this paper, costs for work injuries are incorporated into the modeling framework by referring to labor regulations and historical lawsuit settlements. The standard employment confers a range of labor protections including limits on working hours, redress in case of unjust dismissal, and a safe and healthy workplace. Therefore, employers from the standard employment situation tend to use both passive and active measures to secure the workplace with the least cost. In contrast, non-standard employment promises more flexibility and ownership to employees in exchange for such labor protections to save costs and avoid possible responsibilities. Under the non-standard employment situation, the employment relationship is blurred and substituted by a scheme of personal contracting for services. The self-employed person, as an independent contractor, is supposed to have full control of the working time which also means that he/she is not protected by the labor regulations. The self-employed person is forced by the online platform or the designed contract to work overtime. Due to legislative defects, there is no requirement from the employer side to secure the safety of the workplace for its contractors. The employer still has the dominant power of controlling the contractors while avoiding the costs of taking active or passive measures to compensate for working hours losses. However, an increasing number of lawsuits are filed against non-standard employment in China. Due to the blurred employment relationship, the self-employed person can get limited compensation from the work injury-related lawsuits which is the only way for them. Given the intricate nature of workforce dynamics and the unpredictability associated with labor and climate change, the suggested framework not only has the capability to assess the impact of global warming on labor productivity but also provides optimal solutions for decision-makers to address uncertainties and restore workforce efficiency.

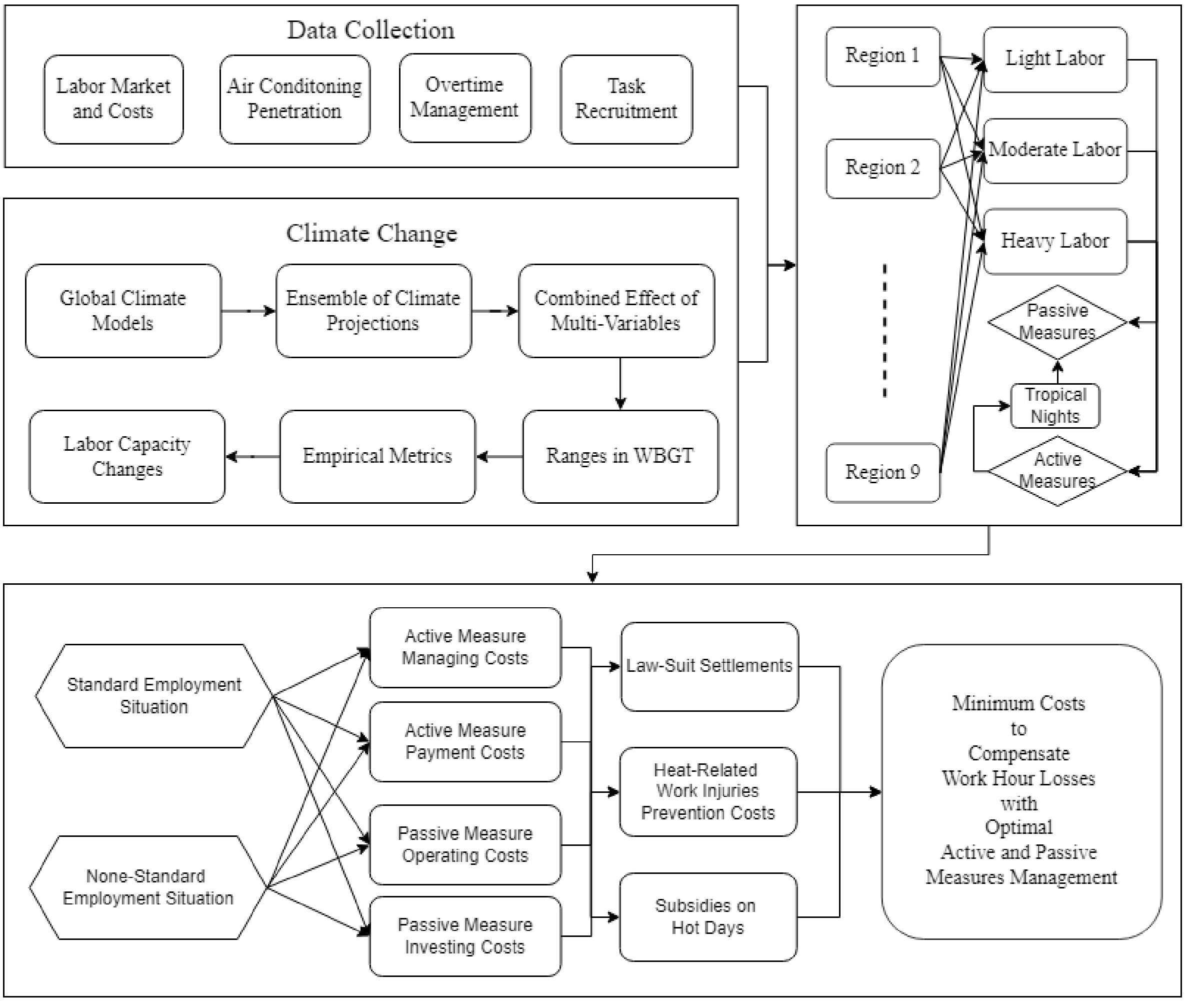

Figure 2. Flow chart for the integrated productivity restoration programming framework.

3. Results

3.1. Projection of heat stress and working hour losses

In **Figure 3**, the projected increase in Wet Bulb Globe Temperature (WBGT) across China is illustrated, derived from the General Circulation Model (GCM) ensemble for the conclusion of the 21st century, relative to the reference period under RCP8.5 (refer to supplementary information **Figure 4** for results under RCP2.6). Five distinct models predict varying magnitudes and spatial distributions of WBGT increase. Specifically, CSIRO-Mk3-6-0 and MIROC5 tend to indicate the smallest WBGT increase (exceeding 5 °C for most regions in China), while the remaining three models project an increase of up to 9 °C. The evidence is clear that heat stress is on the rise in China under both scenarios. Notably, there are considerable discrepancies in the spatial distribution of WBGT changes. Various models identify high-value and low-value centers in different locations with distinct coverage areas. In **Figure 4**, all models depict WBGT increases of more than 1 °C across China under RCP2.6, which is approximately 4 °C lower than the outcomes under RCP8.5. Despite these variations, the ensemble mean change in WBGT suggests an overall intensification of heat stress across the entire country under both RCP2.6 and RCP8.5.

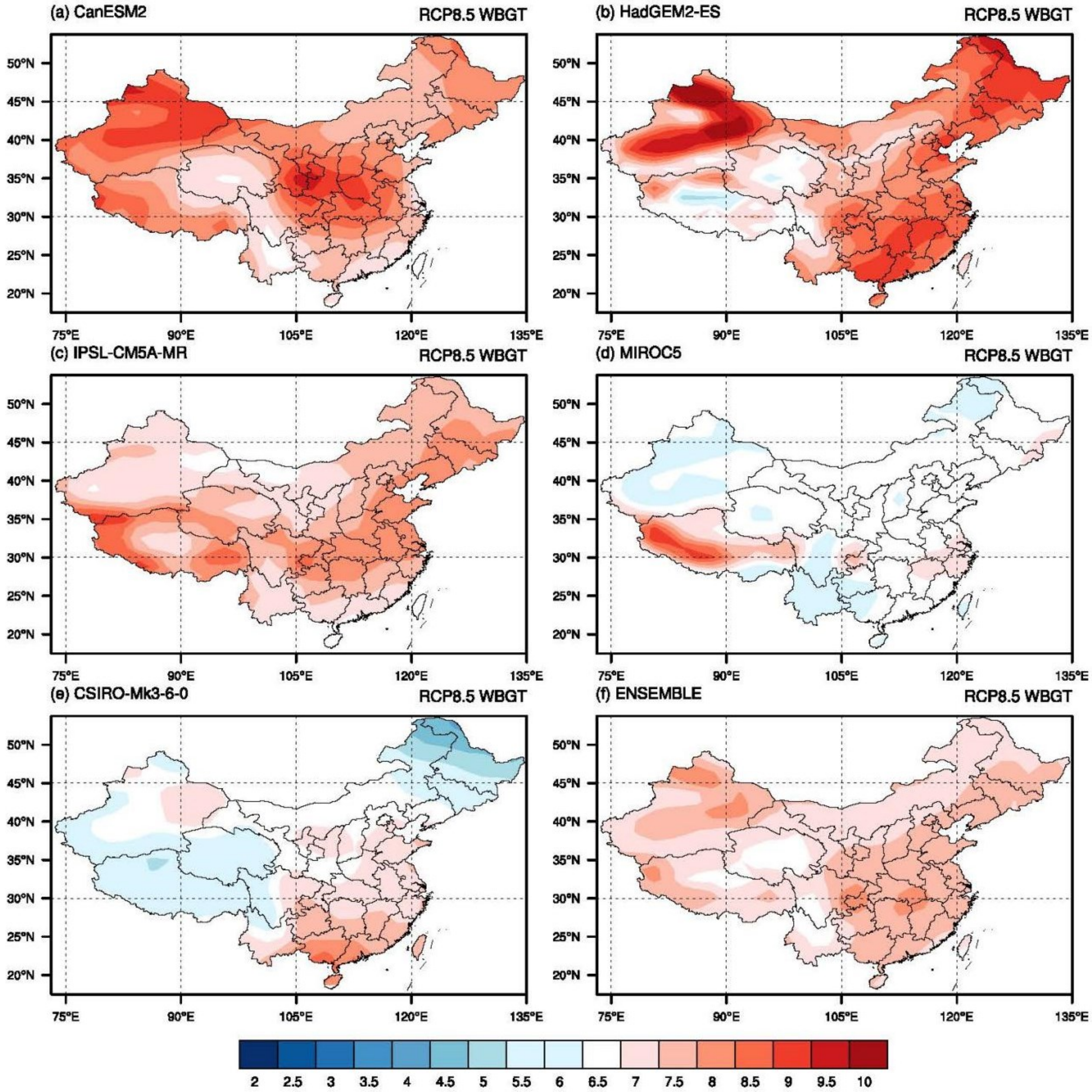

Figure 3. Projected changes in WBGT (°C) for five GCMs and their ensemble mean under RCP8.5 for the end of the 21st century relative to the reference period.

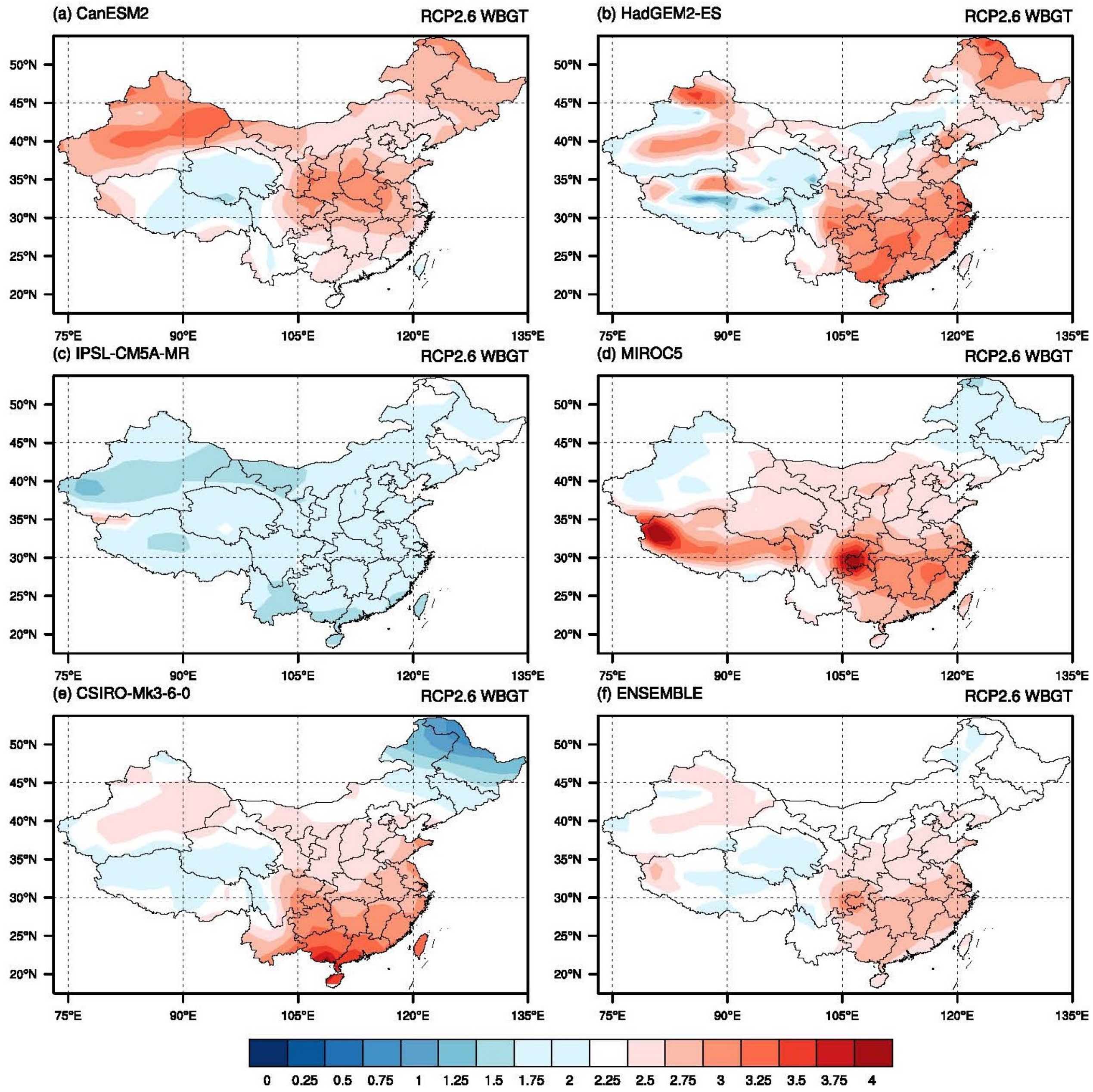

Figure 4. Projected changes in WBGT (°C) for five GCMs and the ensemble mean under RCP2.6 for the end of the 21st century relative to the baseline period.

The anticipated alterations in labor capacities across different intensity levels (light, moderate, and heavy) can be determined utilizing an empirical metric for the period spanning 2076 to 2100, relative to the baseline period. The reduction in labor capacity is subsequently utilized to compute the loss of working hours, accommodating a civilian worker population.

The associated working hour losses for the three labor types are approximated under RCP8.5 and depicted geographically in **Figures 5–7** (refer to **Figures 8–9** for results under RCP2.6). Significant declines in accumulated working hour losses are observed across light, moderate, and heavy labor categories under both RCPs by the close of the 21st century. The most substantial reduction occurs in the moderate labor level, while the least reduction is observed in the heavy labor level. However, this should not be misconstrued as indicating that the moderate level is the most susceptible to heightened heat stress. The greatest loss in working hours for the moderate labor level primarily stems from the proportion of civilian workers involved, rather than the highest sensitivity to increased heat stress. In **Figure 11**, the heavy labor level exhibits the lowest threshold (25 °C) for labor capacity reduction, followed by the moderate level (28 °C), and the light level (30 °C). Despite variations due to model uncertainty, moderate labor activities consistently experience the most significant reduction in annual working hour loss under both RCP2.6 and RCP8.5.

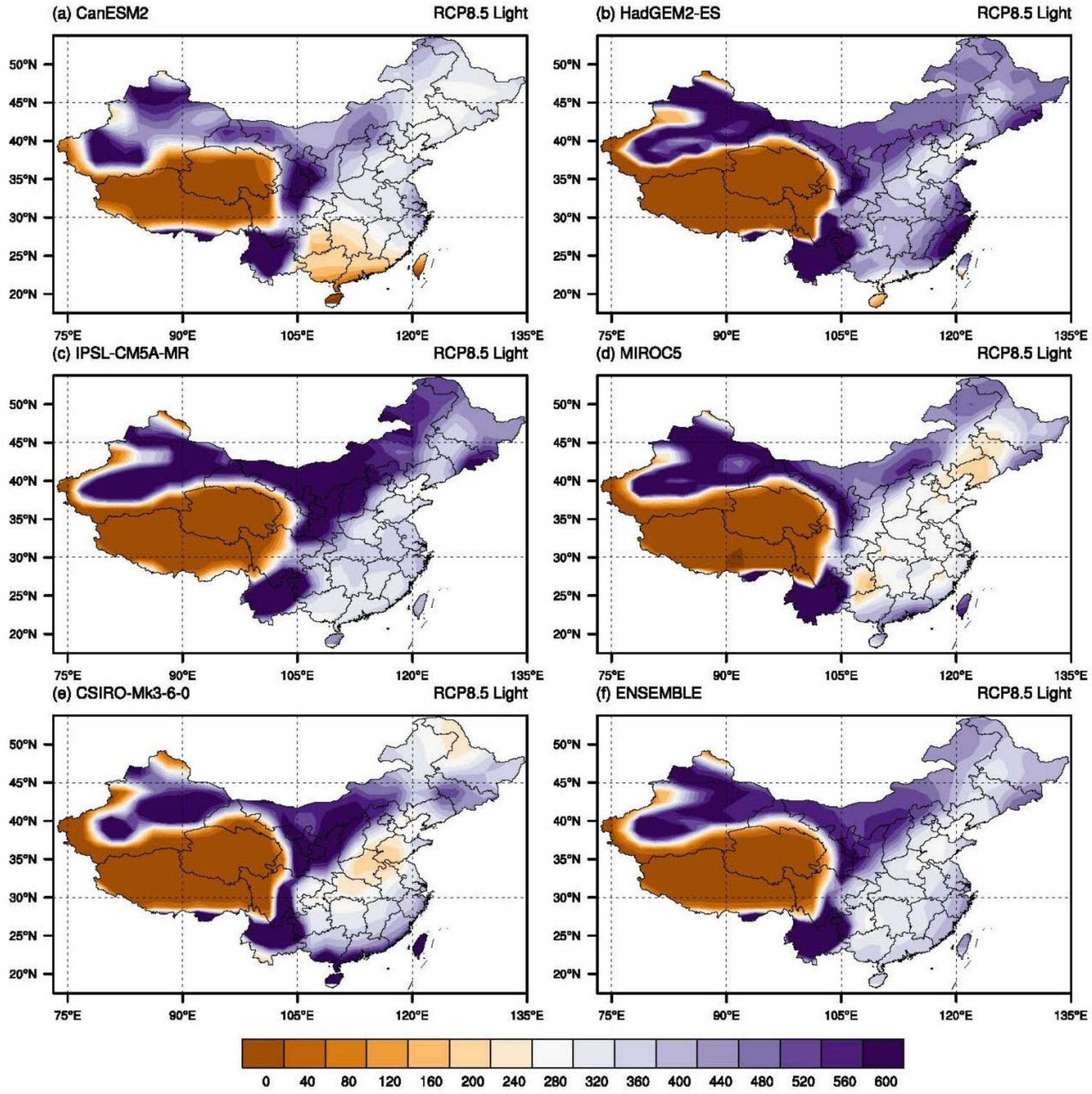

Figure 5. Projected working hour losses (hours) in light labor for five GCMs and ensemble mean under RCP8.5.

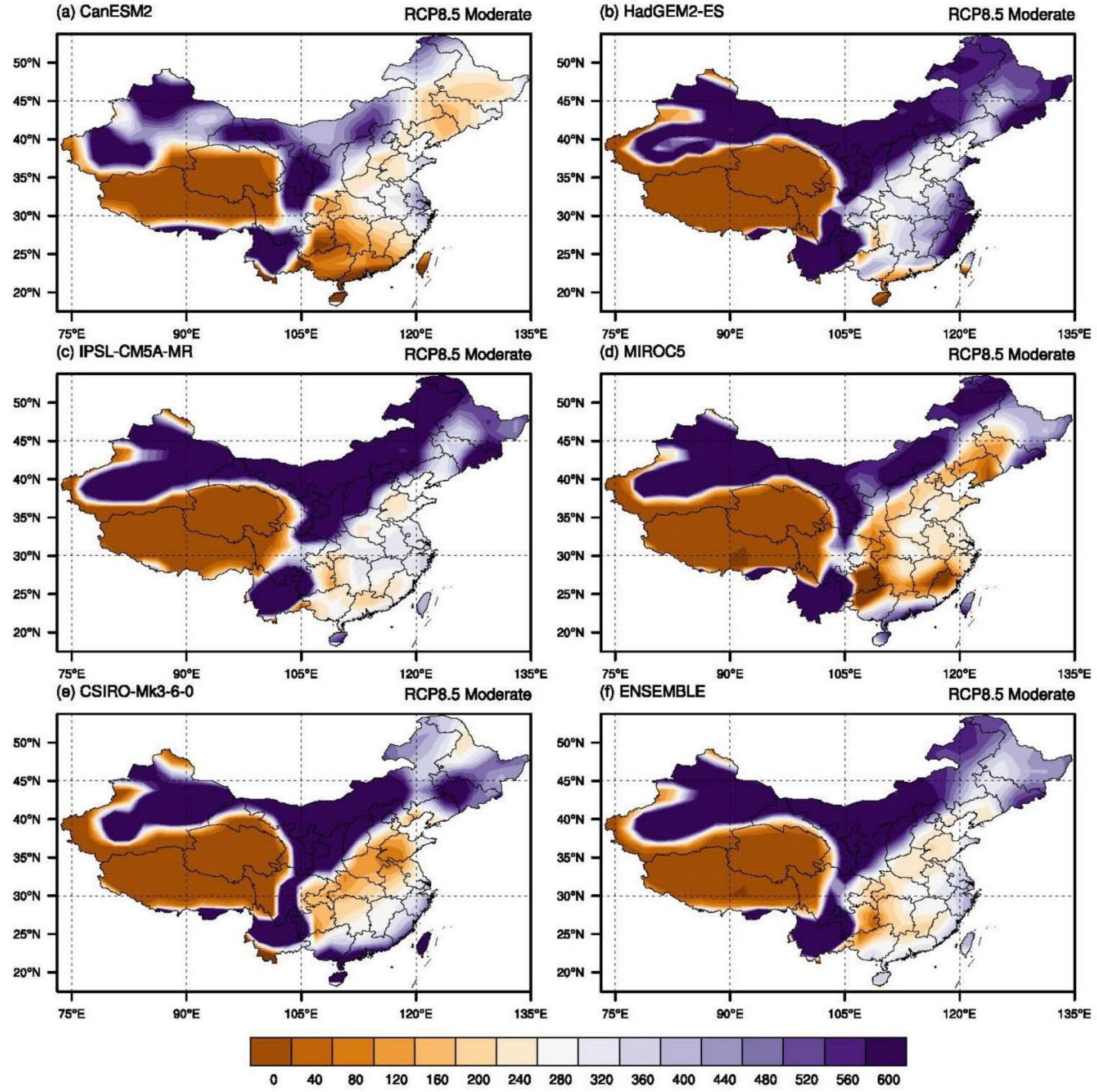

Figure 6. Projected working hour losses (hours) in moderate labor for five GCMs and ensemble mean under RCP8.5.

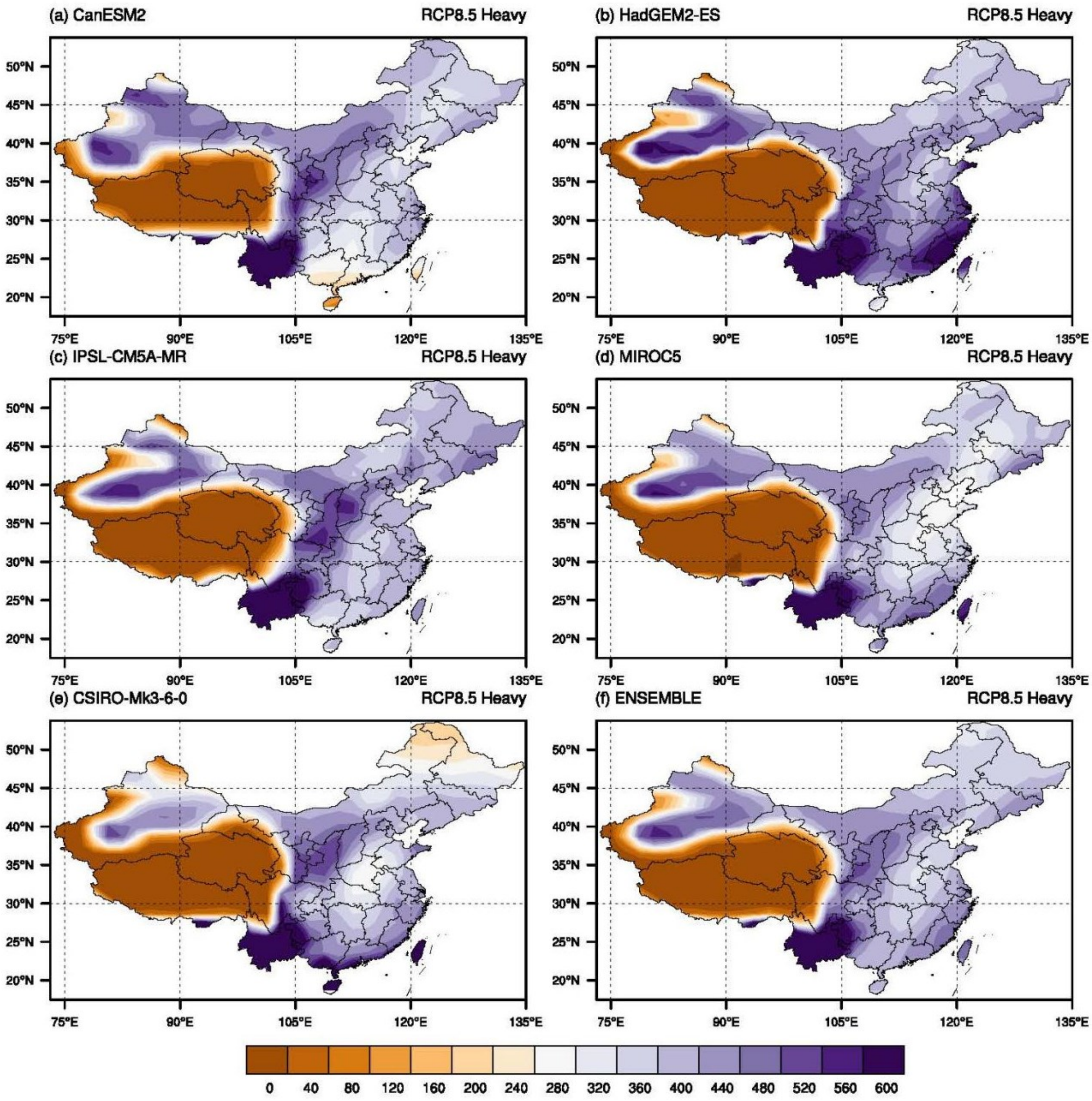

Figure 7. Projected working hour losses (hours) in heavy labor for five GCMs and ensemble mean under RCP8.5.

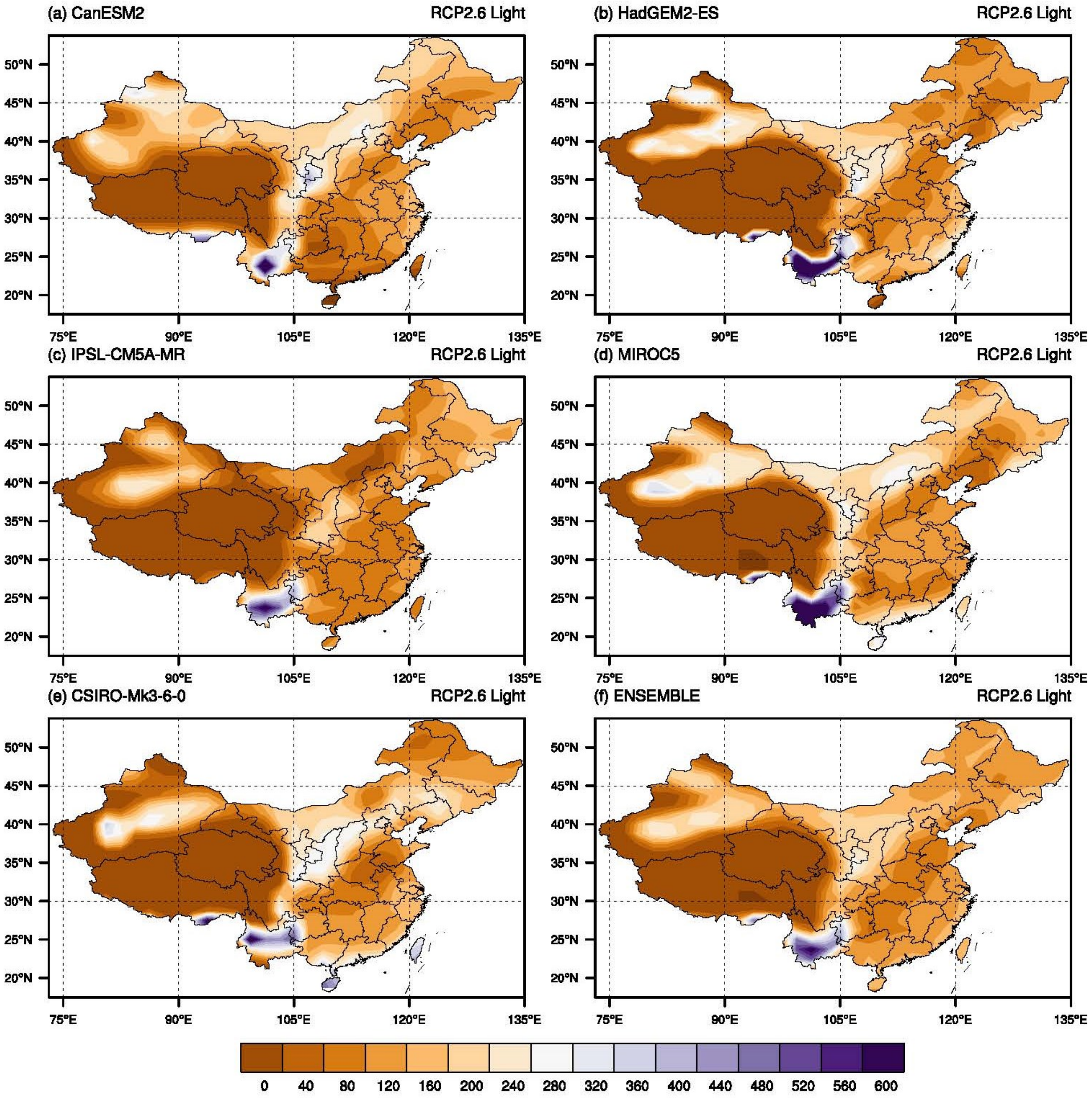

Figure 8. Projected working hour losses (hour) in light labor activity level for five GCMs and the ensemble mean under RCP2.6.

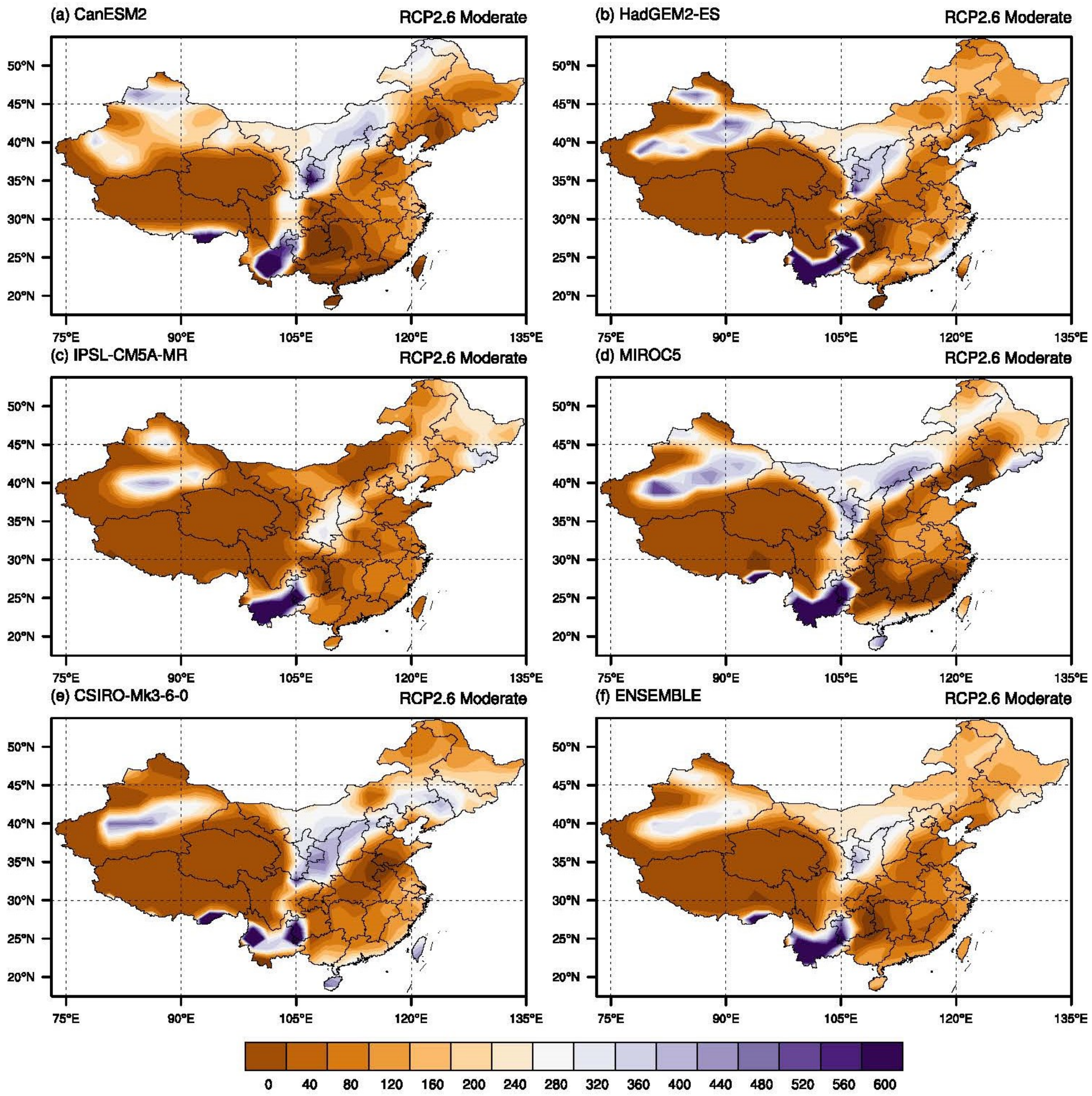

Figure 9. Projected working hour losses (hour) in moderate labor activity level for five GCMs and the ensemble mean under RCP2.6.

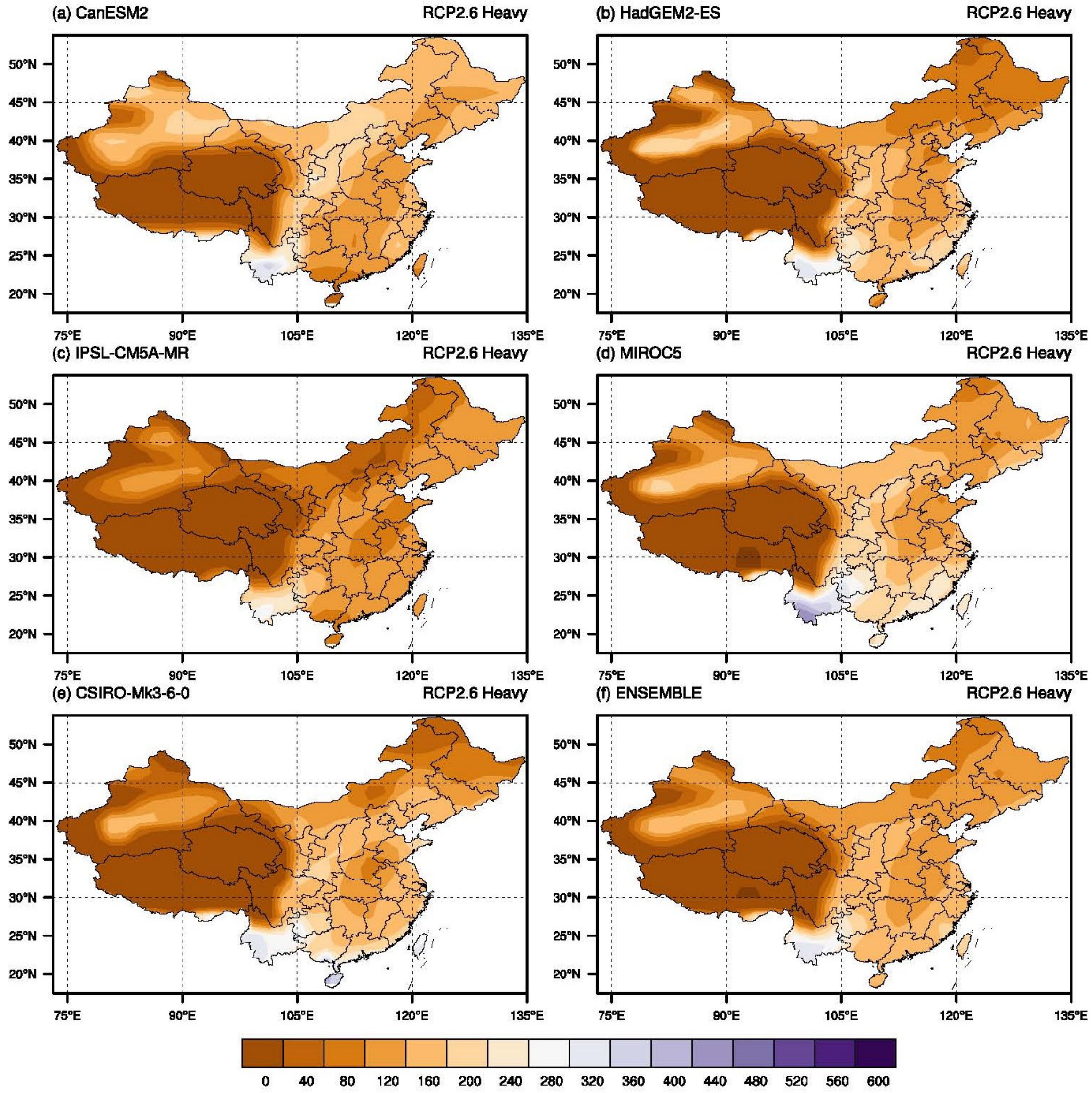

Figure 10. Projected working hour losses (hour) in heavy labor activity level for five GCMs and the ensemble mean under RCP2.6.

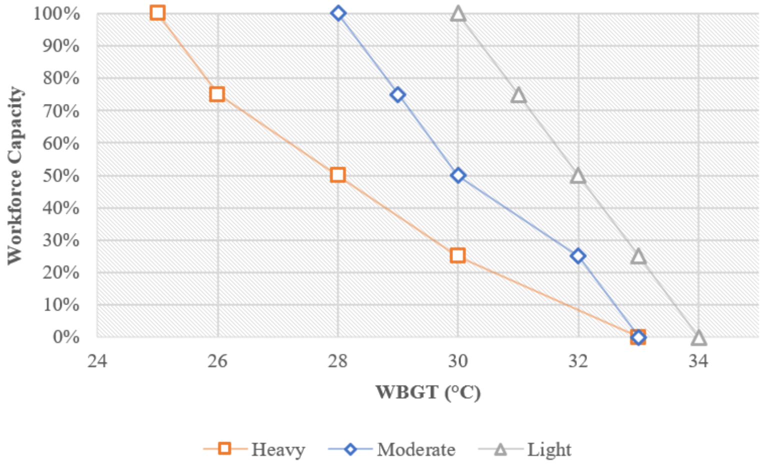

Figure 11. Labor capacity of individuals at different thresholds of the WBGT.

Across all five models, the minimal working hour loss is projected to be 40 hours annually in Tibet (region 3) for all three labor types under both RCPs. Conversely, the most substantial hour loss is expected in the Yunnan Province (region 9), surpassing 600 h annually. With the exception of the Yunnan Province, areas influenced by monsoons (regions 6, 7, 8, and 9) experience fewer working hour losses compared to inland regions (regions 1, 2, and 4) for all labor categories. This geographical contrast arises from the tendency of inland areas to have a smaller population of civilian workers, indicating an economic development imbalance. Despite variations induced by model uncertainty, the spatial distribution of working hour loss for a given labor level exhibits minimal differences across all GCMs, in contrast to the distribution of WBGT.

Table 3. Area-averaged intervals of working hour losses for three labor activity levels over nine regions under RCP2.6 and RCP8.5.

Regions	RCP2.6			RCP8.5		
	Moderate	Light	Heavy	Moderate	Light	Heavy
1	[108, 307]	[81, 222]	[61, 186]	[371, 714]	[282, 549]	[227, 411]
2	[135, 257]	[122, 204]	[81, 171]	[574, 811]	[480, 618]	[339, 474]
3	[0, 0]	[0, 0]	[0, 1]	[0, 12]	[0, 15]	[0, 16]
4	[85, 319]	[85, 226]	[66, 191]	[399, 736]	[405, 593]	[413, 440]
5	[0, 0]	[0, 0]	[0, 2]	[0, 14]	[0, 19]	[0, 22]
6	[115, 236]	[119, 172]	[103, 168]	[254, 512]	[325, 455]	[351, 438]
7	[93, 186]	[124, 167]	[130, 171]	[244, 453]	[304, 452]	[357, 462]
8	[74, 130]	[118, 148]	[123, 175]	[228, 466]	[304, 456]	[372, 453]
9	[149, 216]	[150, 223]	[150, 237]	[273, 654]	[357, 606]	[444, 585]

The combined simulations of multiple models produce a plausible spectrum of climate projections, allowing for an exploration of uncertainties inherent in climate models. This uncertainty permeates through the amalgamation of multi-model ensembles, empirical metrics, and the diverse workforce engaged in various occupations, resulting in varying ranges of working-hour losses across different employment scenarios. Regional area-averaged working hour loss ranges are determined and presented as intervals with defined lower and upper bounds for three labor types under both RCP2.6 and RCP8.5. **Table 3** illustrates that all upper bounds of working hour loss intervals in regions 3 and 5 are below 22 hours per year. These losses are deemed too minimal to be effectively addressed through systematic adaptation strategies. Consequently, the study concentrates on losses in the remaining seven regions, where adaptation options can be allocated to formulate optimal restoration plans. **Figure 12** depicts the projected lower and upper bounds of future working hour losses under RCP8.5 (results under RCP2.6 are displayed in **Figure 13**). Despite variations in labor activity levels, the ranges of working hour losses under RCP2.6 are comparatively smaller than those under RCP8.5 for the seven focal regions. This suggests that proactive measures to mitigate climate change can narrow the range of working hour losses. It is important to note that, irrespective of labor activity levels, the ranges of working hour losses under RCP2.6 are generally smaller than those under

RCP8.5 for the seven focal regions. This indicates that the range of working hour losses can be reduced through aggressive actions to mitigate climate change. Notably, losses associated with moderate activity levels exhibit larger ranges than the other two levels in most regions under both RCPs. Therefore, when formulating strategies to adapt to working hour losses amid uncertainty, special attention should be directed towards moderate labor activities.

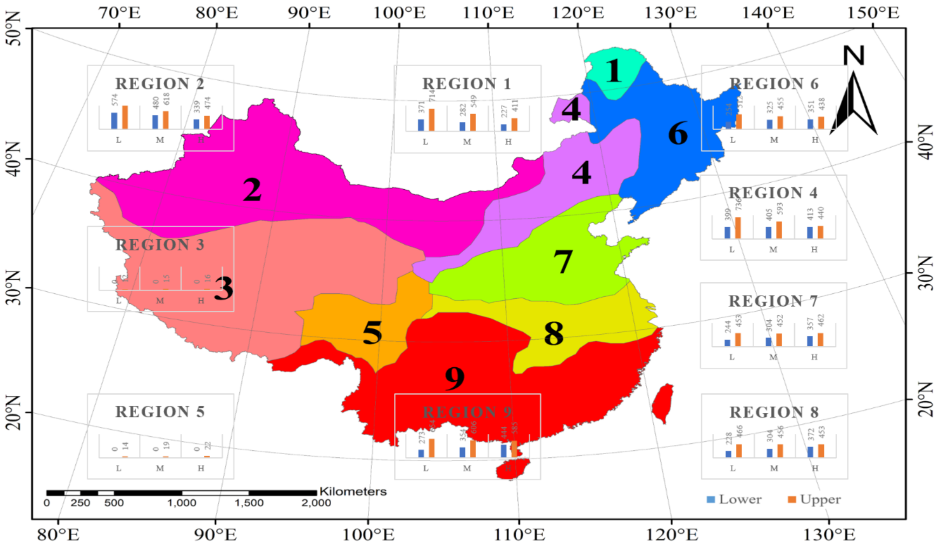

Figure 12. Ranges between the lower and upper bounds of future working hour losses for three labor types over nine regions under RCP8.5.

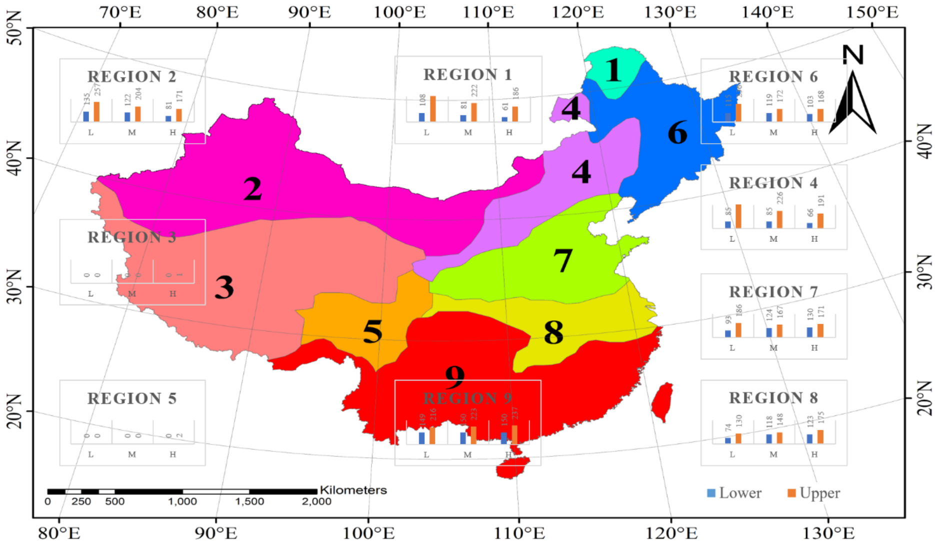

Figure 13. Ranges of the lower and upper bounds of future working hour losses for three labor activity levels over nine regions under RCP2.6.

3.2. Optimal labor productivity restoration under uncertainty

Regions 7, 8, and 9 have high costs for active measures like working overtime because of expensive labor markets (as shown in **Table 4**). Since there is no distinct difference in the electricity consumption rate and prices of air conditioners among all regions, the capital investments for passive measures are most linked to the air-conditioning penetration rate. A low penetration rate would indicate a lack of air conditioners and high costs for application expansion. Regions with underdeveloped economies and cooler climates, such as areas 1, 2, 4, and 6, exhibit lower air-conditioning penetration rates. Consequently, these regions experience higher capital investments in adapting to the escalating heat stress induced by climate change. Additionally, a low penetration rate suggests the potential for increased work-related injuries during exceptionally hot days and nights. Both standard and non-standard employments can mitigate working hour losses through various combinations of active and passive measures. By accounting for capacity constraints in these measures, optimal solutions within specific intervals can be derived by solving the objective function for a productivity restoration system in the interval programming model, while considering inherent uncertainties. Please consult the Supplementary Information for a detailed explanation of the solving procedure for the interval programming model applied to productivity restoration.

Table 4. Costs for using passive and active measures to restore productivity over seven regions for the baseline period.

Regions	**Labor Levels**	**Passive Measures (10^6 \$/hr)**		**Active Measures (10^6 \$/hr)**		**Subsidy (10^6 \$/hr)**	**Lawsuit Settlements (10^5 \$/hr)**
		Non-Standard	**Standard**	**Non-Standard**	**Standard**		
1	Moderate	[34.4, 39.3]	[2.2, 4.7]	[5.3, 7.0]	[14.2, 17.2]	[0, 0]	[0.1, 0.4]
	Light	[33.8, 37.8]	[1.6, 3.4]	[4.7, 6.1]	[10.1, 14.4]	[0, 0]	[0.1, 0.4]
	Heavy	[30.1, 34.1]	[0.3, 1.8]	[2.7, 5.5]	[8.7, 12.1]	[0, 0]	[0.1, 0.4]
2	Moderate	[50.4, 55.3]	[4.4, 7.5]	[10.6, 12.4]	[23.2, 26.1]	[2.6, 5.0]	[0.6, 0.7]
	Light	[41.3, 45.7]	[4.8, 6.7]	[9.8, 12.3]	[19.3, 22.7]	[2.6, 5.0]	[0.5, 0.7]
	Heavy	[41.2, 45.9]	[2.8, 4.9]	[7.7, 10.0]	[17.0, 20.6]	[2.6, 5.0]	[0.7, 0.9]
4	Moderate	[46.2, 50.9]	[7.6, 9.7]	[11.9, 13.1]	[27.9, 33.4]	[1.7, 2.0]	[1.0, 1.2]
	Light	[44.3, 49.0]	[4.8, 6.7]	[10.3, 12.7]	[24.0, 27.7]	[1.7, 2.0]	[0.8, 1.0]
	Heavy	[38.3, 42.8]	[2.8, 3.7]	[9.2, 11.9]	[20.8, 25.0]	[1.8, 2.0]	[1.1, 1.4]
6	Moderate	[42.2, 46.8]	[8.4, 10.3]	[11.7, 13.8]	[40.0, 42.9]	[2.0, 2.4]	[1.4, 1.7]
	Light	[40.5, 45.8]	[5.2, 7.4]	[11.5, 13.1]	[35.1, 40.0]	[2.0, 2.4]	[0.9, 1.3]
	Heavy	[40.3, 44.1]	[5.8, 6.8]	[10.3, 11.5]	[33.4, 36.5]	[2.6, 3.0]	[2.6, 3.0]
7	Moderate	[54.2, 58.9]	[10.3, 12.3]	[14.5, 18.4]	[51.9, 57.0]	[1.0, 1.6]	[2.2, 4.5]
	Light	[43.6, 48.5]	[7.5, 9.2]	[14.7, 18.2]	[51.8, 55.2]	[1.0, 1.6]	[1.0, 3.7]
	Heavy	[39.9, 44.8]	[6.3, 7.8]	[11.8, 14.2]	[48.0, 53.4]	[1.6, 2.0]	[4.0, 8.2]
8	Moderate	[55.0, 60.1]	[9.5, 11.8]	[14.1, 17.5]	[53.2, 57.0]	[1.6, 1.8]	[1.9, 4.0]
	Light	[52.1, 56.5]	[6.5, 10.0]	[15.3, 19.1]	[51.8, 55.6]	[1.2, 1.6]	[1.1, 2.6]
	Heavy	[43.6, 47.3]	[5.9, 7.6]	[11.9, 15.9]	[51.1, 56.4]	[1.8, 2.0]	[2.8, 5.2]
9	Moderate	[59.4, 63.8]	[11.8, 14.7]	[15.3, 19.2]	[67.0, 70.0]	[1.2, 1.6]	[2.0, 4.1]
	Light	[53.3, 58.4]	[8.8, 10.6]	[17.2, 21.0]	[62.2, 66.0]	[1.2, 1.6]	[1.4, 3.0]
	Heavy	[45.8, 49.7]	[7.8, 9.0]	[12.4, 15.0]	[57.2, 61.5]	[2.2, 2.6]	[3.7, 4.5]

Tables 5 and **6** present the optimal solutions for restoring labor productivity at minimal costs in both standard and non-standard employment scenarios under two RCP scenarios. The objective function, constraints, and decision variables are

articulated in interval form. Decision alternatives interact with the costs of adaptation measures and constraints related to processing capacities for three labor types in both RCPs. In the proposed interval programming model, the sub-models for *y*^- and *y*^+ aim to establish the lower and upper bounds of the system cost, respectively, within a specific scenario. Solving the objective function of the interval programming model yields total system costs ranging from 126,195 to 248,700 million dollars under RCP2.6 and from 372,284 to 697,073 million dollars under RCP8.5 for standard employment. For non-standard employment, total system costs range from 109,813 to 244,481 million dollars under RCP2.6 and from 353,616 to 688,583 million dollars under RCP8.5. Notably, the total system cost of non-standard employment is consistently lower than that of standard employment for both lower and upper bounds under both RCPs. Optimal solutions become deterministic when the lower and upper bounds are equal, indicating that decision variables are insensitive to model uncertainty. A wider range between the lower and upper bounds suggests greater sensitivity of decision variables to uncertainty. The high emission scenario amplifies uncertainty in the integrated productivity restoration approach.

Table 5. Optimal solutions to compensate working hour losses with minimum cost in the standard employment situation for seven regions under RCP2.6 and RCP8.5.

Regions	Scenarios	Passive Measures (hr)			Active Measures (hr)		
		Moderate	Light	Heavy	Moderate	Light	Heavy
1	RCP2.6	[108, 307]	[81, 222]	[61, 186]	[22, 61]	[16, 44]	[12, 37]
	RCP8.5	[371, 714]	[282, 549]	[227, 411]	[74, 143]	[56, 110]	[45, 82]
2	RCP2.6	[122, 204]	[81, 171]	[135, 257]	[24, 41]	[16, 34]	[27, 51]
	RCP8.5	[574, 811]	[480, 618]	[339, 474]	[114, 162]	[115, 162]	[68, 95]
4	RCP2.6	[85, 319]	[85, 226]	[66, 191]	[17, 64]	[17, 45]	[13, 38]
	RCP8.5	[399, 643]	[405, 593]	[413, 440]	[80, 129]	[81, 119]	[83, 88]
6	RCP2.6	[115, 236]	[119, 172]	[103,168]	[23, 47]	[24, 34]	[21, 34]
	RCP8.5	[254, 512]	[325, 455]	[351, 438]	[51, 102]	[65, 91]	[70, 88]
7	RCP2.6	[93, 186]	[124, 167]	[130, 171]	[19, 37]	[25, 33]	[26, 34]
	RCP8.5	[244, 453]	[304, 452]	[357, 462]	[49, 91]	[61, 90]	[71, 92]
8	RCP2.6	[74, 130]	[118, 148]	[123, 175]	[15, 26]	[24, 30]	[25, 35]
	RCP8.5	[228, 466]	[304, 456]	[372, 453]	[46, 93]	[61, 91]	[74, 91]
9	RCP2.6	[149, 216]	[150, 223]	[150, 237]	[30, 43]	[30, 45]	[30, 47]
	RCP8.5	[273, 654]	[354, 606]	[444, 585]	[55, 131]	[71, 121]	[89, 117]

In standard employment scenarios, more working hour losses are allocated to passive measures than active measures across all three labor activity levels in seven regions. Conversely, in non-standard employment scenarios, more losses are addressed through active measures than passive measures. It remains consistent in standard employment that more hours are allocated to passive measures than active measures when the working hour loss is below the measures' processing limitation. When the number of hours exceeds the capacity of passive measures, more hours are allocated to active measures across all three labor activity levels under both RCPs.

Notably, the cost of active measures is relatively lower than that of passive measures for non-standard employment. Because employers reduce labor costs to a large extent by avoiding employment protection rights with ambiguities surrounding the distinction between employees and self-employed in the labor law. Without a clear employment status, self-employed individuals have limited entitlements to a safe working environment from their employers. They are forced to use active measures rather than passive measures when working environment hazards appear.

Table 6. Optimal solutions to compensate working hour losses with minimum cost in the non-standard employment situation for seven regions under RCP2.6 and RCP8.5.

Regions	Scenarios	Passive Measures (hr)			Active Measures (hr)		
		Moderate	Light	Heavy	Moderate	Light	Heavy
1	RCP2.6	[19, 54]	[15, 43]	[10, 37]	[90, 251]	[65, 178]	[50, 150]
	RCP8.5	[70, 135]	[48, 99]	[38, 77]	[306, 577]	[234, 453]	[188, 340]
2	RCP2.6	[23, 35]	[15, 29]	[25, 44]	[101, 169]	[66, 138]	[109, 213]
	RCP8.5	[114, 137]	[113, 153]	[61, 87]	[458, 652]	[476, 674]	[273, 394]
4	RCP2.6	[15, 55]	[15, 42]	[12, 37]	[70, 265]	[70, 182]	[53, 156]
	RCP8.5	[80, 120]	[71, 113]	[80, 74]	[320, 518]	[337, 481]	[343, 355]
6	RCP2.6	[22, 44]	[22, 32]	[18, 28]	[95, 195]	[99, 143]	[85, 136]
	RCP8.5	[49, 91]	[62, 91]	[61, 79]	[207, 424]	[268, 376]	[287, 355]
7	RCP2.6	[16, 32]	[22, 31]	[23, 30]	[75, 151]	[103, 138]	[106, 137]
	RCP8.5	[45, 78]	[54, 86]	[66, 87]	[199, 364]	[252, 375]	[296, 384]
8	RCP2.6	[13, 22]	[23, 29]	[25, 35]	[60, 104]	[95, 122]	[99, 141]
	RCP8.5	[45, 89]	[51, 80]	[63, 85]	[190, 385]	[248, 367]	[306, 373]
9	RCP2.6	[26, 36]	[28, 38]	[28, 41]	[124, 180]	[123, 183]	[123, 193]
	RCP8.5	[51, 117]	[67, 117]	[82, 105]	[220, 538]	[288, 499]	[362, 478]

4. Discussions

Every employment scenario exhibits a unique inclination towards mitigating working hour deficits attributed to cost differentials in the implementation of adaptation measures. In the chosen employment context, areas characterized by varying air-conditioning penetration rates and advancements generally seek to recover their working hour losses, displaying no specific preference for adaptation options across all three levels of labor activities. This is because differences in costs for applying passive measures and active measures are not diverse enough to cause a distinct geographical pattern in productivity restoration. While the inland regions, characterized by lower levels of development, experience greater reductions in working hours compared to the monsoon-affected areas, which are more developed, they typically adopt similar adaptation strategies in specific employment scenarios. The expenses associated with preventing and compensating for work-related injuries and fatalities are not factored in, primarily attributed to the absence of health data in the study area. Nevertheless, the number of work injuries is expected to increase because of long-time exposure to heat stress. The self-employed from non-standard employment are more directly exposed to heat stress than the workers from standard employment since non-standard employment avoids obligations of providing safety in the working environment. For the same increment in the WBGT, the self-employed would be more likely exposed to extreme heat days than the worker. It makes the self-employed suffer more from health-related problems in the workplace than those workers from standard employment. We highlight that the non-standard employment situation has the preference for using active measures rather than passive measures to restore productivity due to the relatively low labor costs. Lack of education on occupational safety and awareness of entitlements to protection rights, the self-employed or independent contractors are more vulnerable to work environment hazards than those workers from standard employment. With intensified heat stress, it is foreseeable that there will be more work injuries happening under non-standard employment situations than under standard employment situations. Plus, most non-standard employment are taking place in urban areas where the "heat island effect" combined with climate warming could make the work environment less bearable and further reduce labor productivity. Given the escalating requirements for labor and developmental imperatives, there is an urgent call for action in China to promptly implement measures to pre-empt unfavorable scenarios. This involves crafting comprehensive strategies to restore labor productivity systematically and addressing the progression of climate warming. Specifically, it is imperative for the policymakers to develop comprehensive adaptation policy frameworks that take into account the differential impacts of climate change on standard and non-standard employment sectors. And the government should compel employers engaged in non-standard employment to fulfill their legal obligations in upholding occupational safety standards, thereby diminishing the likelihood of workplace injuries. Businesses, especially those engaged in non-standard employment, are also obligated to cultivate employees' awareness of heat stress risks and use passive measures to preserve employees' health, thus enhancing their social responsibility profile and labor productivity. For other stakeholders, such as NGOs and industry associations, supporting local cooling infrastructure projects and establishing community shelters will be strategic moves that underpin the protection of vulnerable groups from heat stress during work hours, and foster a proactive societal stance towards the challenges of climate change.

5. Conclusions

A modeling framework has been developed to address the reduction in labor productivity caused by climate change, employing optimization techniques to minimize the risk of plagiarism detection. This framework focuses on exploring the influence of labor relations on productivity restoration. It incorporates a multiple GCMs ensemble, empirical metrics for labor capacity, and interval programming models to establish a robust, long-term strategy for productivity restoration in the face of uncertainty. To calculate robust projections of WBGT under RCPs 2.6 and 8.5, the daily time series of air temperature and relative humidity from a GCMs ensemble is utilized. Subsequently, the daily WBGT values are employed to estimate changes in labor productivity based on empirical metrics linking heat stress and labor capacity. Furthermore, an interval programming model is formulated to examine the impact of both standard and non-standard employment on achieving optimal adaptation strategies. This addresses the uncertainty inherent in heat stress projections and labor capacity estimations. The proposed framework offers several advantages, including (i) quantifying the effects of heat stress on labor productivity; (ii) effectively incorporating diverse uncertain information from climate projections, empirical estimations, and limited observations into systems analysis; (iii) systematically comparing different labor relations' logic to implement adaptation options and achieve minimal system costs; (iv) assisting decision-makers in identifying cost-effective adaptation strategies to offset climate change-induced reductions in labor productivity.

In light of growing concerns surrounding employment, particularly non-standard employment, in China, the proposed framework has been employed to assess the impact of labor relations on productivity. It aims to devise optimal adaptation strategies in response to climate change. Projections indicate that by 2100, the anticipated rise in heat stress will result in diminished labor capacity across China, with the exception of the Tibetan Plateau, under both RCP scenarios. The most significant reduction is observed in moderate labor, while the least is in heavy labor. The primary source of working hour loss in moderate labor is attributed to civilian workers' participation rates. Utilizing an interval programming model with uncertain parameters and constraints, total system costs for allocating working hour losses to adaptation options are determined based on robust projections from a multi-model ensemble. Solving the objective function of the interval programming model yields total system costs of [126,195 to 248,700] million dollars under RCP2.6 and [372,284 to 697,073] million dollars under RCP8.5 for standard employment. For non-standard employment, total system costs are [109,813 to 244,481] million dollars under RCP2.6 and [353,616 to 688,583] million dollars under RCP8.5, with the cost of non-standard employment being lower than standard employment for both lower and upper bounds. It's crucial to note that each employment situation has its preference in addressing working hour losses due to cost disparities in implementing adaptation options. Under non-standard employment, active measures account for a higher proportion of losses compared to passive measures, as the relatively lower cost of active measures allows employers to circumvent safety obligations in the working environment. Self-employed individuals are anticipated to face more health-related challenges in the workplace than standard employees. With heightened heat stress, an increase in work injuries is foreseeable under non-standard employment compared to standard employment. Given the escalating labor demands and development needs, urgent action is required to implement aggressive mitigation and adaptation measures. This involves designing systematic strategies to restore labor productivity and alleviate the impact of climate warming.

It is important to acknowledge the presence of several limitations in our study. For example, the estimation of the impact of labor relations on labor productivity relies on simplified functions developed with a restricted set of data. A more comprehensive investigation should be undertaken, taking into account factors such as outdoor/indoor activity, the proportion of acclimated/unacclimated workers, adaptation effectiveness, age, sex, and other relevant variables. For the above potential uncertainties, we have carefully selected and reviewed critical parameters and validation data within the proposed framework, ensuring their reasonableness and alignment with real-world conditions through thorough validation procedures. For other uncertainties present in this paper, such as the uncertainty in the climate models variability, emission scenarios, and implementing adaptation measuresthe uncertainty in implementing adaptation measures, we performed a thorough data analysis by using the combined simulations of multiple models and interval programming models, to reduce these uncertainties and ensure that our analysis is sufficiently reliable. Furthermore, the study of the relationship between hot extremes and work injuries is omitted due to the relatively coarse resolution of the GCMs.

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References

Bastian, N. D., Lunday, B. J., Fisher, C. B., et al. (2020). Models and methods for workforce planning under uncertainty: Optimizing U.S. Army cyber branch readiness and manning. Omega, 92, 102171. https://doi.org/10.1016/j.omega.2019.102171

Borba, B. S. M. C., Fortes, M. Z., Bitencourt, L. A., et al. (2019). A review on optimization methods for workforce planning in electrical distribution utilities. Computers & Industrial Engineering, 135, 286–298. https://doi.org/10.1016/j.cie.2019.06.002

Borg, M. A., Xiang, J., Anikeeva, O., et al. (2021). Occupational heat stress and economic burden: A review of global evidence. Environmental Research, 195, 110781. https://doi.org/10.1016/j.envres.2021.110781

Chen, Y., Guo, F., Wang, J. et al. (2020). Provincial and gridded population projection for China under shared socioeconomic pathways from 2010 to 2100. Scientific Data, 7, 83. https://doi.org/10.1038/s41597-020-0421-y

Chen, C. H., Yan, S., & Chen, M. (2010). Short-term manpower planning for MRT carriage maintenance under mixed deterministic and stochastic demands. Annals of Operations Research, 181(1), 67–88. https://doi.org/10.1007/s10479-010-0689-y

China National Bureau of Statistics. (2021). China Statistics Yearbook. China Statistics Press.

Day, E., Fankhauser, S., Kingsmill, N., et al. (2018). Upholding labour productivity under climate change: an assessment of adaptation options. Climate Policy, 19(3), 367–385. https://doi.org/10.1080/14693062.2018.1517640

De Feyter, T., Guerry, M. A., & Komarudin. (2016). Optimizing cost-effectiveness in a stochastic Markov manpower planning system under control by recruitment. Annals of Operations Research, 253(1), 117–131. https://doi.org/10.1007/s10479-016-2311-4

Di Francesco, M., Díaz-Maroto Llorente, N., Zanda, S., et al. (2016). An optimization model for the short-term manpower planning problem in transhipment container terminals. Computers & Industrial Engineering, 97, 183–190.

https://doi.org/10.1016/j.cie.2016.04.012

Dimitriou, V. A., & Georgiou, A. C. (2019). Introduction, analysis and asymptotic behavior of a multi-level manpower planning model in a continuous time setting under potential department contraction. Communications in Statistics—Theory and Methods, 50(5), 1173–1199. https://doi.org/10.1080/03610926.2019.1648827

Fischereit, J., & Schlünzen, K. H. (2018). Evaluation of thermal indices for their applicability in obstacle-resolving meteorology models. International Journal of Biometeorology, 62(10), 1887–1900. https://doi.org/10.1007/s00484-018-1591-6

Foley, M. (2017). Factors underlying observed injury rate differences between temporary workers and permanent peers. American Journal of Industrial Medicine, 60(10), 841–851. https://doi.org/10.1002/ajim.22763

Gao, C., Kuklane, K., Östergren, P. O., et al. (2017). Occupational heat stress assessment and protective strategies in the context of climate change. International Journal of Biometeorology, 62(3), 359–371. https://doi.org/10.1007/s00484-017-1352-y

Hatvani-Kovacs, G., Belusko, M., Skinner, N., et al. (2016). Drivers and barriers to heat stress resilience. Science of The Total Environment, 571, 603–614. https://doi.org/10.1016/j.scitotenv.2016.07.028

Kjellstrom, T., Freyberg, C., Lemke, B., et al. (2017). Estimating population heat exposure and impacts on working people in conjunction with climate change. International Journal of Biometeorology, 62(3), 291–306. https://doi.org/10.1007/s00484-017-1407-0

Lan, T., Goh, Y. M., Jensen, O., et al. (2022). The impact of climate change on workplace safety and health hazard in facilities management: An in-depth review. Safety Science, 151, 105745. https://doi.org/10.1016/j.ssci.2022.105745

Liu, X., Tang, Q., Zhang, X., et al. (2018). Projected Changes in Extreme High Temperature and Heat Stress in China. Journal of Meteorological Research, 32(3), 351–366. https://doi.org/10.1007/s13351-018-7120-z

Lohrey, S., Chua, M., Gros, C., et al. (2021). Perceptions of heat-health impacts and the effects of knowledge and preventive actions by outdoor workers in Hanoi, Vietnam. Science of The Total Environment, 794, 148260. https://doi.org/10.1016/j.scitotenv.2021.148260

Ma, R., Zhong, S., Morabito, M., et al. (2019). Estimation of work-related injury and economic burden attributable to heat stress in Guangzhou, China. Science of The Total Environment, 666, 147–154. https://doi.org/10.1016/j.scitotenv.2019.02.201

Matsumoto, K. (2019). Climate change impacts on socioeconomic activities through labor productivity changes considering interactions between socioeconomic and climate systems. Journal of Cleaner Production, 216, 528–541. https://doi.org/10.1016/j.jclepro.2018.12.127

Nunfam, V. F., Adusei-Asante, K., Van Etten, E. J., et al. (2018). Social impacts of occupational heat stress and adaptation strategies of workers: A narrative synthesis of the literature. Science of The Total Environment, 643, 1542–1552. https://doi.org/10.1016/j.scitotenv.2018.06.255

Nunfam, V. F., Oosthuizen, J., Adusei-Asante, K., et al. (2019). Perceptions of climate change and occupational heat stress risks and adaptation strategies of mining workers in Ghana. Science of The Total Environment, 657, 365–378. https://doi.org/10.1016/j.scitotenv.2018.11.480

Pogačar, T., Casanueva, A., Kozjek, K., et al. (2018). The effect of hot days on occupational heat stress in the manufacturing industry: implications for workers' well-being and productivity. International Journal of Biometeorology, 62(7), 1251–1264. https://doi.org/10.1007/s00484-018-1530-6

Schwatka, N. V., Atherly, A., Dally, M. J., et al. (2016). Health risk factors as predictors of workers' compensation claim occurrence and cost. Occupational and Environmental Medicine, 74(1), 14–23. https://doi.org/10.1136/oemed-2015-103334

Shakerian, S., Habibnezhad, M., Ojha, A., et al. (2021). Assessing occupational risk of heat stress at construction: A worker-centric wearable sensor-based approach. Safety Science, 142, 105395. https://doi.org/10.1016/j.ssci.2021.105395

Wang, S., & Zhu, J. (2019). Amplified or exaggerated changes in perceived temperature extremes under global warming. Climate Dynamics, 54(1–2), 117–127. https://doi.org/10.1007/s00382-019-04994-9

Xiang, J., Hansen, A., Pisaniello, D., et al. (2018). Correlates of Occupational Heat-Induced Illness Costs. Journal of Occupational & Environmental Medicine, 60(9), e463–e469. https://doi.org/10.1097/jom.0000000000001395

Yan, M., Xie, Y., Zhu, H., et al. (2022). The exceptional heatwaves of 2017 and all-cause mortality: An assessment of nationwide health and economic impacts in China. Science of The Total Environment, 812, 152371. https://doi.org/10.1016/j.scitotenv.2021.152371

Yu, I. T., Yu, W., Li, Z., et al. (2017). Effectiveness of participatory training in preventing accidental occupational injuries: a randomized-controlled trial in China. Scandinavian Journal of Work, Environment & Health, 43(3), 226–233. https://doi.org/10.5271/sjweh.3617

Zhang, P., Deschenes, O., Meng, K., et al. (2018). Temperature effects on productivity and factor reallocation: Evidence from a half million Chinese manufacturing plants. Journal of Environmental Economics and Management, 88, 1–17. https://doi.org/10.1016/j.jeem.2017.11.001

Zhao, Y., Sultan, B., Vautard, R., et al. (2016). Potential escalation of heat-related working costs with climate and socioeconomic changes in China. Proceedings of the National Academy of Sciences, 113(17), 4640–4645. https://doi.org/10.1073/pnas.1521828113

Zhu, J., Wang, S., & Fischer, E. M. (2021). Increased occurrence of day-night hot extremes in a warming climate. Climate Dynamics, 59(5–6), 1297–1307. https://doi.org/10.1007/s00382-021-06038-7

Zhu, J., Wang, S., & Huang, G. (2019). Assessing Climate Change Impacts on Human-Perceived Temperature Extremes and Underlying Uncertainties. Journal of Geophysical Research: Atmospheres, 124(7), 3800–3821. https://doi.org/10.1029/2018jd029444

Zhu, J., Wang, S., Wang, D., et al. (2021). Upholding labor productivity with intensified heat stress: Robust planning for adaptation to climate change under uncertainty. Journal of Cleaner Production, 322, 129083. https://doi.org/10.1016/j.jclepro.2021.129083

Zhu, J., Wang, S., Zhang, B., et al. (2021). Adapting to Changing Labor Productivity as a Result of Intensified Heat Stress in a Changing Climate. GeoHealth, 5(4). https://doi.org/10.1029/2020gh000313