Cost of preventing workplace heat-related illness through worker breaks and the benefit of climate-change mitigation

著者	Takakura Jun ' ya, Fujimori Shinichiro, Takahashi Kiyoshi, Hijioka Yasuaki, Hasegawa Tomoko, Honda Yasushi, Masui Toshihiko
journal or publication title	Environmental research letters
volume	12
number	6
page range	064010
year	2017-06
権利	(C) 2017 IOP Publishing Ltd Original content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence . Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
URL	http://hdl.handle.net/2241/00146807

doi: 10.1088/1748-9326/aa72cc

IOPscience iopscience.iop.org

Home Search Collections Journals About Contact us My IOPscience

Cost of preventing workplace heat-related illness through worker breaks and the benefit of climate-change mitigation

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2017 Environ. Res. Lett. 12 064010

(http://iopscience.iop.org/1748-9326/12/6/064010)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 130.158.56.92
This content was downloaded on 14/07/2017 at 06:08

Please note that terms and conditions apply.

You may also be interested in:

Global-scale projection and its sensitivity analysis of the health burden attributable to childhood undernutrition under the latest scenario framework for climate change research
Hiroyuki Ishida, Shota Kobayashi, Shinjiro Kanae et al.

Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios
Keith Wiebe, Hermann Lotze-Campen, Ronald Sands et al.

Will international emissions trading help achieve the objectives of the Paris Agreement?
Shinichiro Fujimori, Izumi Kubota, Hancheng Dai et al.

Scenarios for the risk of hunger in the twenty first century using shared socioeconomic pathways
Tomoko Hasegawa, Shinichiro Fujimori, Kiyoshi Takahashi et al.

Towards a global water scarcity risk assessment framework: incorporation of probability distributions and hydro-climatic variability
T I E Veldkamp, Y Wada, J C J H Aerts et al.

Implications of climate mitigation for future agricultural production
Christoph Müller, Joshua Elliott, James Chryssanthacopoulos et al.

An impact assessment of sustainable technologies for the Chinese urban residential sector at provincial level
Rui Xing, Tatsuya Hanaoka, Yuko Kanamori et al.

Global crop yield response to extreme heat stress under multiple climate change futures
Delphine Deryng, Declan Conway, Navin Ramankutty et al.

IOP Publishing *Environ. Res. Lett.* **12** (2017) 064010 https://doi.org/10.1088/1748-9326/aa72cc

Environmental Research Letters

OPEN ACCESS

RECEIVED
2 December 2016

REVISED
9 May 2017

ACCEPTED FOR PUBLICATION
12 May 2017

PUBLISHED
13 June 2017

LETTER

Cost of preventing workplace heat-related illness through worker breaks and the benefit of climate-change mitigation

Jun'ya Takakura[1,4], Shinichiro Fujimori[1,2], Kiyoshi Takahashi[1], Yasuaki Hijioka[1], Tomoko Hasegawa[1,2], Yasushi Honda[3] and Toshihiko Masui[1]

[1] Center for Social & Environmental Systems Research, National Institute for Environmental Studies, 16-2, Onogawa, Tsukuba, Ibaraki, 305–8506, Japan
[2] International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361, Laxenburg, Austria
[3] Faculty of Health and Sport Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki, 305–8577, Japan
[4] Author to whom any correspondence should be addressed.

E-mail: takakura.junya@nies.go.jp

Keywords: climate change, labor productivity, economic cost, 2.0 °C goal, 1.5 °C goal

Supplementary material for this article is available online

Abstract

The exposure of workers to hot environments is expected to increase as a result of climate change. In order to prevent heat-related illness, it is recommended that workers take breaks during working hours. However, this would lead to reductions in worktime and labor productivity. In this study, we estimate the economic cost of heat-related illness prevention through worker breaks associated with climate change under a wide range of climatic and socioeconomic conditions. We calculate the worktime reduction based on the recommendation of work/rest ratio and the estimated future wet bulb glove temperature, which is an index of heat stresses. Corresponding GDP losses (cost of heat-related illness prevention through worker breaks) are estimated using a computable general equilibrium model throughout this century. Under the highest emission scenario, GDP losses in 2100 will range from 2.6 to 4.0% compared to the current climate conditions. On the other hand, GDP losses will be less than 0.5% if the 2.0 °C goal is achieved. The benefit of climate-change mitigation for avoiding worktime loss is comparable to the cost of mitigation (cost of the greenhouse gas emission reduction) under the 2.0 °C goal. The relationship between the cost of heat-related illness prevention through worker breaks and global average temperature rise is approximately linear, and the difference in economic loss between the 1.5 °C goal and the 2.0 °C goal is expected to be approximately 0.3% of global GDP in 2100. Although climate mitigation and socioeconomic development can limit the vulnerable regions and sectors, particularly in developing countries, outdoor work is still expected to be affected. The effectiveness of some adaptation measures such as additional installation of air conditioning devices or shifting the time of day for working are also suggested. In order to reduce the economic impacts, adaptation measures should also be implemented as well as pursing ambitious climate change mitigation targets.

1. Introduction

Physical activities in hot environments can elevate the risk of heat-related illness, such as heat exhaustion and heat stroke, some of which may be fatal. In particular, workers are vulnerable to hot environments, and thus, effective preventive measures are necessary in the workplace [1]. In order to prevent heat-related illness, the human core body temperature must be maintained within an adequate range. Human body temperature is regulated by the balance between heat dissipation to the surrounding environment and metabolic heat production inside the body [2]. Heat dissipation is determined by the thermodynamic relationship between the body surface and the surrounding thermal environment. On the other hand, the amount of metabolic heat produced inside the body depends on the intensity and duration of physical activity. When the level of physical activity becomes higher, heat production increases. In many workplaces, the thermal environment is uncontrollable and the intensity of physical activity is determined based on the type of work in which workers engage. Therefore, the duration of physical activity must be reduced so that workers can properly maintain their core body temperatures in harsh thermal environments. There are also other ways to reduce the risk of heat-related illness, such as wearing ventilated clothes or consuming ice slurry, but taking breaks is an effective and recommended method.

The International Organization for Standardization (ISO) and several other governmental agencies have recommended that workers take breaks according to the specific thermal environment and work intensity [3,4]. However, such intervention reduces worktime and labor productivity. Thus, preventing heat stroke by reducing worktime is economically costly. Furthermore, climate change is expected to increase these costs. A number of studies have investigated this topic. For example, Kjellstrom *et al* estimated worktime reduction [5] and Rosen *et al* calculated the corresponding GDP loss [6]. The estimated GDP loss attributed to worktime reduction was found to be several percent of GDP, and its contribution to the total GDP loss caused by climate change including the effects other than worktime reduction (e.g. yield change, sea-level rise, etc.) was found to be dominant in many regions. These pioneering studies have increasingly focused attention on worktime loss due to heat stress in relation to climate change [7–10]. The results of these studies indicated that the worktime reduction will be large in the future.

In December 2015, nations agreed that the global average temperature increase should be maintained well below 2.0 °C, and a target of 1.5 °C was discussed [11]. Thus, estimation of economic cost under a wide range of climatic conditions is important for two reasons. First, the benefit of mitigating climate change should be quantified, which would provide policymakers with further information to decide emissions reduction targets for the coming nationally determined contribution (NDC) revisions in 2020. Second, the effect of climate change may be substantial even if the target temperature increase is achieved. However, neither the economic cost of worktime loss under climate-change mitigation nor the benefit of climate-change mitigation has been clarified under a wide range of socioeconomic and climatic conditions. Thus, estimation of the economic cost associated with preventing workplace heat-related illness through worker breaks under a wide range of socioeconomic and climate-change mitigation conditions is urgently needed.

There are also several methodological obstacles to be overcome that were not addressed in earlier pioneering attempts to estimate the economic cost of worktime losses. First, the socioeconomic conditions, which play crucial roles in many climate impact studies [12–14], should be incorporated into the estimation. Factors such as industrial structure, labor intensiveness of industries, and air-conditioning device availability may affect the estimation of the economic cost of worktime reduction [5, 7, 15]. Second, it is important to consider air-conditioning device use and sub-daily thermal environmental variation in order to accurately estimate labor losses.

Here, we present, for the first time, a comprehensive assessment of the macroeconomic cost of workplace heat stroke prevention through worker breaks in the future by considering the future penetration rate of air-conditioning devices and sub-daily thermal environmental variation, under a wide range of possible climatic and socioeconomic pathways using the shared socioeconomic pathway/representative concentration pathway (SSP/RCP) framework. In order to estimate the macroeconomic cost, we used the Asia-Pacific integrated model/computable general equilibrium (AIM/CGE) model. We ran the simulation from 2005 (base year) to 2100 and estimated the macroeconomic consequences.

2. Method

2.1. AIM/CGE model

We used the AIM/CGE model as a core tool to estimate the future macroeconomic cost of workplace heat-related illness prevention. The AIM/CGE model is a one-year-step, recursive computable general equilibrium model coupled with the Asia-Pacific Integrated Model/End-Use (AIM/End-Use) database. The AIM/CGE model has already been applied to various types of macroeconomic assessments of the impact of climate change, including food production [16, 17], land use changes [18], hydropower generation [19], the health impact of $PM_{2.5}$ [20], and heating and cooling energy demand [21]. In the AIM/CGE model, the world is divided into 17 regions, and the model considers 42 industrial sectors and one aggregated household sector in each region. Industrial sectors have multi-nested constant elasticity substitution (CES) production functions. Industrial sectors maximize their profits under constraints, and households maximize their utilities. Other types of economic activity, such as investments, capital formation, and trading between regions, are also considered in the AIM/CGE model. Socioeconomic conditions are expressed based on socioeconomic scenarios. The detailed structure of the model is described elsewhere [22]. The outline of the framework used in the present study is shown in figure 1.

2.2. Estimating the WBGT

We used the WBGT as a heat-stress index. The WBGT was originally developed for the US Army and is now

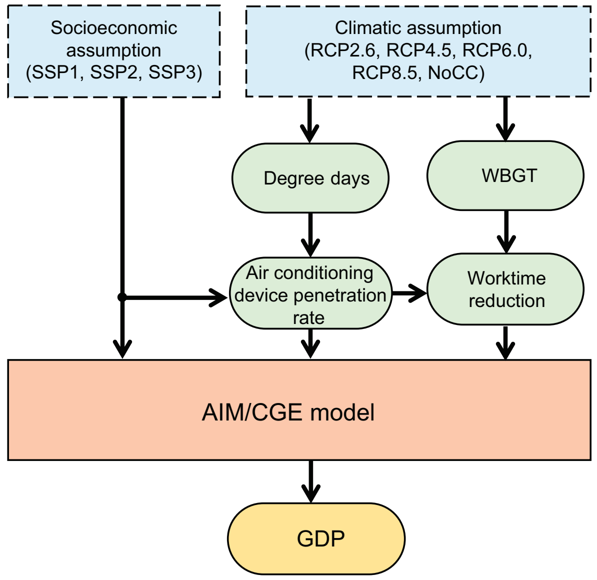

Figure 1. Framework of the present study. Socioeconomic assumptions are based on the SSP, and climatic assumptions are based on the RCP. The air-conditioning device penetration rate is estimated based on the climatic (number of degree days) and socioeconomic (per capita GDP) conditions. Worktime loss is calculated based on the estimated WBGT and the air-conditioning device penetration rate, and the AIM/CGE model also calculates the GDP based on these variables.

widely used in the field of occupational safety to prevent heat-related illness [23]. Heat transfer between the human body and the surrounding environment is determined not only by air temperature, but also depends on conduction, convection, evaporation, and radiation. The WBGT incorporates all of these factors. Recommendations of worker breaks also adopt the WBGT as the environmental heat-stress index. The WBGT can be measured as the weighted sum of the wet bulb temperature, the globe temperature, and the ambient air temperature, although the first two variables are not available from general circulation models (GCMs). Therefore, it is necessary to estimate the future WBGT from data that can be acquired from GCMs. There are several formulas for estimating the WBGT if instantaneous standard meteorological observation data are available [24–26]. Using these formulas and past meteorological observation data, we developed a method by which to estimate the hourly WBGT from the daily data of GCMs. First, we acquired hourly meteorological observation data from the database of the National Oceanic and Atmospheric Administration (NOAA) and daily solar radiation data from the database of the Atmospheric Science Data Center of NASA. Daily solar radiation data was disaggregated to hourly data based on the solar position of each hour. Then, we calculated the hourly outdoor WBGT using the formula of Liljegren *et al* [25] and the indoor WBGT using the formula of Bernard *et al* [24] modified by Lemke *et al* [26]. We also calculated the daily representative (average) value of meteorological data. At this point, we have pairs of hourly WBGTs, which we want to estimate, and daily representative values of meteorological data, which are available from GCMs. Based on the statistical relationship between these data sets, we can estimate (regress) the hourly WBGT. Considering the performance and computational load, support vector regression of LIBLINEAR [27] was used for this purpose. The validity of this method was evaluated by a cross-validation technique for historical data, and the average root mean square error (RMSE) was 1.25 °C for outdoor WBGT and 0.86 °C for indoor WBGT. Additional details and validation results are presented in supplementary information S7, available at stacks.iop.org/ERL/12/064010/mmedia. We estimated future indoor and outdoor hourly WBGT using the regressors with a resolution of 0.5° × 0.5°.

2.3. Worktime reduction

The recommended work/rest ratio is defined depending on the WBGT and the intensity of physical activity [3, 4]. It is recommended that the higher the WBGT and the higher the work intensity, the longer workers should rest. The relationship among the WBGT, the work intensity, and the recommended work/rest ratio is shown in supplementary information S8. The recommended relationship is defined differently for acclimatized people and for non-acclimatized people. Here, we adopted the recommendation for acclimatized people. The work intensity and workplace differ among industrial sectors. We assumed the workplaces of the primary industry sector and the construction sector to be outdoors and those of the other sectors to be indoors. The work intensity of the primary industry sectors and the construction sector was assumed to be high (400 W), and that for other manufacturing sectors was assumed to be moderate (300 W). The work intensity of service sectors was assumed to be low (200 W). We also assumed that the recommended work/rest ratio was strictly followed.

The WBGT varies depending on the time of day, i.e. the WBGT tends to be low in morning or evening, and tends to be highest around noon. Therefore, the work capacity also varies diurnally depending on time of day. As explained in the previous section, we estimated the hourly WBGT. In order to calculate the daily total worktime, we calculated the hourly work capacity and summed the hourly work capacity from 9:00 AM to 5:00 PM. The calculation was conducted for all grids having a resolution of 0.5° × 0.5°, and the results were then aggregated for each region and sector weighted by population distribution.

2.4. Air-conditioning devices

The estimation of the future air-conditioning device penetration rate is based on research from a previous study [21]. We assumed that the potential maximum demand for air-conditioning devices depends on the climate conditions (number of degree days) and that the affordability depends on the income level (per capita GDP) of the region. The number of degree days is calculated based on the daily mean temperature obtained from GCMs with a resolution of 0.5 °C × 0.5 °C and is then averaged for each region weighted by population distribution. The per capita GDP is taken from the socioeconomic assumptions corresponding to SSPs. Using these two variables, air-conditioning device penetration rates were estimated using formulas proposed by Isaac and van Vuuren [15]. We estimated the device penetration rate for each region and updated the value every year. The air-conditioning device penetration rate was assumed to be the same across industrial sectors within a region. The energy service demand and investment cost of air-conditioning devices are also expressed in the AIM/CGE model. Additional details are provided in [21]. In the present study, however, they were excluded from the estimation of economic cost because we assumed air-conditioning device penetration to be autonomous and independent of the explicit goal of preventing worktime reduction. We assumed that if air-conditioning devices were available, then the worktime of indoor work was not reduced, regardless of the thermal environment.

2.5. Input and output of the AIM/CGE model

In the AIM/CGE model, each industrial sector includes a CES production function, and one of its inputs is labor. In order to express the labor productivity loss due to reduced worktime, the labor input was multiplied by the ratio of the worktime reduction, and their product was used as the effective labor input to the production function.

The economic cost of heat-related illness prevention through worker breaks was measured based on the change in GDP from the baseline (no climate change) scenario. The costs of air-conditioning devices and their associated energy consumption were excluded from the estimation of the economic cost of heat stroke prevention because these costs were regarded as normal economic activity. We also calculated the direct cost of worktime loss for each industrial sector based on the additional wage required to compensate the worktime loss by the additional input of labor.

2.6. Scenario settings

We conducted simulations under three different socioeconomic assumptions and five climate conditions. Socioeconomic conditions were based on SSPs [28]. We adopted three SSPs (SSP1: sustainability, SSP2: middle of the road, and SSP3: regional rivalry). Projection of population was based on the SSP scenarios [29], and the spatial distribution of population [30] was also considered in the calculations. Four representative concentration pathways (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) [31] and no climate change (NoCC), which corresponds to fixing the climate of the base year (2005), were used as the climate conditions. Here, RCP2.6 (radiative forcing of 2.6 W m^{-2}) corresponds to the 2.0 °C goal, and RCP8.5 (radiative forcing of 8.5 W m^{-2}) corresponds to the continued increase of greenhouse gas emissions. Representative concentration pathways RCP4.5 and RCP6.0 are intermediate RCPs. For all scenarios, we assumed air-conditioning device penetration to be autonomous and independent of the explicit goal of preventing worktime reduction. In order to cope with uncertainty regarding the future climate, we used climate data from five different GCMs provided by CMIP5 [32].

Note that not all combinations of SSPs and RCPs are equally probable. Baseline radiative forcing values are approximately 6.0 W m^{-2} in SSP1, and 7.0 W m^{-2} in SSP2 and SSP3 [33–36]. Therefore, the climate condition corresponding to RCP8.5 is unlikely to happen under SSP1, SSP2, and SSP3. Achieving the emission reduction corresponding to RCP2.6 is also virtually impossible under SSP3 [36]. However, we conducted simulations for all combinations (three SSPs and four RCPs) for the purpose of comparison. We conducted a simulation under the assumption of business as usual (BaU), in which no mitigation measures would be taken, in order to compare the cost of the climate change independently from the cost of the climate-change mitigation such as cost of intensive use of renewable energies, and cost of installing carbon capture and storage technologies.

2.7. Sensitivity analysis

In order to check the robustness of the result, we conducted sensitivity analyses under two assumptions. The first sensitivity analysis was for the assumption of the air-conditioning device penetration rate, and the second sensitivity analyses was for the time of day for working. For the air-conditioning device penetration rate, we conducted simulations under the situation in which a lower propensity to

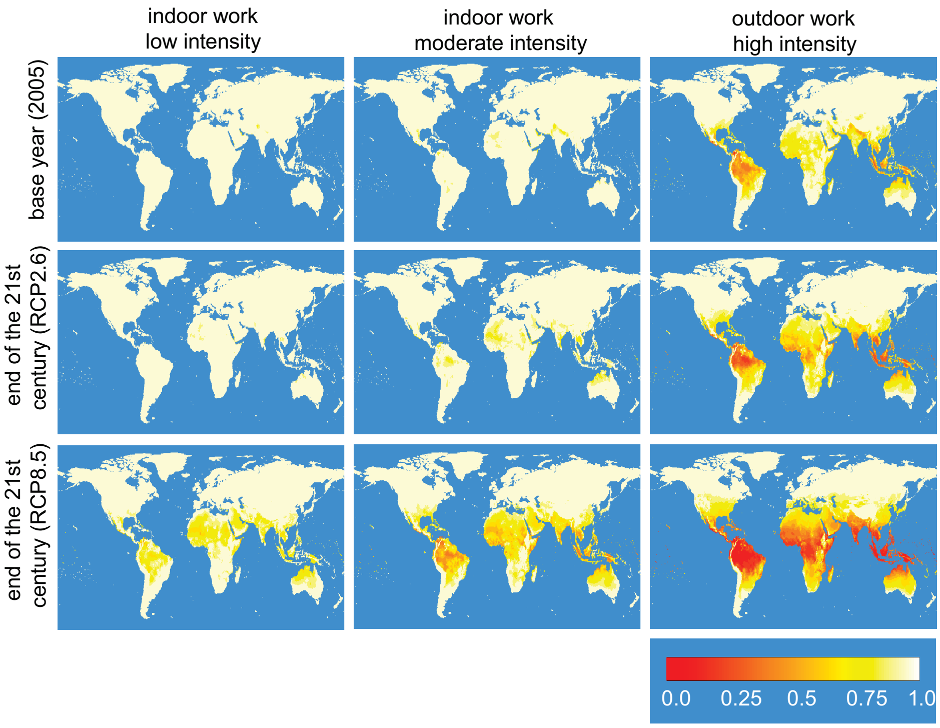

Figure 2. Estimated worktime ratio. Estimated yearly average worktime ratio with a resolution of 0.5° × 0.5°. When the worktime ratio is x, the recommended work-rest ratio is $x/(1-x)$. The left-hand and center columns of panels show the values for low-intensity and moderate-intensity work, respectively, performed indoors (without air-conditioning). The right-hand column of panels shows the values for high-intensity work performed outdoors. The median values of 5 GCMs are shown.

install the air-conditioning device was assumed. Two parameters were used in calculating the air-conditioning device availability based on the per capita GDP, which were estimated statistically. We set their values to the original value plus the standard error of the estimate. This yields lower and slower air-conditioning device penetration (additional details are provided in supplementary information S1). For the time of day for working, we conducted simulations under the situation in which the starting time of working is earlier by 3 hours, but the total number of working hours is the same. This situation corresponds to the avoidance of daytime heat stresses by working during the early morning, which is already implemented in some regions. These simulations were conducted for only two RCPs (RCP2.6 and RCP8.5) and for one GCM (IPSL-CM5A-LR).

3. Results

3.1. Worktime Reduction

First, we calculated the yearly average worktime reduction for each grid based on the estimated future WBGT. The estimated global mapping of worktime reduction expressed as worktime ratio is shown in figure 2. This figure represents the effect on worktime reduction of not using an air-conditioning device. The reduction is concentrated in low-latitude areas because of the higher temperatures and humidities in these areas throughout the year. In the base year (2005), worktime is already affected. For example, the aggregated worktime ratios of outdoor/high-intensity work were 0.66 in South-East Asia, 0.71 in India, and 0.86 in Sub-Saharan Africa in 2005. Here, aggregated worktime ratio of x means that the ratio of work/rest time during working hour is $x/(1-x)$. However, these distinct adverse effects were limited to outdoor work. At the end of the 21st century, under the high-emission scenario (RCP8.5), the aggregated worktime ratios decrease to 0.23 in South-East Asia, 0.36 in India, and 0.42 in Sub-Saharan Africa. Even under the low-emission scenario (RCP2.6), the worktime ratios decrease to 0.44 in South-East Asia, 0.65 in India, and 0.74 in Sub-Saharan Africa, but these decreases are smaller than those under the RCP8.5 condition. Indoor work is also adversely affected under RCP8.5. For example, in India, the worktime ratio was 0.62 for indoor/moderate work, and 0.76 for indoor/light work if air-conditioning devices are not available.

3.2. Global economic cost

The global economic cost due to worktime reduction (economic cost of heat-related illness prevention through worker breaks) is calculated based on the percentage change of GDP from the NoCC condition. The calculated global cost for each SSP is shown in figure 3. For all SSPs, the economic cost increases steadily, except under RCP2.6. Under RCP8.5, the GDP loss rate (median value) reaches as high as 2.8%,

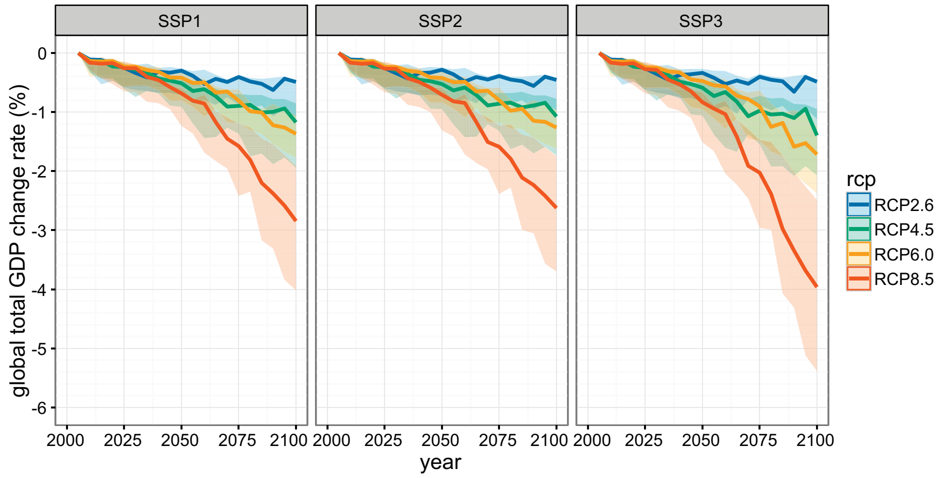

Figure 3. Global total GDP change rate. Differences from the GDP under the NoCC condition. Bold lines represent median values, and shaded areas represent the minimum and maximum range of simulation for five different GCMs.

2.6%, and 4.0% for SSP1, SSP2, and SSP3, respectively. On the other hand, under RCP2.6, the GDP loss rate saturates at around the middle of the 21st century, and the median value for SSP1, SSP2, and SSP3 in 2100 is 0.49%, 0.46%, and 0.49%, respectively. In order to determine which factors contributed to the difference in the GDP loss rates, we conducted an analysis of variance (ANOVA) for the global total GDP change rates (see supplementary information S2). Until the middle of the 21st century, when the climate is not yet stabilized, the difference in GCM is the primary contributor to the variance of the result of the global total GDP loss rates. On the other hand, at the end of the 21st century, when the climate is almost stabilized except RCP8.5, RCP is the primary contributor to this variance. The proportion of the variance due to GCM and RCP is more than 80%, whereas that due to SSP is less than 5% throughout the simulation periods. This means that the global GDP loss rate is more sensitive to climate conditions and choice of climate models than to socioeconomic conditions in the simulated range.

The change in household consumption exhibited a similar tendency to that for the GDP change rate (see supplementary information S3).

3.3. Regional Characteristics

The GDP change rates for 17 regions in 2100 are shown in table 1. Distinct GDP losses are observed in India (IND) and South-East Asia (XSE). Under RCP8.5, the GDP loss rates (median values) are 14.3%–17.3% in India, and 4.6%–6.9% in South-East Asia. Under SSP1 and SSP2, the losses are concentrated in these two regions. However, under SSP3, comparable GDP losses are also observed in Sub-Saharan Africa (XAF) and other Asian regions (XSA) under RCP8.5 (7.9% and 7.1%, respectively). Such regional differences in GDP loss rates could be attributed to differences in sensitivity to the climatic and socioeconomic conditions. The characteristics of each region are plotted according to sensitivity to climatic conditions and sensitivity to socioeconomic conditions (figure 4). The four above-mentioned regions are sensitive to climatic conditions, whereas other Asian regions and Sub-Saharan Africa are very sensitive to socioeconomic conditions, too. We conducted the ANOVA, which was applied to global GDP change rate in the section 3.2, for each region. The result of the ANOVA also showed that the GDP change rates of these two regions are sensitive to socioeconomic conditions or its interaction term (supplementary information S4). Thus, these two regions are not seriously affected when high socioeconomic development is achieved because of higher air-conditioning device availability. This result indicates that, even if the apparent global GDP loss rates are similar among SSPs, their component losses differ. Under the low-economic-growth scenario (SSP3), wider regions are affected.

3.4. Direct cost and sectoral differences

The direct cost disaggregated to each industrial sector is shown in figure 5. The direct cost is calculated as the additional wages required to compensate the work-time loss associated with the additional labor requirements. The construction sector is affected primarily by worktime loss. The primary industry sector is also adversely affected, but its proportion to economic scale is smaller. Under SSP1 or SSP2, the manufacturing and service sectors, which are assumed to represent indoor work environments, are not affected in 2100. On the other hand, under SSP3, the manufacturing and service sectors are also affected by worktime loss. This is due to the difference in the air-conditioning device penetration rate. Figure 5 indicates the global average penetration rate weighted by population for each SSP (the value for each region is shown in supplementary information S5). Under SSP1 or SSP2, the penetration rate reaches saturation (more than 90%). Under SSP3, the penetration rate is less than

Table 1. Region GDP change rate. GDP change rates for 17 regions in 2100. The values are shown as percentages of the GDP change rate under the NoCC condition. In each cell, the median (minimum, maximum) value from five different GCMs is presented. RCPs marked by * indicate that the possibility of corresponding radiative forcing under that SSP is low. USA: United States, XE25: European Union, XER: Rest of Europe, TUR: Turkey, XOC: Oceania, CHN: China, IND: India, JPN: Japan, XSE: South-East Asia, XSA: Rest of Asia, CAN: Canada, BRA: Brazil, XLM: Rest of Latin America, CIS: Former USSR, XME: Middle East, XNF: North Africa, XAF: Sub-Saharan Africa, WLD: World.

	SSP1				SSP2				SSP3			
	RCP2.6	RCP4.5	RCP6.0	RCP8.5*	RCP2.6	RCP4.5	RCP6.0	RCP8.5*	RCP2.6*	RCP4.5	RCP6.0	RCP8.5*
USA	-0.15 (-0.27, -0.11)	-0.35 (-0.51, -0.05)	-0.38 (-0.77, -0.30)	-0.79 (-1.28, -0.67)	-0.15 (-0.27, -0.11)	-0.34 (-0.50, -0.05)	-0.38 (-0.77, -0.29)	-0.78 (-1.27, -0.67)	-0.16 (-0.27, -0.12)	-0.35 (-0.51, -0.06)	-0.40 (-0.78, -0.30)	-0.80 (-1.28, -0.68)
XE25	-0.04 (-0.10, 0.00)	-0.06 (-0.25, -0.03)	-0.08 (-0.29, -0.05)	-0.17 (-0.76, -0.12)	-0.05 (-0.10, 0.00)	-0.06 (-0.18, -0.04)	-0.09 (-0.29, -0.06)	-0.18 (-0.76, -0.12)	-0.05 (-0.10, 0.00)	-0.06 (-0.19, -0.03)	-0.08 (-0.31, -0.06)	-0.19 (-0.80, -0.12)
XER	0.26 (-0.32, 0.87)	1.08 (0.34, 1.94)	1.45 (0.44, 2.13)	2.72 (1.48, 3.13)	0.50 (-0.26, 1.27)	1.50 (0.59, 2.59)	1.94 (0.66, 2.79)	3.46 (2.00, 4.00)	1.52 (0.45, 2.67)	2.82 (1.71, 4.28)	3.49 (1.74, 4.47)	5.29 (3.60, 6.03)
TUR	-0.26 (-0.29, 0.04)	-0.43 (-0.63, -0.09)	-0.47 (-0.91, -0.07)	-1.24 (-1.52, -0.36)	-0.25 (-0.28, 0.04)	-0.42 (-0.60, -0.09)	-0.46 (-0.88, -0.07)	-1.20 (-1.47, -0.35)	-0.27 (-0.33, 0.05)	-0.49 (-0.70, -0.10)	-0.55 (-1.13, -0.07)	-1.62 (-1.98, -0.41)
XOC	-0.02 (-0.11, 0.00)	-0.07 (-0.16, -0.03)	-0.14 (-0.19, -0.06)	-0.26 (-0.46, -0.12)	0.01 (-0.07, 0.04)	0.00 (-0.06, 0.05)	-0.07 (-0.12, 0.01)	-0.16 (-0.28, -0.01)	-0.03 (-0.13, -0.01)	-0.10 (-0.20, -0.05)	-0.19 (-0.24, -0.08)	-0.32 (-0.57, -0.16)
CHN	-0.31 (-0.34, -0.18)	-0.59 (-0.66, -0.37)	-0.59 (-0.68, -0.51)	-1.05 (-1.38, -0.72)	-0.31 (-0.34, -0.18)	-0.58 (-0.67, -0.36)	-0.58 (-0.68, -0.51)	-1.05 (-1.38, -0.73)	-0.38 (-0.42, -0.21)	-0.70 (-0.81, -0.43)	-0.72 (-0.83, -0.62)	-1.28 (-1.68, -0.89)
IND	-2.83 (-7.27, -2.12)	-6.73 (-13.94, -4.44)	-8.02 (-10.32, -6.22)	-17.29 (-25.85, -11.97)	-2.32 (-6.06, -1.73)	-5.60 (-11.75, -3.71)	-6.76 (-8.63, -5.18)	-14.77 (-22.19, -10.12)	-1.56 (-5.30, -1.15)	-4.74 (-10.7, -2.81)	-5.98 (-8.54, -4.12)	-14.34 (-21.22, -9.18)
JPN	-0.18 (-0.42, -0.08)	-0.42 (-0.55, -0.26)	-0.69 (-0.84, -0.27)	-1.26 (-1.61, -1.06)	-0.17 (-0.41, -0.08)	-0.40 (-0.52, -0.25)	-0.66 (-0.80, -0.26)	-1.20 (-1.52, -1.02)	-0.13 (-0.36, -0.05)	-0.35 (-0.47, -0.20)	-0.60 (-0.74, -0.21)	-1.13 (-1.43, -0.96)
XSE	-1.64 (-3.08, -0.84)	-2.54 (-3.87, -1.81)	-2.98 (-4.18, -2.31)	-4.61 (-8.28, -3.65)	-1.66 (-3.14, -0.82)	-2.54 (-3.89, -1.77)	-3.01 (-4.25, -2.33)	-4.70 (-8.67, -3.69)	-2.05 (-4.22, -0.95)	-3.23 (-5.34, -2.22)	-3.98 (-6.13, -3.00)	-6.89 (-13.53, -5.19)
XSA	0.14 (-0.10, 0.15)	0.05 (-0.21, 0.14)	-0.01 (-0.23, 0.07)	-0.16 (-0.46, -0.04)	0.18 (-0.12, 0.20)	0.07 (-0.27, 0.19)	-0.01 (-0.31, 0.09)	-0.22 (-0.60, -0.06)	1.81 (-1.39, 1.99)	0.01 (-4.93, 1.47)	-1.25 (-7.09, 0.70)	-7.09 (-12.59, -2.07)
CAN	0.00 (-0.10, 0.01)	-0.11 (-0.26, -0.02)	-0.09 (-0.40, -0.05)	-0.30 (-0.86, -0.14)	-0.01 (-0.11, 0.01)	-0.11 (-0.26, -0.02)	-0.10 (-0.40, -0.05)	-0.31 (-0.88, -0.15)	-0.01 (-0.11, 0.01)	-0.12 (-0.27, -0.02)	-0.10 (-0.42, -0.06)	-0.33 (-0.92, -0.16)
BRA	-0.02 (-0.07, 0.01)	-0.10 (-0.15, -0.03)	-0.10 (-0.19, -0.05)	-0.31 (-0.38, -0.08)	-0.03 (-0.1, 0.01)	-0.13 (-0.19, -0.03)	-0.14 (-0.25, -0.07)	-0.40 (-0.51, -0.11)	-0.09 (-0.41, 0.01)	-0.53 (-0.77, -0.13)	-0.59 (-1.34, -0.30)	-3.04 (-3.62, -0.76)
XLM	-0.12 (-0.14, 0.02)	-0.29 (-0.44, -0.11)	-0.43 (-0.45, -0.21)	-0.86 (-0.98, -0.44)	-0.09 (-0.12, 0.05)	-0.24 (-0.40, -0.05)	-0.39 (-0.41, -0.15)	-0.71 (-0.96, -0.37)	-0.18 (-0.24, 0.01)	-0.53 (-0.78, -0.18)	-0.76 (-0.86, -0.37)	-1.76 (-1.97, -0.80)
CIS	0.01 (-0.02, 0.01)	-0.06 (-0.07, 0.02)	-0.06 (-0.10, 0.00)	-0.20 (-0.29, -0.06)	0.06 (0.02, 0.11)	0.11 (0.04, 0.12)	0.06 (0.03, 0.11)	0.11 (0.07, 0.17)	0.02 (-0.01, 0.05)	-0.03 (-0.08, 0.07)	-0.04 (-0.12, 0.04)	-0.18 (-0.28, -0.02)
XME	-0.05 (-0.10, 0.02)	-0.09 (-0.22, -0.02)	-0.22 (-0.26, -0.07)	-0.44 (-0.48, -0.19)	-0.03 (-0.10, 0.03)	-0.07 (-0.20, 0.00)	-0.20 (-0.23, -0.04)	-0.39 (-0.46, -0.15)	-0.28 (-0.32, -0.05)	-0.47 (-0.84, -0.19)	-0.85 (-1.15, -0.35)	-2.04 (-2.17, -1.05)
XNF	-0.23 (-0.35, 0.04)	-0.49 (-0.53, -0.08)	-0.60 (-0.64, -0.15)	-0.93 (-1.04, -0.39)	-0.25 (-0.38, 0.01)	-0.57 (-0.58, -0.08)	-0.65 (-0.73, -0.20)	-1.00 (-1.12, -0.42)	-0.30 (-0.48, 0.07)	-0.63 (-0.66, -0.08)	-0.78 (-0.85, -0.17)	-1.33 (-1.60, -0.53)
XAF	-0.35 (-0.48, -0.35)	-0.68 (-0.84, -0.64)	-0.90 (-1.06, -0.77)	-1.74 (-1.95, -1.12)	-0.42 (-0.55, -0.41)	-0.79 (-0.98, -0.75)	-1.07 (-1.24, -0.92)	-2.10 (-2.36, -1.32)	-1.22 (-1.76, -0.89)	-2.44 (-2.95, -2.16)	-3.66 (-4.06, -2.99)	-7.93 (-9.75, -4.74)
WLD	-0.49 (-1.09, -0.46)	-1.17 (-1.94, -0.85)	-1.37 (-1.77, -1.06)	-2.84 (-4.02, -1.91)	-0.45 (-0.97, -0.43)	-1.07 (-1.74, -0.77)	-1.26 (-1.62, -0.97)	-2.62 (-3.70, -1.75)	-0.49 (-1.12, -0.47)	-1.39 (-2.07, -0.95)	-1.71 (-2.38, -1.25)	-3.96 (-5.39, -2.49)

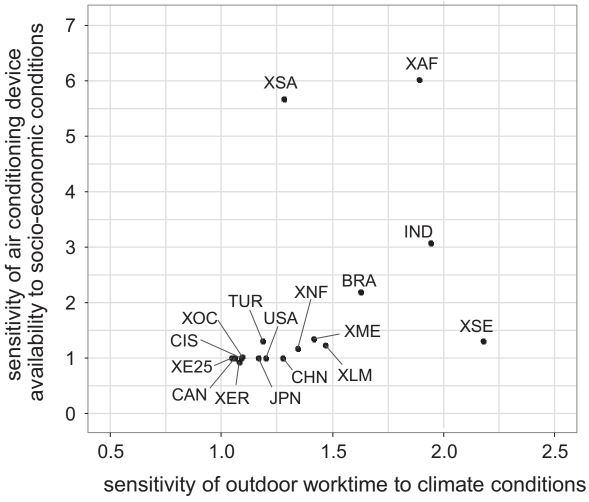

Figure 4. Regional sensitivity to climatic and socioeconomic conditions. The horizontal axis indicates the ratio of outdoor/high-intensity worktime under the RCP8.5 condition to outdoor/high-intensity worktime under the NoCC condition. The vertical axis indicates the ratio of the air-conditioning device penetration rate in SSP1 to that in SSP3. See the caption of table 1 for a description of region names.

50%, and thus there will still be a number of workers who do not benefit by air-conditioning devices even at the end of the 21st century. In such a situation, particularly in developing countries, a substantial number of workers are exposed to heat stress, even if they work indoors.

3.5. Relationship between temperature increase and GDP loss

We examined the relationship between temperature increase and GDP loss rate to examine the benefit of achieving the 1.5 °C goal. Figure 7 shows the relationship between temperature increase and global

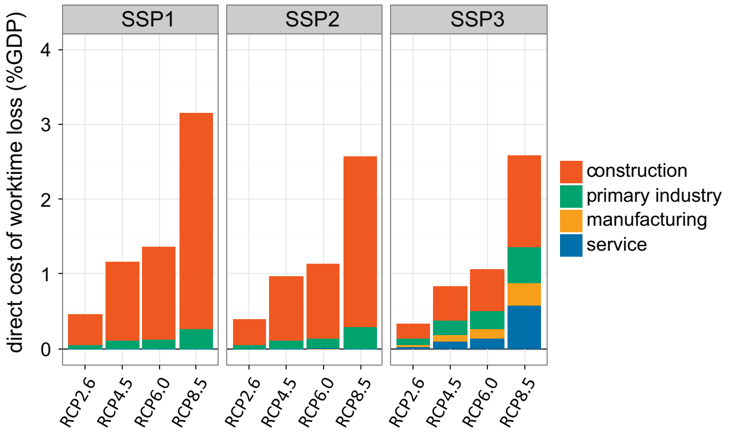

Figure 5. Direct cost of worktime loss for each industrial sector. The direct cost was calculated as the additional wages needed to compensate the worktime loss. This cost is shown as the percentage of the GDP in 2100.

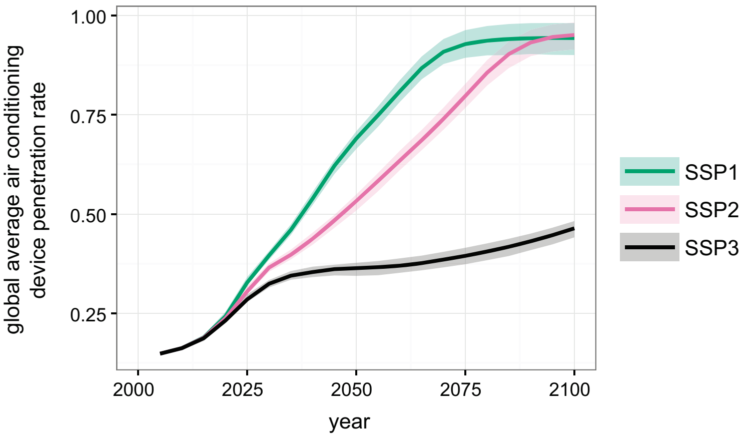

Figure 6. Global air-conditioning device penetration rate. Bold lines represent the median value for individual SSPs, and shaded areas indicate the minimum and maximum values obtained by four RCPs and five GCMs under each SSP.

GDP loss rate in 2100 under SSP1. We selected SSP1 because the possibility of achieving the 1.5 °C goal is low, except in the case of SSP1. (The results for SSP2 and SSP3 are shown in supplementary information S6.) The temperature increase was calculated based on the difference from the value in the simulation base year (2005) and from the pre-industrial level. The lower bound of the simulated range (RCP2.6) is expected to include the temperature increase corresponding to a 1.5 °C temperature increase as compared to the pre-industrial level. In the simulated range, the relationship is approximately linear, and the existence of a distinct inflection point is not expected. The slope of the linear regression line was −0.63%/°C, which indicates that if the 1.5 °C goal were achieved, the GDP loss rate would be reduced by approximately 0.3%, as compared to that of the 2.0 °C goal.

3.6. Sensitivity Analysis

Global total GDP change rates were calculated for the result of the sensitivity analyses, as shown in figure 8. When a lower propensity to install the air-conditioning device was assumed, GDP loss rates were larger than those under the normal assumption, particularly under lower-economic-growth scenarios. The difference in percentage GDP in 2100 were less than 0.05% for all SSPs under RCP2.6, and 0.00%, 0.13%, and 0.87% for SSP1, SSP2, and SSP3, respectively, under RCP8.5. Because of lower air-conditioning device penetration rates, more indoor worktime loss would occur and would cause additional GDP loss. However, in the highest-economic-growth scenario (SSP1), even for a lower propensity to install the air-conditioning device were assumed, the income level was still above the ‘threshold’, and the air-conditioning device penetration rate was high enough to prevent indoor worktime loss. On the other hand, when the starting time for working was assumed to be earlier by 3 hours, GDP loss rates were smaller than those under the normal assumption, regardless of the socioeconomic assumption. The differences in percentage GDP in 2100 were 0.11%, 0.10%, and 0.14% for SSP1, SSP2, and SSP3, respectively, under RCP2.6, and were 0.57%, 0.55%, and 1.08% for SSP1, SSP2, and SSP3, respectively, under RCP8.5. In the early morning, WBGT tends to be low compared to that in the

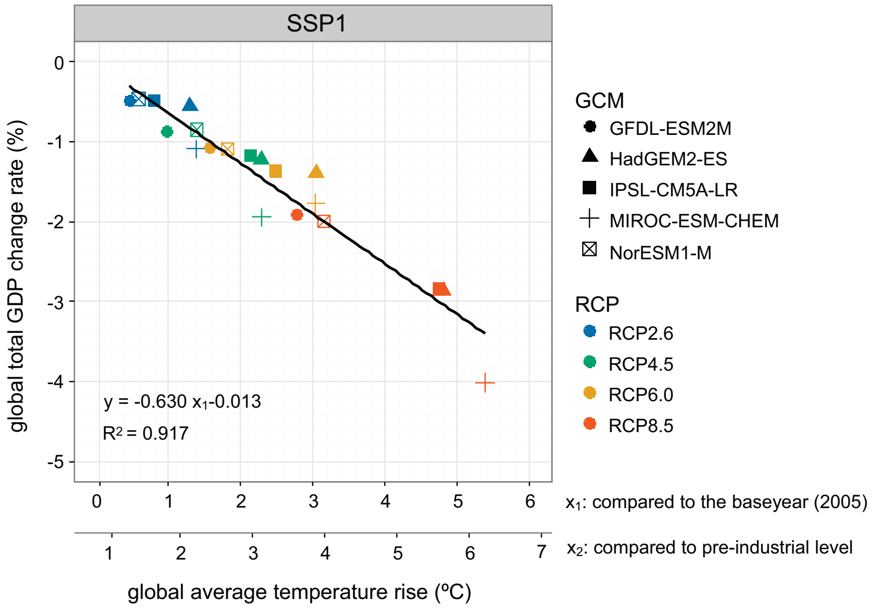

Figure 7. Relationship between GDP change rate and temperature increase. The global average temperature increase is calculated as the difference from the simulation base year (2005) level (x_1) and from pre-industrial level (x_2). The GDP change rate is represented as the difference from the GDP under the NoCC condition in 2100.

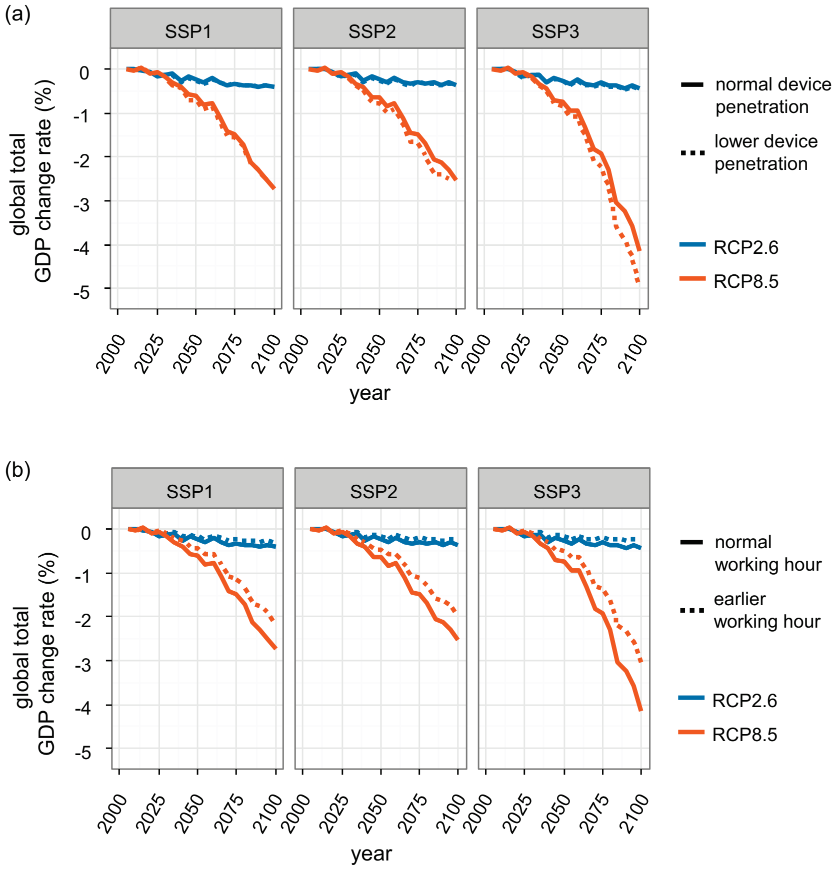

Figure 8. Result of sensitivity analyses. Differences from the GDP under the NoCC condition for normal assumptions and alterative assumptions. (*a*) Alternative assumption for air-conditioning device availability, and (*b*) alternative assumptions for working hours. This figure corresponds to figure 3.

afternoon. Thus, worktime reduction was smaller and consequently yielded lower GDP loss. However, the general characteristics and qualitative results hold for both alternative assumptions.

4. Discussion

The present study is the first to provide a quantitative estimation of the economic cost for workplace heat-related illness prevention through worker breaks under a wide range of climatic and socioeconomic conditions and of the benefit of mitigating climate change and socioeconomic development. A considerably high economic cost of up to 2.6%–4.0% of global total GDP under a high-emission scenario (RCP8.5) is on the same order of magnitude as predicted by previous studies [6, 7]. While a direct comparison is difficult due to differences in the assumptions, the cost estimated in the present study is substantial, or even dominant, as compared to the estimated total economic cost associated with climate change including the effects other than worktime reduction [37]. For reference, the global annual GDP growth rate during the 1995–2015 period was approximately 3.5%. On the other hand, the cost in the low-emission scenario (RCP2.6) was substantially lower compared to that in the high-emission scenario (0.46%–0.49%). The differences in these values between RCP8.5 and RCP2.6 correspond to the benefit of climate change mitigation, and the values are 2.1%–3.5% of global total GDP. The result indicates that pursing a 2.0 °C goal is valuable from the viewpoint of the economic cost of workplace heat-related illness prevention. However, the cost was not negligible even under RCP2.6. In addition to the benefit of climate change mitigation, the cost effectiveness of climate change mitigation is also of interest. Although there is a large uncertainty, the cost of mitigation corresponding to RCP2.6 measured by GDP loss rate (median value) is estimated to be approximately 5% in 2100 [38]. This means that approximately 40%–70% of the mitigation cost may be recovered by only the cost benefit derived from the worktime reduction. This may be a strong incentive for achieving the mitigation target. In particular, climate mitigation would benefit severely affected regions, such as India and South-East Asia. Although conducting a region-by-region cost-benefit analysis may be interesting, how to distribute the global cost of mitigation for each region or country depends on the design of rules and policies, such as emission trading [39], which is beyond the scope of the present study.

The apparent global total GDP loss rates were similar among SSPs, but their disaggregated components differed substantially. In particular, under the low-economic-growth scenario (SSP3), broader regions and industrial sectors were affected. This difference is attributed primarily to the lower availability of air-conditioning devices in SSP3. In SSP1 or SSP2, the worktime loss for indoor work was negligible or even over-compensated as a result of air-conditioning device use. In the present study, the additional penetration of air-conditioning devices is assumed to be independent of the explicit goal of preventing worktime reduction. However, the results revealed that such penetration, which was driven primarily by socioeconomic status, played an important role.

In addition, under SSP3, the total economic cost (GDP loss) was greater than the direct cost of worktime loss (figures 3 and 5). This indicates that the economy in SSP3 is more vulnerable to worktime loss. In the AIM/CGE model, each industrial sector has a constant elasticity substitution (CES) production function. Moreover, the CES production function receives labor and capital as inputs, and labor and capital are substitutable. In SPP3, the production function tends to depend on labor rather than capital (production is more labor intensive). Therefore, an adverse effect on labor (worktime loss) can result in a greater reduction in output for the production in SSP3.

These results imply that higher growth in socioeconomic status can reduce the vulnerability to worktime loss due to climate change, particularly in developing countries. However, even if high socioeconomic growth is achieved, a substantial effect on the economy associated with outdoor industrial sectors is still expected. For these sectors, some intentional countermeasures, which include intentional acclimatization, mechanization of work, and worktime shifting, are necessary. In addition to these measures, further mitigation of climate change (i.e. the 1.5 °C goal) is also worthwhile to consider. The regression analysis of the present study revealed that the economic cost would decrease in proportion to the degree of climate change mitigation. The difference in economic loss between the 1.5 °C goal and the 2.0 °C goal is expected to be approximately 0.3% of global GDP in 2100. However, this estimation is based on a simple regression analysis, and thus further study is needed.

Although the present study quantified the relationship between the economic cost of heat-related illness prevention through worker breaks and climatic/socioeconomic conditions, caution is needed when interpreting these results. The estimated economic cost should not be interpreted as an estimation of GDP loss simply caused by heat-related stress in workers. Heat stress can reduce the efficiency of work [40, 41], but this type of reduction differs from the recommended reduction in worktime considered in the present study. In addition, possible reduction of cold-induced labor productivity losses was not considered in this study. The recommendation is not an obligation and is not always followed at actual worksites. Therefore, the cost determined in the present study should be regarded as the economic cost of heat-related illness prevention through worker breaks under the situation in which the worktime recommendation is strictly followed.

Several limitations also exist. In the present study, homogeneous assumptions were applied across regions and industrial sub-sectors, i.e. the work place and intensity of each industrial sector were assumed to be the same across regions, and air-conditioning device availability was assumed to be the same across sectors within a region. However, the actual situation of the workplace varies according to region and sector. The situation may change depending on the technological or social innovations in the future. For example, several type of industry may be mechanized, or outdoor works may be replaced by indoor works, but such kind of innovations were not included in the model. We did not consider non-uniform thermal conditions, such as the urban heat-island effect, within a grid cell. The model structure also has a limitation. The labor market is assumed to be a perfect market, and reallocation of labor across sectors is also assumed to occur freely in the model. For example, construction sectors increase the input of labor to compensate the worktime loss. In the real economy, however, construction work requires specialized skills. Although the perfect-market assumption would be reasonable for long-term prediction of, for example, the labor market, the perfect assumption is too strong for predictions in the real economy. Therefore, reallocation of labor in the real economy could be smaller than predicted by the model. These factors may affect the results. In particular, if we focus on local-level or short-term issues in future studies, these factors should also be considered.

In addition, proactive responses to climate change were not considered in this study. This assumption is somewhat unrealistic because, if the world faces serious economic losses due to worktime losses, society will adapt to this situation by, for example, installation of additional air-conditioning devices, shifting the time of day for working, or changing the industrial structure. In other words, adaptation measures may change the situation. However, it is important to quantify the economic impact under the situation in which no countermeasures are taken as the worst-case-scenario analysis, and so this study remains significant. Estimating the size of the impact reduction by adaptation is also important. For example, as indicated in the sensitivity analysis, shifting the time of day for working could reduce the adverse effects, and the availability of air-conditioning devices could also affect the results. In this study, we established a framework to quantify the benefit of these effects. A cost-benefit analysis of these adaptation measures and identification of the optimal level of adaptation is a subject for future research.

5. Conclusion

This study provided a comprehensive assessment of the economic cost of heat-related illness prevention through worker breaks in the workplace. The economic cost is expected to increase continuously throughout the 21st century, and the GDP loss rate is expected to reach 2.8% (SSP1), 2.6% (SSP2), and 4.0% (SSP3) under RCP8.5 in 2100. Limiting the temperature increase lowers the cost effectively. Under RCP2.6, the GDP loss rate is expected to be 0.49%, 0.46%, and 0.49% for SSP1, SSP2, and SSP3, respectively. This implies that a large portion of the climate-change mitigation cost can be recovered from the cost benefit derived from worktime reduction under RCP2.6. In addition, more stringent climate mitigation (i.e. 1.5 °C goal) is expected to proportionally reduce the economic cost of the worktime reduction, but further study is needed.

The development of socio-economic states limits indoor worker's exposure to heat stress and lowers the vulnerability of the economy to worktime losses. However, even if stringent climate mitigation and the highest socio-economic development are achieved, the cost remains non-negligible due to outdoor work. The effectiveness and cost of adaptation measures that can be applied to outdoor work should be quantitatively investigated in the future.

Acknowledgments

This study was supported by the Environmental Research and Technology Development Fund (S-14) of the Ministry of the Environment of Japan.

References

[1] Xiang J *et al* 2014 Health impacts of workplace heat exposure: an epidemiological review *Ind. Health* **52** 91–101

[2] Parsons K 2014 *Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort, and Performance* 3rd edn (New York: CRC Press)

[3] ISO FDIS 7243 2015 *Ergonomics of the Thermal Environment—Assessment of Heat Stress using the WBGT (Wet Bulb Globe Temperature) Index* (International Organisation for Standardization)

[4] NIOSH 2016 Occupational exposure to heat and hot environments: criteria for a recommended standard 2016-106

[5] Kjellstrom T *et al* 2009 The direct impact of climate change on regional labor productivity *Arch. Environ. Occup. Health* **64** 217–27

[6] Roson R and Van der Mensbrugghe D 2012 Climate change and economic growth: impacts and interactions *Int. J. Sustain. Econ.* **4** 270–285

[7] Kjellstrom T 2016 Impact of climate conditions on occupational health and related economic losses: a new feature of global and urban health in the context of climate change *Asia Pac. J. Public Health* **28** 28S–37S

[8] Dunne J P, Stouffer R J and John J G 2013 Reductions in labour capacity from heat stress under climate warming *Nat. Clim. Change* **3** 563–6

[9] Kjellstrom T, Lemke B and Otto M 2013 Mapping occupational heat exposure and effects in South-East Asia: ongoing time trends 1980–2011 and future estimates to 2050 *Ind. Health* **51** 56–67

[10] Suzuki-Parker A and Kusaka H 2016 Future projections of labor hours based on WBGT for Tokyo and Osaka, Japan, using multi-period ensemble dynamical downscale simulations *Int. J. Biometeorol.* **60** 307–10

[11] UNFCCC 2015 *Adoption of the Paris Agreement*

[12] Wiebe K *et al* 2015 Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios *Environ. Res. Lett.* **10** 085010

[13] Hanasaki N *et al* 2013 A global water scarcity assessment under shared socio-economic pathways—Part 2: water availability and scarcity *Hydrol. Earth Syst. Sci.* **17** 2393–413

[14] Hasegawa T *et al* 2014 Climate change impact and adaptation assessment on food consumption utilizing a new scenario framework *Environ. Sci. Technol.* **48** 438–45

[15] Isaac M and van Vuuren D P 2009 Modeling global residential sector energy demand for heating and air conditioning in the context of climate change *Energ. Policy* **37** 507–21

[16] Hasegawa T *et al* 2015 Consequence of climate mitigation on the risk of hunger *Environ. Sci. Technol.* **49** 7245–53

[17] Hasegawa T *et al* 2016 Economic implications of climate change impacts on human health through undernourishment *Clim. Change* **136** 189–202

[18] Hasegawa T *et al* 2016 Introducing detailed land-based mitigation measures into a computable general equilibrium model *J. Cleaner Prod.* **114** 233–42

[19] Zhou Q, Hanasaki N, Fujimori S, Masaki Y and Hijioka Y 2016 Model-based analysis of impact of climate change and mitigation on hydropower *J. Jpn. Soc. Civl. Eng.* B **72** 19–24

[20] Xie Y *et al* 2016 Economic impacts from $PM_{2.5}$ pollution-related health effects in China: a provincial-level analysis *Environ. Sci. Technol.* **50** 4836–43

[21] Hasegawa T *et al* 2016 Quantifying the economic impact of changes in energy demand for space heating and cooling systems under varying climatic scenarios *Palgrave Commun.* **2** 16013

[22] Fujimori S, Masui T and Matsuoka Y 2012 AIM/CGE [basic] manual *Discussion paper series, Center for Social and Environmental Systems Research, NIES 2012-01*

[23] Budd G M 2008 Wet-bulb globe temperature (WBGT)—its history and its limitations *J. Sci. Med. Sport* **11** 20–32

[24] Bernard T E and Pourmoghani M 1999 Prediction of workplace wet bulb global temperature *Appl. Occup. Environ. Hyg.* **14** 126–34

[25] Liljegren J C *et al* 2008 Modeling the wet bulb globe temperature using standard meteorological measurements *J. Occup. Environ. Hyg.* **5** 645–55

[26] Lemke B and Kjellstrom T 2012 Calculating workplace WBGT from meteorological data: a tool for climate change assessment *Ind. Health* **50** 267–78

[27] Fan R-E *et al* 2008 LIBLINEAR: A library for large linear classification *J. Mach. Learn. Res.* **9** 1871–74

[28] O'Neill B C *et al* 2013 A new scenario framework for climate change research: the concept of shared socioeconomic pathways *Clim. Change* **122** 387–400

[29] KC S and Lutz W 2017 The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100 *Glob. Environ. Change* **42** 181–92

[30] Jones B and O'Neill B C 2016 Spatially explicit global population scenarios consistent with the shared socioeconomic pathways *Environ. Res. Lett.* **11** 084003

[31] van Vuuren D P *et al* 2013 A new scenario framework for climate change research: scenario matrix architecture *Clim. Change* **122** 373–86

[32] Hempel S *et al* 2013 A trend-preserving bias correction—the ISI-MIP approach *Earth Syst. Dynam.* **4** 219–36

[33] Riahi K *et al* 2017 The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Glob. Environ. Change* **42** 153–68

[34] van Vuuren D P *et al* 2017 Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm *Glob. Environ. Change* **42** 237–250

[35] Fricko O *et al* 2017 The marker quantification of the shared socioeconomic pathway 2: a middle-of-the-road scenario for the 21st century *Glob. Environ. Change* **42** 251–67

[36] Fujimori S *et al* 2017 SSP3: AIM implementation of shared socioeconomic pathways *Glob. Environ. Change* **42** 268–83

[37] IPCC 2014 Key economic sectors and services *Climate Change 2014: Impacts, Adaptation, and Vulnerability IPCC Working Group II Contribution to AR5* (New York: Cambridge University Press) pp 659–708

[38] IPCC 2014 Assessing transformation pathways *Climate Change 2014: Mitigation of Climate Change IPCC Working Group III Contribution to AR5* (New York: Cambridge University Press) pp 413–510

[39] Fujimori S *et al* 2016 Will international emissions trading help achieve the objectives of the Paris Agreement? *Environ. Res. Lett.* **11** 104001

[40] Pilcher J J, Nadler E and Busch C 2002 Effects of hot and cold temperature exposure on performance: a meta-analytic review *Ergonomics* **45** 682–98

[41] Hancock P A, Ross J M and Szalma J L 2007 A meta-analysis of performance response under thermal stressors *Hum. Fact.: J. Hum. Fact. Ergonomics Soc.* **49** 851–77