Potential escalation of heat-related working costs with climate and socioeconomic changes in China

Yan Zhao[a,b,1], Benjamin Sultan[a,b], Robert Vautard[a,c], Pascale Braconnot[a,c], Huijun J. Wang[d], and Agnes Ducharne[a,e]

[a]Institut Pierre Simon Laplace (IPSL), 75005 Paris, France; [b]LOCEAN, UMR 7159, Unité mixte Universite Pierre et Marie Curie (UPMC)-Centre National de la Recherche Scientifique (CNRS)-Institut de Recherche pour le Developpement (IRD)-Muséum national d'Histoire naturelle (MNHN), Sorbonne Universités, 75005 Paris, France; [c]LSCE, UMR 1572, Unité mixte Joint Unit of Commissariat à l'energie atomique et aux energies alternatives (CEA)-CNRS-Universite de Versailles Saint-Quentin (UVSQ), 91191 Gif-sur-Yvette, France; [d]Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China; and [e]METIS, UMR 7619, Unité mixte UPMC-CNRS-Ecole Pratique des Hautes Etudes (EPHE), Sorbonne Universités, 75005 Paris, France

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Global climate change will increase the frequency of hot temperatures, impairing health and productivity for millions of working people and raising labor costs. In mainland China, high-temperature subsidies (HTSs) are allocated to employees for each working day in extremely hot environments, but the potential heat-related increase in labor cost has not been evaluated so far. Here, we estimate the potential HTS cost in current and future climates under different scenarios of socioeconomic development and radiative forcing (Representative Concentration Pathway), taking uncertainties from the climate model structure and bias correction into account. On average, the total HTS in China is estimated at 38.6 billion yuan/y (US $6.22 billion/y) over the 1979–2005 period, which is equivalent to 0.2% of the gross domestic product (GDP). Assuming that the HTS standards (per employee per hot day) remain unchanged throughout the 21st century, the total HTS may reach 250 billion yuan/y in the 2030s and 1,000 billion yuan/y in 2100. We further show that, without specific adaptation, the increased HTS cost is mainly determined by population growth until the 2030s and climate change after the mid-21st century because of increasingly frequent hot weather. Accounting for the likely possibility that HTS standards follow the wages, the share of GDP devoted to HTS could become as high as 3% at the end of 21st century.

high-temperature subsidies | CMIP5 | GDP | ANOVA | climate change

Despite a recent relative global warming slowdown, excessive heat on land progresses at a sustained rate (1). Heat waves have disastrous consequences on human health and occupational safety (2–6). The more than 70,000 excess deaths during the European heat wave in 2003 are a dramatic example (5), similar to the more recent 2013 heatwave in China, when over 5,600 heat-related illnesses were reported, roughly two times more than in the previous years (6). To cope with intensive heat exposure, the volume of work is reduced, whether it occurs through "self-pacing" (7) or an occupational health management intervention (8). The end result is a loss of work productivity, which has already been observed during the hottest seasons in low-income tropical regions (9–11). There is a strong agreement in the 2014 report from the Intergovernmental Panel on Climate Change (*SI Appendix*, Table S1 shows a list of abbreviations used in this study) that labor productivity will decrease as a result of increased global temperature (12). Productivity resulting from climate change may decrease by 11–27% by 2080 in hot regions, such as Asia and the Caribbean, and globally, by up to 20% in hot months by 2050 (3). Even under the moderate emission scenario [Representative Concentration Pathway 4.5 (RCP4.5)], productivity is projected to decrease by 20% globally by 2100 (3).

Despite the growing body of literature regarding the effects of heat exposure on occupational health and productivity loss, few studies have estimated the economic costs caused by excessive heat exposure (13). One such study addresses Germany from a macroeconomic point of view, estimating losses between US $771 million and $3.4 billion for the year 2004 (14). Using an approach derived from health economics and based on self-reported estimates of work performance, another study estimates the annual economic burden of heat in Australia to be US $5.2–7.3 billion in 2013 and 2014 [i.e., 0.33–0.47% of Australia's gross domestic product (GDP)] (4).

The case of China is particularly interesting in this context. Extreme heat events have increased significantly since the 1960s, particularly in the heavily populated North China Plain and the coastal areas of south China after 1995 (15). This trend is projected to continue in the 21st century under global warming scenarios (16), and ~50% of summers in China will be hotter in two decades than they were in 2013, even under a moderate climate change scenario (17). Since the 1980s, fast-growing urbanization combined with increasingly hot weather made occupational heat stress a nonnegligible societal concern in China. Severe hot working environments are not only public health (5, 6) and work safety concerns (18) but also, a question of decreasing productivity (2–4). Hence, the Chinese government has set up a new regulation to tackle this issue: the Administrative Measures on Heatstroke Prevention (AMHP2012) (8).

This governmental regulation requires that employers pay high-temperature subsidies (HTSs) to workers during high-temperature days [HTDs; when the daily maximum temperature ($T_{\max}$) exceeds 35 °C]. Although indoor heat stress is also addressed in the AMHP2012 (with a threshold of 33 °C to define indoor HTDs), we focus here on the outdoor heat stress, because it is more consistent with the available temperature data from

Significance

China is a country with a large population, and it is very affected by heatwaves, which have disastrous consequences on human health and occupational safety. Governmental high-temperature subsidies (HTSs) are allocated to workers during hot days but this increases the labor cost. This work is the first study, to our knowledge, to estimate the HTS cost in China from the present day to the end of the 21st century. We identified three main driving factors for HTS, namely population, employment structure, and climate. The HTS cost is bound to increase during the 21st century, despite substantial uncertainty arising from the evolution scenarios of the driving factors. The evolution of the heat-related labor cost in China may serve as an example for other countries.

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[1]To whom correspondence should be addressed. Email: yan.zhao@locean-ipsl.upmc.fr.

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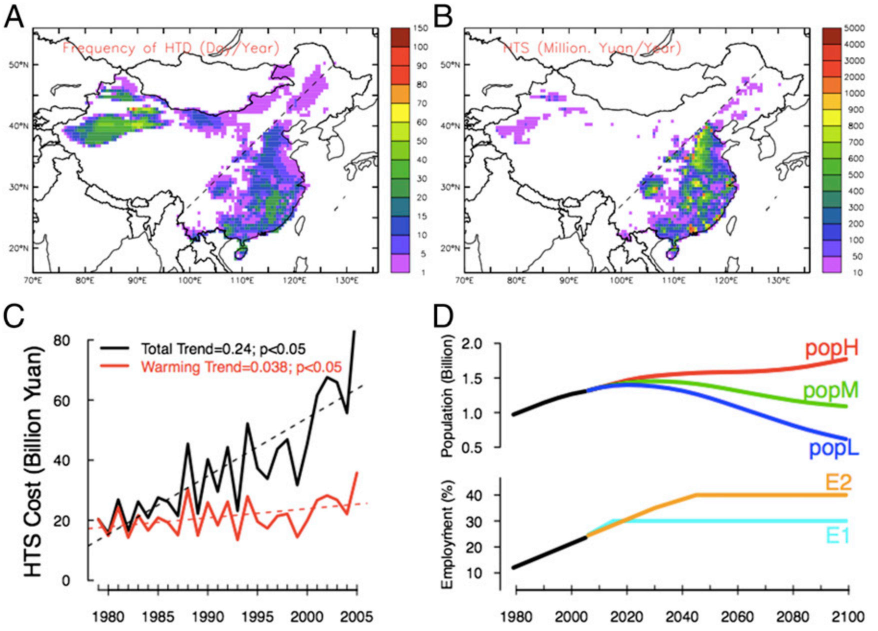

Fig. 1. HTDs and HTSs in China over the 1979–2005 period based on the WFDEI dataset. (*A*) Multiyear mean of the annual frequency of HTDs. (*B*) Multiyear mean of estimated HTS. In *A* and *B*, the black dashed line indicates the Hu line. (*C*) Evolution of the $\mathrm{HTS_{CHN}}$ accounting for both climatic and socioeconomic drivers (total trend; black) or the climatic driver alone (warming trend; red; i.e., assuming that the population and employment structure have remained as they were in 1979 over the entire period). Both trends are statistically significant at the 5% level according to the Mann–Kendall test and Sen's slope estimates. (*D*) Evolution of the population size and number of formal employees under the selected scenarios.

meteorological stations, reanalyses, and climate models. HTS regulation implementation is generally left to the provinces and applies differently to different types of employees (*SI Appendix*, Table S2). Although aspects of its operation could be improved, to our knowledge, the AMHP2012 is the first national regulation in the world concerning the protection of workers from heatstroke by explicitly taking the impact of hot weather into account in the labor cost (19). In contrast with previous costs inferred from economic approaches (4, 14), HTSs correspond to heat-related costs that are effectively implemented in the present day and may continue to exist for a certain period in the future. Given the large population and widespread heatwaves in China, the expense of HTSs is becoming a significant issue, especially in the context of global warming. We investigate here how HTS cost may evolve in the future under the combined effects of climate change and socioeconomic drivers.

The 1979–2005 period is used as a theoretical baseline, although the AMHP2012 was not effective at that time. We use the 0.5° × 0.5° WFDEI reanalysis data (20) (*SI Appendix*, *SI Data*, section 1) to first calculate the annual frequency of HTDs from daily $T_{\max}$ and then, infer the annual HTS. Note that crude but representative assumptions are made to calculate the annual HTS. In other words, by neglecting the difference in HTS regulation implementation in the different provinces, we assume uniform rules across China: at each grid point, the yearly frequency of $T_{\max}$ within the three classes of HTDs offering subsidies (35–37 °C, 37–40 °C, and above 40 °C) is weighted by the formal employee population and multiplied by a uniform subsidy cost per employee and per HTDs class, which is representative of usual practice (*Materials and Methods* and *SI Appendix*, *SI Data*, section 3 and Table S2).

For the future climate, we use the outputs of five global climate model (GCM) simulations performed within the Coupled Model

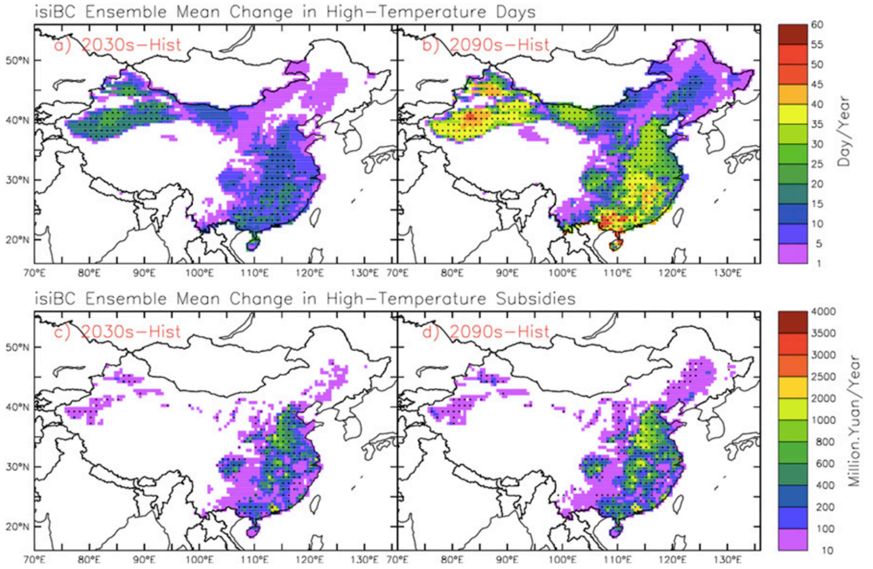

Fig. 2. Change in HTDs and HTSs in China in the near and far future (2020–2039 and 2080–2099, respectively) relative to the present day (1979–2005) under isiBC RCP4.5 projections, a medium population projection, and *E1* employment scenarios. (*A* and *B*) Ensemble mean change in the annual frequency of HTDs in the 2030s and 2090s. (*C* and *D*) Ensemble mean change in HTSs in the 2030s and 2090s. The grids with significant changes (more than 1 SD) appear as dots. Hist, history.

Intercomparison Project Phase 5 (21) (*SI Appendix*, Table S3) under three RCPs (RCP8.5, RCP4.5, and RCP2.6). These model outputs were downscaled and bias-corrected based on the early version of the WFDEI data covering the 1960–1999 period (22) by the Inter-Sectoral Impact Model Intercomparison Project (hereafter called the isiBC dataset) (23) (*SI Appendix*, *SI Data*, section 2). The resulting $T_{\max}$ is used to continue the HTS time series from 2006 to 2099. To account for uncertainties stemming from bias correction (*SI Appendix*, *SI Data*, section 2), we also use another simple correction method applied directly on heat stress indicators (reBC) and raw GCM outputs without bias correction (noBC).

We also consider a range of plausible socioeconomic scenarios: three population scenarios scaling up the gridded population in 2005 (24) with high, medium, and low population growth rates (*popH*, *popM*, and *popL*, respectively) (Fig. 1*D* and *SI Appendix*, *SI Data*, section 3) and two employment structure scenarios, *E1* and *E2* (Fig. 1*D*), resulting in formal employees to total population ratios of 30% and 40%, respectively, after the midcentury. The current estimate is between 12% and 24% (*Materials and Methods*). The future evolution of HTS costs (Fig. 2 *C* and *D*) also depend on one of the HTS standards. In absence of dedicated projections, we considered two scenarios: "fixed standard" and "varying standard." The former one keeps the present uniform HTS standard unchanged in the future, and it is used throughout the study if not otherwise mentioned; in the latter one, the HTS standard follows the wages as implemented in Tianjin (*SI Appendix*, Table S2) and suggested by AMHP2012 (8), and therefore, it is proportional to GDP (*Materials and Methods*).

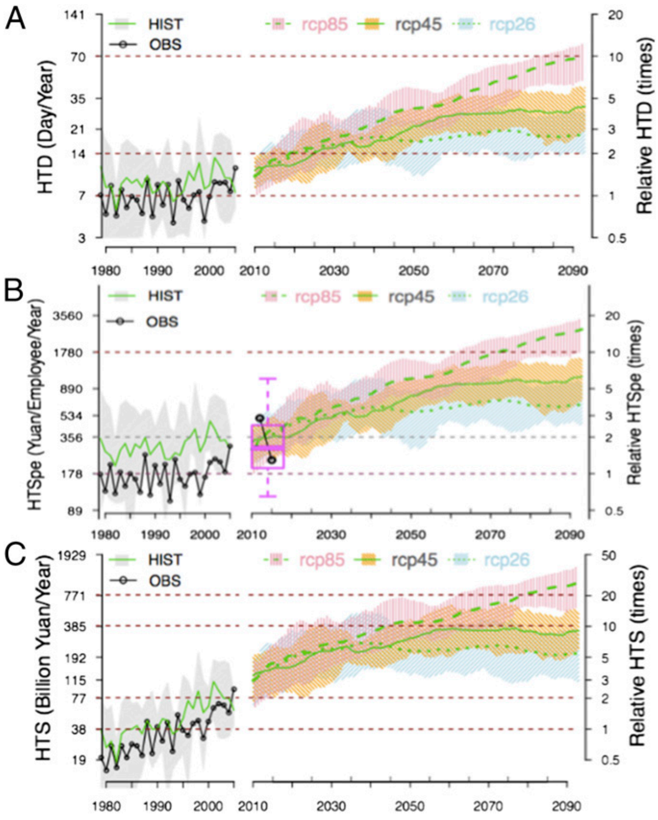

Fig. 3. Estimated evolution of HTDs, $\mathrm{HTS_{PE}}$, and $\mathrm{HTS_{CHN}}$ with isiBC between 1979 and 2099. (*A*) Population-weighted HTDs (days per year). (*B*) $\mathrm{HTS_{PE}}$ (yuan per employee per year). (*C*) Total $\mathrm{HTS_{CHN}}$ in billion yuan per year under the *popM* and *E1* scenarios. Black circles indicate the WFDEI-based reference (OBS, observation), and shaded areas show the span of the isiBC ensembles of five GCMs, with corresponding ensemble means shown as green lines (using 11-y running means from 2006 to 2100). The right *y* axis gives the relative change (multiplicative factor) compared with the 1979–2005 mean (horizontal purple dashed line). For ease of presentation, the projected HTS is the change in the modeled HTS plus the mean reference value. In *B*, the big black circles give $\mathrm{HTS_{PE}}$ estimates based on meteorological station data in 2013 and 2014, and the whisker box gives the HTS statistics using the isiBC ensemble over these 2 y (5 GCMs × 3 RCPs × 2 y): from bottom to top, the five bars give the minimum; 25th, 50th, and 75th percentiles; and maximum. HIST, history.

Results

In China over the recent past (1979–2005), regions with a high frequency of HTDs (Fig. 1*A*) are located in northwest China (50 d/y), east and southeast China (southeastern coast, middle and lower reaches of the Yangtze River, and the Sichuan Basin; 20–30 d/y), and north China (15–20 d/y). The high HTS costs (Fig. 1*B*) are concentrated in north China and the east and southeast parts of the country, corresponding to China's most populated (*SI Appendix*, Fig. S1) and economically developed regions. On average over the period, the total Chinese high-temperature subsidy ($\mathrm{HTS_{CHN}}$) is 38.6 billion yuan/y, 95.4% of which is spent in the north, east, and southeast regions. Fig. 1*C* shows that the estimated $\mathrm{HTS_{CHN}}$ increases dramatically in the 1979–2005 period because of the combined effects of increased HTDs, population size, and fast-growing urbanization. The upward trend is approximately +0.24 billion yuan/y, of which only 15% is attributable to the warming trend.

A relevant question is to what extent the estimation of $\mathrm{HTS_{CHN}}$ in this study is consistent with the real cost. It is difficult to validate the $\mathrm{HTS_{CHN}}$ value, because no statistics are available at the national scale, although HTSs have long existed in some economic sectors (19) and provinces, even before the official operation of the AMHP2012 in 2012 (*SI Appendix*, Table S2). However, we use local meteorological station data, the latest population distribution statistics, and the practiced HTS standards in each province, which lead to national mean high-temperature subsidy per employee ($\mathrm{HTS_{PE}}$) estimates of 510 and 230 yuan per employee per year in 2013 and 2014, respectively (*SI Appendix*, *SI Methods*, section 1). These values correspond to ∼1% and 0.41% of the mean Chinese gross annual salary in 2013 and 2014, respectively, and fall within the spread of the simulated $\mathrm{HTS_{PE}}$ values across the five GCMs and the three RCPs (Fig. 3*B*). The assumption of a conservative employment structure (scenario *E1*, with $E \sim 0.28$ in 2013 and 2014) (*Materials and Methods*) leads to $\mathrm{HTS_{CHN}}$ estimates of 195 and 88 billion yuan/y in 2013 and 2014, respectively (i.e., 0.33% and 0.14% of the Chinese GDP in 2013 and 2014, respectively, which is consistent with our estimates at the end of the 1979–2005 period) (Figs. 1*C* and 3*C*).

The comparison of the simulations over the 1979–2005 period with the values estimated from the WFDEI dataset reveals significant biases at the regional scale, both positive and negative, in the absence of bias correction (*SI Appendix*, Fig. S2). Because HTSs are calculated based on the HTDs, they contain the same biases, which are logically reduced under the isiBC bias correction, whereas there is zero bias when the reBC dataset is used. At the national scale, however, $\mathrm{HTS_{CHN}}$ estimates (*SI Appendix*, Table S4) are better simulated without bias correction (noBC) than with the isiBC dataset because of the larger geographical bias compensation in the former. Complementary analyses suggest that this overestimation is mostly caused by the differences in the reference datasets as well as the climate period.

Under the moderate climate change scenario (RCP4.5) with isiBC-based projections, the frequency of HTDs is projected to significantly increase in northwest, north, east, and southeast China (Fig. 2 *A* and *B*). The additional number of HTDs is 5–20 d/y in the 2030s and 30–60 d/y in the 2090s. As a result, HTSs are also projected to significantly increase (Fig. 2 *C* and *D*), in particular in the heavily populated part of China. Under the conservative employment rate (*E1*) and medium population scenario (*popM*), the ensemble mean changes in HTSs are ∼400–1,000 and ∼1,000–2,000 million yuan/y per grid, respectively, resulting in a cost of 20.9 and 35.6 billion yuan/y in the near and far future, respectively.

We further compare the evolutions of HTDs, $\mathrm{HTS_{PE}}$, and $\mathrm{HTS_{CHN}}$ between the different RCPs under the employment ratio *E1*, the population scenario *popM*, and the fixed standard

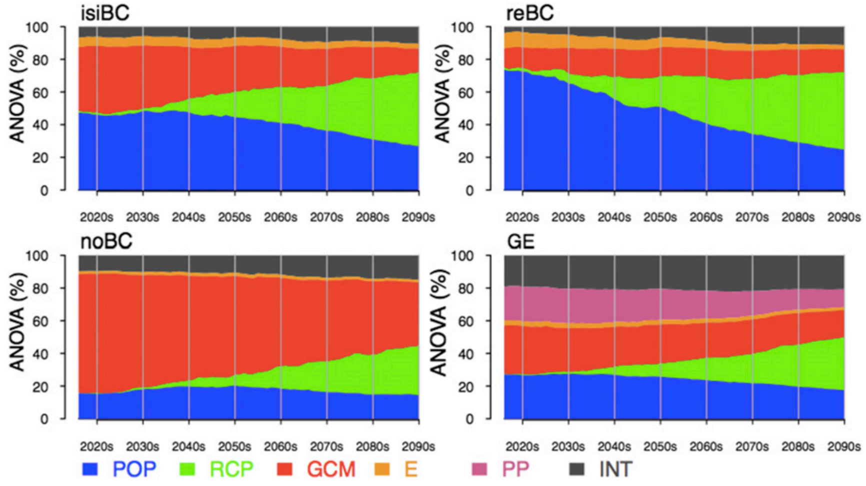

Fig. 4. Evolution of the variance fraction of the HTS_{CHN} attributed by ANOVA to population (POP), radiative forcing (RCP), GCMs, employment structure (*E*), postprocessing (PP), and the interactions among them (INT). isiBC, reBC, and noBC indicate that ANOVA was applied to isiBC, reBC, and noBC datasets; GE indicates that ANOVA was applied to the whole ensemble of the noBC, isiBC, and reBC datasets.

(Fig. 3). These interlinked parameters show large interannual variability and increase remarkably in the future. Based on the observation-derived WFDEI dataset, the mean number of HTDs is 7 d/y and rather stable over the reference period (Fig. 3*A*). In contrast, HTS_{CHN} shows a sharp increase, which is controlled by the increase in both the active population and formal employment ratio, so that the variations of HTS_{PE} closely follow the HTDs. This trend remains largely true in the future projections, although HTS_{PE} estimates exhibit a sharper rise than the number of HTDs under RCP8.5. This difference is caused by the increase in the frequency of "extreme" (above 40 °C) HTDs from 0.5 d/y at present day to 18.0 d/y in the 2090s (*SI Appendix*, Fig. S3).

The three parameters also show a much larger sensitivity to climate change scenarios after 2040 than beforehand. For instance, HTS_{PE} estimates are multiplied three to four times compared with those of the reference period around year 2030, irrespective of the RCP. Under RCP2.6, they then remain more or less stable, whereas they stabilize around a factor of 6 close to year 2060 under RCP4.5 and increase through the 21st century under RCP8.5, reaching a factor of 15 by the 2090s. Under RCP2.6, HTS_{CHN} shows a plateau after 2040 (Fig. 3*C*) because of a projected decreasing population size (Fig. 1*D*). This effect, however, cannot offset the effect of an increased number of HTDs on the HTS_{CHN} under higher emission scenarios: under RCP8.5, HTS_{CHN} estimates reach 550–1300 billion yuan in the 2090s, ∼15–35 times their present day value. Similar evolutions are also found with the noBC and reBC datasets, although with larger and smaller changes in reBC and noBC datasets, respectively, compared with isiBC. This similarity indicates that the results are moderately sensitive to the bias correction methods.

Assuming the uncertainty of the HTS_{CHN} is represented by the spread of our model simulations, we use an ANOVA approach (25) (*SI Appendix*, *SI Methods*, section 2) to hierarchize the selected sources of spread, namely scenarios of radiative forcing (RCP), population growth (*pop*), employment structure (*E*), GCM structure, postprocessing (PP), such as bias correction, and their interactions (INTs). The employment structure is the smallest factor (<10%) in most cases, and it is always much smaller than the population contribution. The main drivers of the HTS_{CHN} spread are RCP scenarios, population growth, and GCMs, with an order of importance that varies with time (Fig. 4). The RCP contribution increases with time and becomes dominant by the end of the 21st century. Without bias correction (noBC), the spread of the GCMs is so large that the estimation of HTS_{CHN} from one GCM only is questionable. Even if the bias correction significantly reduces the GCM-induced spread, it induces an additional uncertainty, contributing to 10–20% of the total variance, and yet, it is always less than the contribution of the GCMs. Taking all spread factors together, the major elements impacting HTS_{CHN} estimation are population (27%), GCMs (27%), and postprocessing (21%) in the 2030s, whereas the order of importance turns to climate (32%), population (17%), GCMs (16%), and postprocessing (11%) in the 2090s.

It is of great interest to compare the increasing HTS costs to the GDP, because it is also expected to increase in China (26). This estimate can only be made as a rough guess, however, because of the large uncertainties in the projections of GDP (*SI Appendix*, *SI Methods*, section 4 and Fig. S4) and also, the implementation of the AMHP2012 (discussed below). The ratio of HTS_{CHN} to China's GDP varies between 0.1% and 0.4% in the reference period, with a mean of 0.2% (Fig. 5*A*). Under the fixed standard, it is projected to decrease in the near future, because the GDP increase overrides the one of HTD frequency. The ratio only increases under RCP8.5 after 2060, when HTS_{CHN} reaches 0.3–0.7% of the projected GDP, beyond the experienced range over the reference period. The assumption of varying standard (Fig. 5*B*) leverages the increase in formal employment and temperature, and the share of GDP oriented to HTSs exceeds the reference values over most of the 21st century. It climbs to 0.5% in the 2030s under RCP2.6 and 1% under RCP4.5 in the 2060s, and it reaches 3% at the end of 21st century under RCP8.5.

Discussion

This study shows a potentially very large increase of occupational heat-related costs in China over the recent past and the 21st

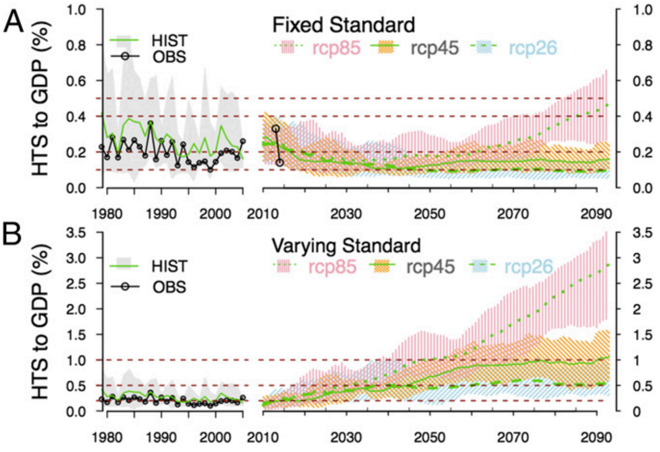

Fig. 5. Estimated evolution of the ratio of HTS_{CHN} to Chinese GDP. The HTS_{CHN} estimates are calculated with the isiBC data between 1979 and 2099 under the *popM* and *E1* scenarios and (*A*) fixed standard or (*B*) varying standard. Other details are in Fig. 3. HIST, history. OBS, observation.

century based on the existing regulation (the AMHP2012). The share of GDP oriented to HTSs is about 0.2% in the recent period, with a very large possible span at the end of 21st century between 0.1% and 3%, depending mostly on the climate change scenarios and the future implementation of the AMHP2012. In all tested cases, the soaring HTS cost attributed to climate change may not emerge until the 2030s.

Every modeling study has its limitations, and we recognize a few caveats to the design of our cost estimation. First, the estimated HTS is based on simplified modeling, assuming a homogeneous implementation across China, because of a lack of appropriate information. Employment data were only found at the province/municipality scale from 1991 to 1995; this information led us to an estimation of the HTS_{CHN} only 5% higher than the cost under homogeneous assumption (*SI Appendix*, *SI Methods*, section 3), which indicates that this assumption is reasonable. Climate change may also impact the population distribution within the country (12). Two very distinct zones of population density can be defined in modern China divided by the "Hu" line (Fig. 1*A*). This imaginary geodemographic demarcation line was first proposed in 1935 (27), and there has been little change in relative population density on each side since then (28). We also tested the effect of using the population pattern of either 1979 or 2005 through the entire 1979–2005 period, with differences smaller than 1% compared with our initial estimate. It can be concluded that the Chinese population pattern is relatively stable and has little impact on our HTS_{CHN} estimation compared with the uncertainty arising from GCMs and RCPs.

Our estimates are based on the current regulation, and like the AMHP2012, they neglect the effect of high humidity, which is well-known to aggravate heat stress when combined with hot temperature (29, 30). They also neglect adaptation, although it could significantly reduce the adverse effects of global warming. The reason for this is that even straightforward measures, such as air conditioning and mechanization, are difficult to quantify and protected, because they will vary by region and sector, depending on the willingness and capacity to adapt to the projected climate change (31, 32). Moving away from regions affected by extreme temperatures is another possible adaptation, but the stability of the Hu line reminds us that the choice of a living place is a complex matter, which depends not only on climate but also, culture, economical activities, and environment.

There is a large amount of uncertainty in the AMHP2012 regarding who may receive HTSs in which conditions and the amount of each subsidy. In practice, many workers do not get the HTSs to which they are entitled, especially migrant workers and those in small enterprises (33). However, some state-owned enterprises give HTSs to all of their employees as a benefit, even sometimes to workers in air-conditioned environments (34). Finally, there is an inherent ambiguity in the AMHP2012. The stated goal is to prevent employers from exposing workers to health-impairing heat, but if the HTS cost is not large enough, as revealed in most cases under the fixed standard, the employers may prefer to pay the subsidy rather than reducing the working time (35). Weak costs could have additional perverse effects, such as encouraging work in potentially dangerous conditions or conversely, discouraging employers from investment into costly protecting measures, like air conditioning, for indoor workers. However, the increase of HTS cost found when conditioning HTS standards to wages may have other perverse effects, such as simply cancelling the regulation. This possibility calls for complementary strategies to protect the workers while limiting escalation of heat-related working costs. The recent enforcement of mandatory heat standards in two states in the United States, California and Washington, which do not include any HTS but focus on education and training (35–37), may offer lessons to guide a more effective implementation of the Chinese heat stress prevention.

However simplified it is, this preliminary analysis highlights an important but overlooked aspect of climate change impact on labor cost. The case of China is representative of many developing countries in southeast Asia, which hold a dense population, experience severe and frequent heat exposure, and face rapid urbanization but have a low capacity to adapt to climate change (32). However, the AMHP2012 is the first national regulation in the world to improve heat protection for workers by means of increased labor cost, and this example may well spread into developed countries as an adaptation to climate change, with unclear intervention modes and economic impacts.

Given that the implementation of the AMHP2012 is still far from satisfactory, the various scenarios considered in this study may help guide future regulations. In doing so, it should not be forgotten that the HTS cost is just a part of the economic burden of workplace heat exposure and that it is aimed at reducing the other costs of heat-related productivity loss, heat illness, and injuries (4, 14). Future research should, thus, refine the socioeconomic constraints of HTS cost and its possible international equivalents at both local and regional levels and for various economic sectors. It is especially important to reexamine the present day assessments and the projections of the HTS cost with the best local socioeconomic data and comprehend the relationships between HTS cost and other heat-related costs, because it will act as a baseline for policy decisions and adaption regarding labor regulations.

Materials and Methods

A summary of the access to the datasets used in this study is listed below (more details are in *SI Appendix*, *SI Data*, sections 1–3 and *SI Methods*, sections 1–4).

The WFDEI climate reanalysis dataset is available at ftp://ftp.iiasa.ac.at/. The modeled daily T_{max} from five GCMs with or without bias correction are available from Coupled Model Intercomparison Project Phase 5 databases (https://pcmdi.llnl.gov/projects/esgf-llnl/). The station datasets of daily T_{max} in the summers of 2013 and 2014 are available at https://files.lsce.ipsl.fr/public.php?service=files&t=e75c9b38909287779a43804ea89219e3. The gridded population data are available at ftp://ftp.pbl.nl/hyde/ for 1970 and 1980 and sedac.ciesin.columbia.edu/data/collection/gpw-v3 for 1990, 1995, 2000, and 2005. The projected Chinese population is available at www.un.org/en/development/desa/population/ from 2006 to 2100. The projected Chinese GDP per capita is available at https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=welcome. Statistics on Chinese population, employment, annual salary, and GDP in the period of 1979–2014 are obtained from the online database of the National Bureau of Statistics of China (www.stats.gov.cn).

Estimation of HTS. The AMHP2012 (8) is a Chinese regulation defining subsidies for employees in case of hot temperatures. It is based on three classes of HTDs, namely moderate, strong, and extreme HTDs when T_{max} is within 35–37 °C, 37–40 °C, and above 40 °C, respectively. However, the regulation is left to local implementation in practice. It stipulates that local labor authorities are responsible for setting local subsidy standards, so that subsidies paid to employees during HTDs vary largely among provinces. In particular, the standard HTSs in one-half of the provinces are fixed sums, regardless of the weather conditions (*SI Appendix*, Table S2). In this study, we assume uniform daily standard subsidies across China of 20, 40, and 80 yuan per person per HTD for the moderate, strong, and extreme classes, respectively. These standards are a synthesis of the various provincial standards and agree well with the practiced standards in terms of the national mean and climate variability (*SI Appendix*, *SI Methods*, section 1 and Fig. S4). These values are kept constant throughout the 21st century under the fixed standard scenario, whereas they follow the GDP increase under the varying standard scenario, assuming that HTS payment amounts 10% of daily gross wage (which was approximately the case, on average, in 2012) and that the wage share constitutes 50% of the GDP (*SI Appendix*, *SI Methods*, section 4).

In both cases, as theoretical upper-limit estimations, we assume that HTSs are equally paid to all formal employees (38) during HTDs, neglecting the differences in temperature at different workplaces given that certain employees benefiting from air conditioning still receive HTS as a benefit (34). At each grid point i and each year, the HTSs are estimated as

$$\mathrm{HTS}_i = \sum_i^3 \left(E \times P_i \times S_j \times F_{ij}\right), \qquad [1]$$

where E is the formal employee to total population ratio. Because of limited available data for this study, we assume that E is evenly distributed across China. P_i is the population at the ith grid point in units of people (*SI Appendix*, *SI Data*, section 3). S_j is the daily subsidy at the jth class in yuan per person per day; F_{ij} is the frequency of HTDs at the jth class and ith grid point in days per year.

Thus, the $\mathrm{HTS_{CHN}}$ in yuan per year is estimated each year as

$$\mathrm{HTS_{CHN}} = \sum_{i}^{N} \mathrm{HTS}_i, \tag{2}$$

where N (4,129) is the total number of grid points within mainland China. The $\mathrm{HTS_{PE}}$ values in yuan per employee per year are calculated as $\mathrm{HTS_{CHN}}$ divided by the national total number of formal employees. Thus, $\mathrm{HTS_{PE}}$ only reflects the labor cost related to hot weather, regardless of the employment structure and population total, which is consistent with our assumption that the population is not redistributed in the future.

Formal Employment to Total Population Ratio. The formal employment to total population ratio (E) reflects the employment structure. It is derived from population data and employment-related statistics and studies:

$$E = FE \times EP, \tag{3}$$

where FE is the national formal to total employment ratio (38, 39), and EP is the national employees to total population ratio (40, 41).

Owing to the "reform and open-up" policy, FE in China has increased from 30% in 1978 to 50% in 2010 (38). Meanwhile, EP has increased from 42.1% in 1979 to 58.2% in 2005 (41). Thus, E has increased from 12% to 24% over the 1970–2005 period (Fig. 1*D*), but it remains lower than in industrialized countries. As an example, FE is 85% in the European Union and 90% in the United States (39), but the employees to total population ratio is relatively low ($EP \sim 40$–50%) (39), leading to an $E \sim 35$–45%.

For the future, we consider two scenarios for E (Fig. 1*D*):

E1 (conservative scenario): E increases linearly from 24% in 2005 to 30% in 2015, which is consistent with the latest published relevant statistical data (41), and then remains unchanged until 2099.

E2 (optimistic scenario): E increases linearly from 24% in 2005 to 35% in 2030 up to the present mean level of developed countries (40%) in 2050, after which it remains unchanged until 2099.

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