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Heat stress, labor productivity, and economic impacts: analysis of climate change impacts using two-way coupled modeling

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Abstract

Climate change affects various fundamental human activities, and understanding the consequences of its impacts is essential. Among them, heat stress considerably affects economic conditions. Furthermore, when analyzing the socioeconomic impacts of climate change, both socioeconomic and climate systems must be considered simultaneously, though such studies are scarce. This study aimed to evaluate the socioeconomic impacts of changes in labor productivity due to heat stress (measured by wet bulb globe temperature) under various climate change scenarios through a new modeling framework that coupled a computable general equilibrium model and an Earth system model of intermediate complexity to realize the interactions between the two systems through the relationship between heat stress and labor productivity. Results indicated that labor productivity declined as climate change progressed (particularly in hot and humid regions), driving a gradual decline in total global gross domestic product (GDP). Although regional GDP largely decreased where labor productivity considerably declined, it slightly increased in some areas because of a comparative advantage brought about by the difference in the impact on labor productivity by region. Consequently, carbon dioxide (CO_2) emissions and concentrations and the resulting temperature were slightly reduced when examining the impact of climate change on labor productivity. These tendencies were similar in both business-as-usual and climate change mitigation scenarios, but the overall impacts were smaller under the latter. There was a limited impact on CO_2 emissions, CO_2 concentrations, and temperature via integrated socioeconomic and climate systems. However, this study focused on only a single channel of the various interactions between the two systems. For a more complete evaluation of the impacts of climate change, further development of the integrated model is required.

1. Introduction

Climate change affects various socioeconomic activities (Burke *et al* 2015, Carleton and Hsiang 2016, Hsiang *et al* 2017, Doğanlar *et al* 2021, Kahn *et al* 2021). The projected negative impact on the global economy is between 5%–20% for the business-as-usual (BaU) or representative concentration pathway (RCP) 8.5 scenarios (Stern 2007, Burke *et al* 2015, Takakura *et al* 2019). Chen *et al* (2020) also found that climate change damage could cost ~47% of the global gross domestic product (GDP) in 2100. However, this notably drops to ~1% for the 2 °C scenarios (Nordhaus 2017, Nordhaus 2018). Indeed, a low level (1 °C–2 °C increase) of warming could induce a positive effect on the economy, particularly when considering mitigation and adaptation costs (Tol 2018, Ueckerdt *et al* 2019).

The economic impacts of climate change are broad, incorporating changes in agricultural productivity (Roson and van der Mensbrugghe 2012, Boonwichai *et al* 2018), increases in natural disaster frequency (Neumann *et al* 2015, Gariano and Guzzetti 2016), declines in labor productivity (Kjellstrom *et al* 2009a, 2009b,

Roson and van der Mensbrugghe 2012), greater prevalence of infectious diseases (Béguin *et al* 2011, Leal Filho *et al* 2018), and decreases in ecosystem services (Forsius *et al* 2013, Lee *et al* 2015). These phenomena (often negatively) affect economic activities and anthropogenic greenhouse gas (GHG) emissions in particular, making it important to understand their intrinsic interactions. Moreover, coupling the component of the impact of climate change with a socioeconomic (or economic) model may reveal that the extent of climate change differs from initial assumptions (i.e., when climate change impacts are not explicitly considered). Among them, the economic impact of labor productivity affected by heat stress is considered larger than that of agriculture, natural disasters due to sea level rise, and ecosystem services, with a decline in labor productivity associated with a 0.5%–4.6% loss of GDP by 2100, depending on the scenario (Tachiiri *et al* 2021). To assess the economic impacts of climate-change- or heat-induced labor productivity changes, Takakura *et al* (2017) employed a computable general equilibrium (CGE) model with a spatiotemporally high-resolution heat exposure index, revealing that the global GDP loss by 2100 will be 2.6%–4.0% under RCP 8.5, and 0.46%–0.49% under RCP 2.6 (median values). Such impacts cannot be avoided or counteracted by an adaptation measure such as shifting working time to cooler hours of the day (Takakura *et al* 2018).

Heat stress due to hot and humid weather affects human activities, in addition to increasing the risk of heat-related illnesses. The frequency of heatwaves is predicted to increase due to climate change (Coffel *et al* 2018), and so is the number of people impacted by dangerous heat conditions (Matthews *et al* 2017). Such severe conditions also affect the working environment (Kjellstrom *et al* 2009b, Xiang *et al* 2014, Li *et al* 2016). Although reducing work intensity or increasing the frequency of short breaks are effective in preventing heat-related negative influences (Kjellstrom *et al* 2009b), such measures inherently reduce work hours and labor productivity (Kjellstrom *et al* 2009a, Dunne *et al* 2013, Donadelli *et al* 2017). Accordingly, hot and humid weather causes unavoidable economic loss (Roson and Sartori 2016, Donadelli *et al* 2017, Rezai *et al* 2018, Zhang *et al* 2018). This impact is higher for outdoor (e.g., agricultural sector) than indoor work (e.g., service sectors) (Kjellstrom *et al* 2009b). For a more comprehensive literature review on the economic impact of labor productivity changes due to heat stress and climate change, see Matsumoto (2019) and Tachiiri *et al* (2021).

Changes in economic activity due to climate change can in turn affect anthropogenic GHG emissions, and subsequently, climate change levels (i.e., feedback effects). Woodard *et al* (2019) indicated that feedback from the economy to climate change via GHG emissions is comparable to natural feedback effects. Roson and van der Mensbrugghe (2012) also concluded that changes in GHG emissions (including carbon dioxide [CO_2], methane, and nitrous oxide) caused by climate change were non-negligible.

A few studies that couple socioeconomic and climate models have considered this effect more thoroughly manner (Collins *et al* 2015, Paltsev *et al* 2015, Thornton *et al* 2017, Mercure *et al* 2018, Monier *et al* 2018). Most studies do not consider the interactions between socioeconomic and climate systems when assessing the labor productivity-based impact of climate change on the economy, but Matsumoto (2019) combined CGE and simple climate models to consider interactions or feedback effects, and used an integrated framework to evaluate this impact; however, the simple climate model employed can only calculate climate change annually across a global scale, and is unable to distinguish between daytime (normal working hours) and nighttime temperatures for calculating labor productivity.

This study sought to conduct a more accurate assessment of the future economic impacts of climate change via shifting labor productivity by considering the interactions between socioeconomic and climate systems using a two-way coupled CGE model (socioeconomic aspect)-Earth system model of intermediate complexity (EMIC; climate aspect) based on daytime conditions, obtaining finer spatiotemporal resolutions than previous research. Its main contribution to the literature is the evaluation of the socioeconomic impacts of climate change by considering the feedback effects between the socioeconomic and climate models through the relationship between heat stress and labor productivity.

2. Methods

2.1. Model integration

Of the coupled socioeconomic and climate models, the CGE model is based on the Economic Projection and Policy Analysis (EPPA) model *v*.6 (Chen *et al* 2015, Monier *et al* 2018) for socioeconomic analysis, and the Japan Uncertainty Modeling Project/Model for Interdisciplinary Research on Climate (JUMP/MIROC)–Loosely Coupled Model (LCM) is an EMIC for climate analysis (Tachiiri *et al* 2010). These two models realize vital interactions between socioeconomic and climate systems through their coupled relationship between climate change and labor productivity (figure 1). GHG emissions obtained by the CGE model calculation were inputted into the EMIC to calculate future climate conditions. The predicted temperature from EMIC and relative humidity are inputted back into the CGE model using the relationship between climate conditions and labor productivity as a connector.

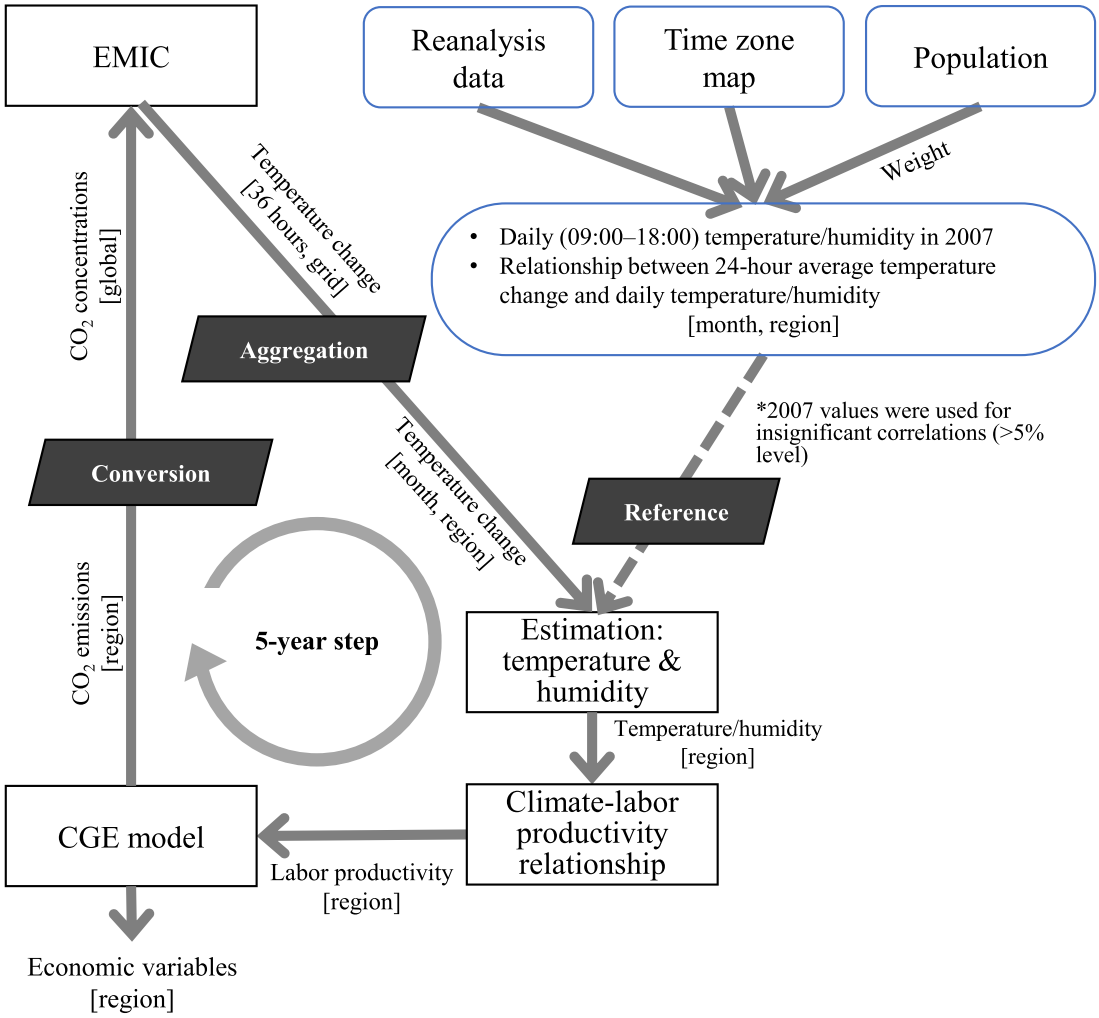

Figure 1. Conceptual modeling framework for assessing global-scale socioeconomic impacts of climate change through shifting labor productivity.

The spatiotemporal resolutions of the two models are different. The CGE model is an annual, regional model, while EMIC uses 6°×6° grids over 36 h. GHG emissions obtained from the CGE model were aggregated to the global scale, and converted to reflect the change in concentration levels to be inputted into the EMIC. By contrast, climate conditions from the EMIC were aggregated to the regional scale of the CGE model. Temporally, the daytime climate conditions were used to calculate the monthly labor productivity changes (see section 2.3.2), and subsequently converted to annual averages.

2.2. Socioeconomic aspects

A multi-regional, multi-sectoral, recursive dynamic CGE model with energy and environmental components was used to analyze future scenarios from socioeconomic perspectives. The model is developed on the General Algebraic Modeling System. We depict the basic model information based on Chen *et al* (2015), with a detailed description of the original model and its structure.

The model's input-output structure for regional economies and international trade is based on the Global Trade Analysis Project (GTAP) database (*v*.8; 2007 base year; https://www.gtap.agecon.purdue.edu/databases/v8/default.asp). The model was initially calibrated with GTAP data for the base-year economic conditions, and was also calibrated based on International Monetary Fund (2013) and International Energy Agency (2012) for the near-term economic conditions. The original 129 regions and 57 sectors of the GTAP database were aggregated into 18 and 14, respectively (table 1). Although the electricity sector involves various power generation technologies, including thermal, nuclear, hydro, solar, wind, biomass, and other renewables, the commodity produced is identical (i.e., electricity).

Similar to many other CGE models (e.g., Matsumoto 2015, Matsumoto and Andriosopoulos 2016, Yu *et al* 2018, Li and Masui 2019), the current model applied nested constant elasticity of substitution functions to

Table 1. Definitions of regions and sectors of the CGE model.

Code	Region	Code[a]	Sector
USA	United States	CROP	Agriculture - crops
CAN	Canada	LIVE	Agriculture - livestock
MEX	Mexico	FORS	Agriculture - forestry
JPN	Japan	FOOD	Food products
ANZ	Australia, New Zealand, & Oceania	COAL	Coal
EUR	European Union+8	OIL	Crude oil
ROE	Eastern Europe and Central Asia	ROIL	Refined oil
RUS	Russia	GAS	Gas
ASI	Southeast Asia	ELEC	Electricity
KOR	South Korea	EINT	Energy-intensive industries
IDZ	Indonesia	OTHR	Other industries
CHN	China	DWE	Ownership of dwellings
IND	India	SERV	Services
BRA	Brazil	TRAN	Transport
AFR	Africa		
MES	Middle East		
LAM	Latin America		
REA	Rest of Asia		

[a] CROP, LIVE, and FORS were treated as the agricultural sector, FOOD, COAL, OIL, ROIL, GAS, ELEC, EINT, and OTHR were treated as the manufacturing sector, and DWE, SERV, and TRAN were treated as the service sector when calculating labor productivity changes (see equations (1)–(3) for the details). Source: Created based on Chen *et al* (2015)

specify preferences and production technologies. Regarding the environmental aspect, the model considered emissions of CO_2, non-CO_2 GHGs, and other air pollutants emitted from energy consumption and industrial activities.

The model was run along with the socioeconomic (demographic and economic) scenarios presented in section 2.4. The model considers global emissions trading under mitigation scenarios; global emission pathways between the base year and 2100 were given as constraints, although similar constraints were not applied in the BaU scenario.

The present study modified the original model to express the climate change impact on labor productivity (the relationship between heat stress measured by wet bulb globe temperature [WBGT] and labor productivity). Changes in labor productivity affect the labor input necessary to produce goods/services in the production functions. To this end, the model introduced the relationships based on empirical studies by Kjellstrom *et al* (2009a) and Kjellstrom (2009b), updated by Roson and Sartori (2016) (equations (1)–(5)).

$$\begin{cases} lab_{agr,r} = 1 & \text{if } wbgt_r \leqslant 26 \\ lab_{agr,r} = 1 - \dfrac{1-0.25}{36-26}(wbgt_r - 26) & \text{if } 26 < wbgt_r \leqslant 36, \\ lab_{agr,r} = 0.25 & \text{if } wbgt_r > 36 \end{cases} \tag{1}$$

$$\begin{cases} lab_{man,r} = 1 & \text{if } wbgt_r \leqslant 28 \\ lab_{man,r} = 1 - \dfrac{1-0.25}{43-28}(wbgt_r - 28) & \text{if } 28 < wbgt_r \leqslant 43, \\ lab_{man,r} = 0.25 & \text{if } wbgt_r > 43 \end{cases} \tag{2}$$

$$\begin{cases} lab_{ser,r} = 1 & \text{if } wbgt_r \leqslant 30 \\ lab_{ser,r} = 1 - \dfrac{1-0.25}{50-30}(wbgt_r - 30) & \text{if } 30 < wbgt_r \leqslant 50, \\ lab_{ser,r} = 0.25 & \text{if } wbgt_r > 50 \end{cases} \tag{3}$$

$$wbgt_r = 0.567T_r + 3.94 + 0.393E_r, \tag{4}$$

$$E_r = \frac{RH_r}{100} \times 6.105 \times \exp\left(\frac{17.27T_r}{237.7 + T_r}\right), \quad (5)$$

where $lab_{x,r}$: labor productivity of sector x (*agr*: agriculture, *man*: manufacturing, and *ser*: service) of region r, $wbgt_r$: WBGT of r (°C), T_r: temperature of r (°C), E_r: average absolute humidity (water vapor pressure) in r (hPa), and RH_r: relative humidity of r (%).

These global-scale estimates (no region-specific estimates exist) were prepared for three groups of sectors—agriculture, manufacturing, and services—following Roson and Sartori (2016). The agricultural sectors were the most sensitive to WBGT because of the associated workplaces. Monthly, daily, or even sub-daily climate data have been applied to calculate the changes in labor productivity within a given year (Kjellstrom *et al* 2009b, Roson and Sartori 2016, Takakura *et al* 2017, Matsumoto 2019). In this study, monthly averages of daytime climate conditions (09:00–18:00) were taken, based on normal working hours, and monthly changes in labor productivity were averaged to obtain annual estimates. Predetermined labor productivity improvement in the future, as considered in labor endowment, is the same for all the scenarios.

2.3. Climate aspects

2.3.1. Climatic model

JUMP-LCM (Tachiiri *et al* 2010) was employed as an EMIC, which is an Earth system model with some parts simplified (Claussen *et al* 2002). It consists of a two-dimensional energy-moisture balanced atmosphere, ocean general circulation model, and a loosely coupled land ecosystem model. The grid resolution was 6°×6°. The model reads CO_2 emissions (converted to the change in CO_2 concentrations) and uses the forcing levels for non-CO_2 GHGs (RCP 8.5 for BaU, RCP 4.5 for S45, and RCP 2.6 for S2; see section 2.4 for the scenario description), and outputs surface air temperature.

2.3.2. Estimates of future daytime temperature and relative humidity

Future daytime temperature and relative humidity were estimated according to equation (6):

$$x_{i,r,m,y} = \frac{dx'_{i,r,m}}{dT'_{r,m}} \Delta T_{r,m,y} + x_{i,r,m,2007}, \quad (6)$$

where $x_{i,r,m,y}$: value of i (temperature or relative humidity) in month m of region r for year y, $dx'_{i,r,m}$ and $dT'_{r,m}$: changes in daytime temperature (or humidity) and 24-hour temperature observed within the past data in m of r, $\Delta T_{r,m,y}$: (24 h) temperature anomaly (from 2007) in m of r for y, and $x_{i,r,m,2007}$: value of temperature (or humidity) in m of r for 2007.

$dx'_{i,r,m}/dT'_{r,m}$ is the ratio of the changes in item i for the daytime and 24-hour temperature anomalies obtained from 1979–2019. When the correlations between $dx'_{i,r,m}$ and $dT'_{r,m}$ were weak (i.e., ⩾5% statistical significance level), the first term on the right-hand side of equation (6) was omitted, and x was fixed as the 2007 value (i.e., $x_{i,r,m,2007}$). For slopes, among the 228 cases (12 months × 19 regions [18 regions of the CGE model + Antarctica]), two cases (April and December of the LAM region) lacked a statistically significant linear relationship with temperature, and 47% (107 cases) maintained insignificant relationships with relative humidity. In calculating $x_{i,r,m,2007}$ and $dx'_{i,r,m}$, for consistency with the (current) worker distribution, the population weight based on Center for International Earth Science Information Network (2018) was considered, while for consistency of $dT'_{i,r,m}$, with $\Delta T_{r,m,y}$, only areal weight (not population weight) was applied.

Among the terms on the right-hand side of equation (6), $\Delta T_{r,m,y}$ was obtained from the EMIC calculation. From 2007, the grid-based anomaly calculated from the EMIC output was converted to a region of the CGE model using an areal weight-based matrix for conversion. Other terms on the right-hand side were obtained from the procedure carried out in advance using ERA5 (ECMWF Reanalysis *v*.5) monthly averaged data on single levels from 1979–present (Copernicus Climate Change Service 2017). Monthly averages of hourly measurements were compiled for a spatial resolution of 0.25° × 0.25° from 09:00–18:00 local time to assess daytime conditions. The local time zone map was obtained from ESRI (2013), and rounded to the nearest hour. $x_{i,m,2007}$ values were directly obtained from the ERA5 dataset. As relative humidity data are only available every 3 h, the ratios of saturated vapor pressure of the dew point temperature (available in the same dataset) to current temperature were calculated. Saturated vapor pressure was calculated using the empirical equation presented in equation (7):

$$e_s(t) = \exp\left(19.482 - \frac{4303.4}{t + 243.5}\right), \quad (7)$$

where t: temperature (°C).

This is the approximation of World Meteorological Organization (1988) (equation (S1) available online at stacks.iop.org/ERC/3/125001/mmedia) used by the Japan Meteorological Agency (Abo 2006). Indeed, the

differences between the calculations by equations (7) and (S1) were only less than 0.5% in the temperature range of −20 °C and 40 °C.

2.4. Scenarios

Using the CGE model and EMIC, three scenarios with and without climate change impacts were analyzed: BaU, and two emission-reduction scenarios ('S45' and 'S2'). BaU analyzed the socioeconomic impacts of climate change through labor productivity changes without mitigation measures, whereas the other two evaluated the impact of climate change on the introduction of mitigation measures.

The BaU scenario followed the original EPPA model, incorporating projections of various socioeconomic conditions, including GDP, population, and energy technology (Paltsev *et al* 2005, Energy Information Administration 2010, Gitiaux *et al* 2012, Gordon 2012, International Monetary Fund 2013, United Nations Population Division 2013, World Bank 2013). GDP, population, and primary energy supply for BaU without climate change impacts are shown in figure S1. In this scenario, global GDP, population, and energy supply will expand considerably. The resultant rise in the global average temperature from the 2006 levels will be ∼3.0 °C by 2100, assuming average climate sensitivity.

For the mitigation scenarios, S45 aims to control emissions to stabilize the radiative forcing level at 4.5 $W{\cdot}m^{-2}$ by 2100 or RCP 4.5 (Thomson *et al* 2011). By contrast, S2 is directed at limiting emissions to a 2 °C temperature rise from pre-industrial levels by 2100, with emission pathways similar to S45 in the early part of the century, and decreasing significantly thereafter. Thus, S45 represents an intermediate mitigation scenario (Matsumoto *et al* 2016), and S2 corresponds to the mitigation target of the Paris Agreement (Bataille *et al* 2018). The S2 scenario evaluates the impacts of a successful realization of the 2 °C target, while the S45 scenario evaluates the impacts of the failure to achieve the target but with a certain level of climate change mitigation achieved. The CO_2 emissions across the three scenarios are depicted in figure S2. In the mitigation scenarios, the same settings as for BaU were applied for future assumptions, such as population growth and autonomous energy efficiency improvements, while GDP and other economic activities were calculated using the CGE model.

3. Results

Figure 2 depicts how climate change affected labor productivity in each region by sector (figures 2(a)–(c), (e)–(f)) and season (figure 2(d)). In the BaU scenario, labor productivity was negatively affected by the future increase in the temperature; however, the degree of impact varied by sector and region. Among the sectors, the impacts were the largest for the agricultural (36.8%–100% labor productivity by 2100), and the lowest for the service sectors (83.0%–100% productivity by 2100). Comparing regional impacts, ASI, IDZ, and IND were the three most affected regions. These regions are located in Southeast and South Asia, characterized by hot and humid conditions, and the projected climatic conditions detrimentally impacted labor productivity. MES is also considered a hot area, but the decrease in labor productivity was moderate because of its low relative humidity (<40% every year). By contrast, the high-latitude regions, such as CAN and RUS, revealed no effects, as the WBGT did not reach the lower threshold at which labor productivity begins to decline in any month. Note that some aggregated regions, such as LAM, also showed no effects, but it is due to the sparse spatiotemporal resolution of the CGE model and the impact on labor productivity can be observed in the real world.

Regarding the two mitigation scenarios, the decrease in labor productivity was predictably smaller than that under the BaU scenario because of the lower temperature increases— 49.4%–100% and 52.7%–100% by 2100 for S45 and S2 in the agricultural sector, respectively (figures 2(e)–(f); see figures S3–S4 for full results).

Labor productivity showed strong seasonal trends (figure 2(d)), lower in the hot seasons and higher in the cool/cold seasons. Although labor productivity was not affected in the winter seasons of some regions because the WBGT did not reach the lower threshold, it still declined in the summer. Labor productivity reached its minimum levels during the warmest and wettest parts of the year in already hot and humid regions (similar trends were observed for both of the mitigation scenarios as well). Such declines in labor productivity reduced production and, consequently, affected the macroeconomy.

Figure 3 shows the impact on GDP of each region, as well as the average global impact relative to the no-climate-change-impact case. The global-level negative impact grew with temperature increases, which was about 2% per 1 °C (see figure S8 for the relationship between temperature increase and total global GDP impact). The macroeconomic impacts (positive or negative) also tended to be larger over time for all regions, and can be further classified into three groups: (1) large-negative impacts, (2) small-negative impacts, and (3) positive impacts. Four regions (REA, IDZ, ASI, and IND) were in Group (1), with ASI, IDZ, and IND comprising the three most impacted regions in terms of labor productivity as mentioned above. As mentioned, the regions in this group are located in known hot and humid areas; thus, labor productivity, and subsequently GDP, are considerably reduced (figures 2–3). In particular, the share of production of the primary industry decreased

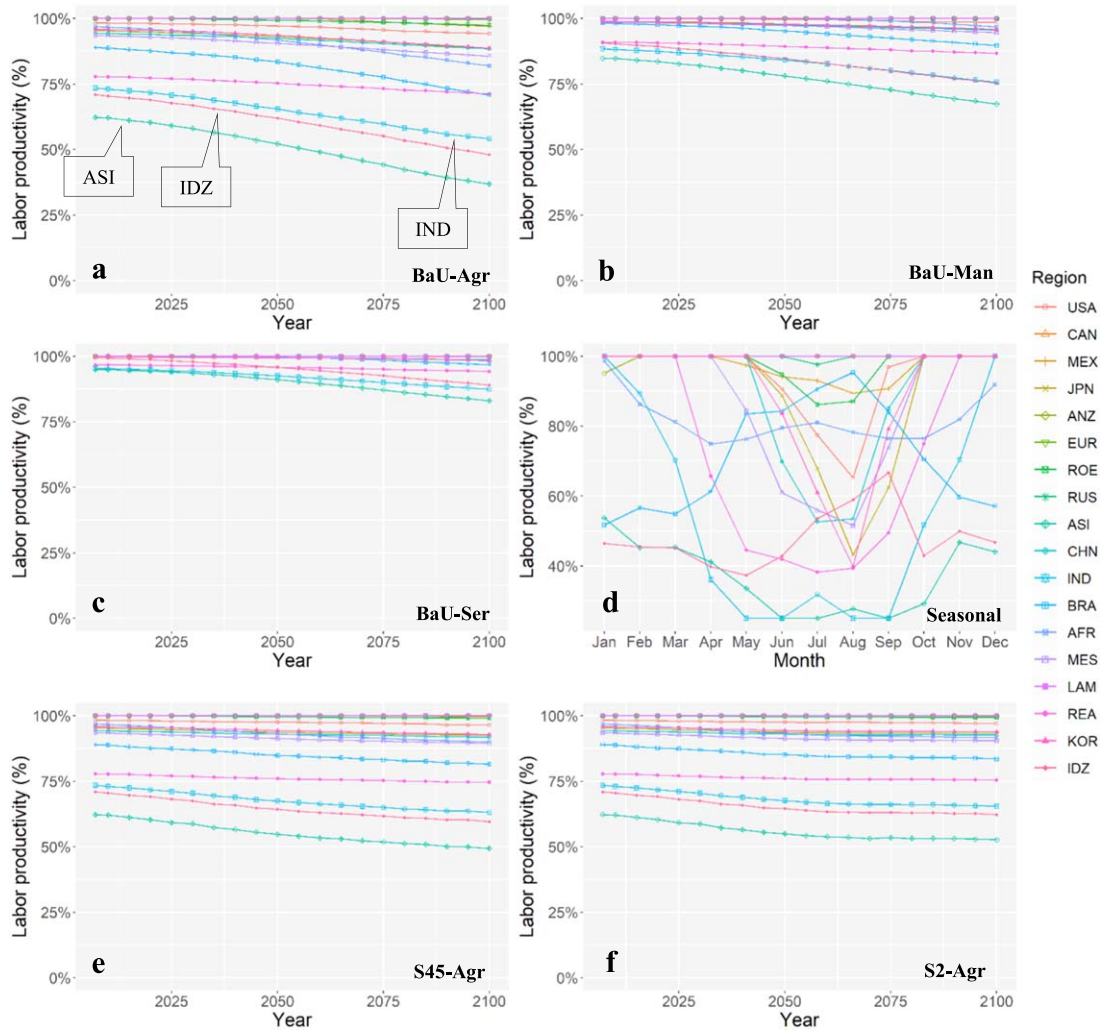

Figure 2. Labor productivity impacts on the following annual scenarios and sectors: (a) BaU-agriculture, (b) BaU-manufacturing, (c) BaU-service, (d) BaU-(seasonal) agriculture in 2100, (e) S45-agriculture, and (f) S2-agriculture. Annual labor productivity is the average of monthly estimates. The supplementary Excel file provides the data for these figures. Figures S3 and S4 show the remaining sector results for S45 and S2, respectively.

around 0.74–1.04 percentage points in these areas (BaU scenario). Most others were classified into Group (2), that is, small-negative impact, also closely related to a decline in labor productivity, although notably smaller than in Group (1). By contrast, USA, CAN, JPN, and EUR experienced positive impacts over the entire analysis period for the USA and EUR, and for part of the periods for the BaU scenario for CAN (2007–2015, 2050) and JPN (2020–2055). In these regions, the impact of climate change on labor productivity was small or non-existent, creating a positive effect on GDP through a comparative advantage. As the impact on labor productivity differed by region, less-affected regions will have a relative advantage in terms of labor input in production activities, increase production, and secure gains through international trade.

While these tendencies were similar across all scenarios, the negative impacts on GDP were reduced by the larger mitigation efforts of correspondingly lower temperature increases, and the resultant lower impact on labor productivity.

Table 2 shows how the components of GDP (expenditure side) were affected under the BaU scenario (see tables S1–S2 for the S45 and S2 scenarios). Consumption was one of the main factors reducing GDP in many regions, considering its share in GDP. The decline in consumption was the largest in the regions that experienced large-negative GDP impacts such as IND, IDZ, and ASI. By contrast, the decline was relatively small in other regions, especially MEX, EUR, and LAM in 2100. Further, export and import also drove regional-dependent impacts on GDP (see also figure S5). Notably, a decline in exports reduced GDP, while a decline in imports increased GDP. In the regions where GDP considerably declined (e.g., REA, IDZ, ASI, and IND), the decline in exports was larger than that in imports, indicating that the impact on trade would be an important factor driving lowered GDP levels. In monetary values, exports in the EINT and OTHR sectors were largely reduced in these regions. Additionally, the shares of exports in the agricultural sectors were often negatively and

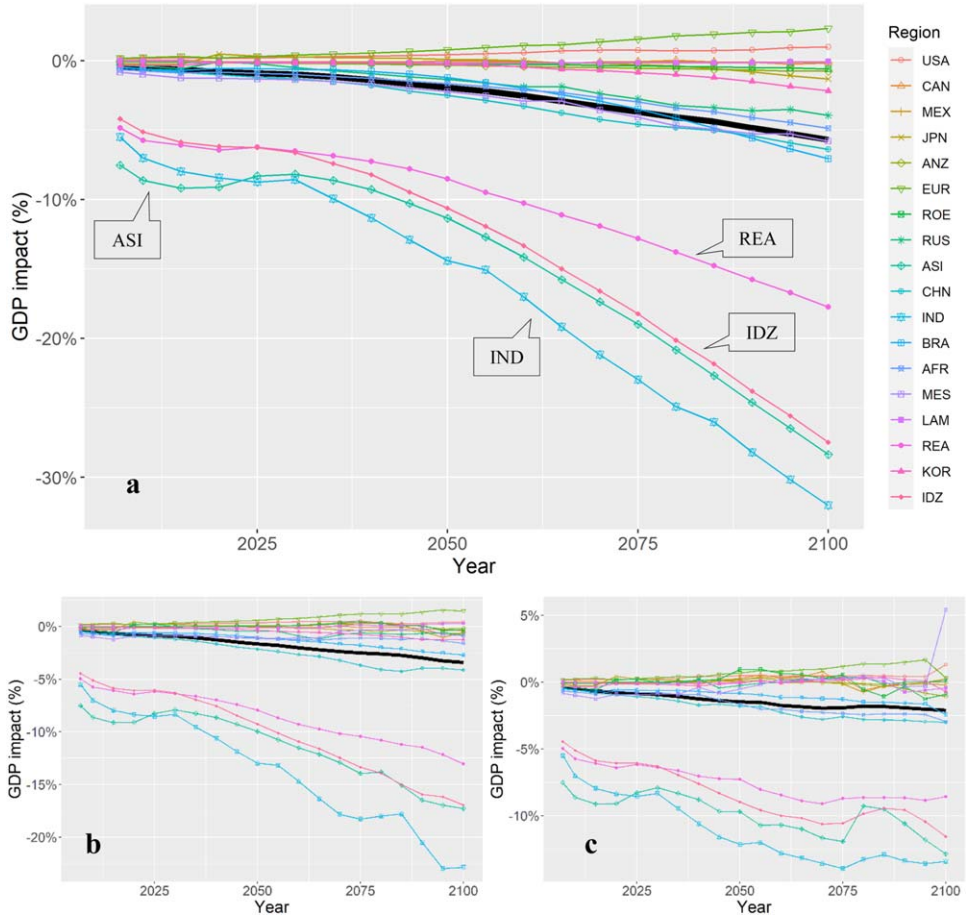

Figure 3. GDP levels relative to the no-impact case for: (a) BaU, (b) S45, and (c) S2 scenarios. Black lines indicate the average global impact (Data for these figures are available in the supplementary Excel file).

Table 2. Levels of the GDP components relative to the no-impact case for 2100 (BaU scenario).

	Consumption	Government expenditure	Investment	Export	Import	GDP
USA	−0.82%	0.88%	0.05%	−0.40%	−5.91%	0.99%
CAN	−0.62%	−0.09%	−0.17%	−0.19%	−0.94%	−0.17%
MEX	−0.31%	0.11%	0.19%	0.00%	0.02%	−0.13%
JPN	−3.14%	−0.50%	−0.72%	−3.37%	−6.97%	−1.32%
ANZ	−1.08%	−0.56%	−0.36%	−1.92%	−4.89%	−0.76%
EUR	−0.57%	2.12%	−0.21%	−0.51%	−6.21%	2.32%
ROE	−0.61%	−0.40%	−0.38%	−0.87%	−0.37%	−0.60%
RUS	−3.38%	−3.42%	−2.21%	−5.17%	1.15%	−3.94%
ASI	−28.85%	−20.37%	−20.36%	−23.19%	−8.17%	−28.36%
CHN	−7.23%	−7.02%	−6.55%	−7.53%	−13.17%	−6.38%
IND	−33.90%	−28.12%	−29.96%	−29.80%	−14.33%	−32.02%
BRA	−8.12%	−6.47%	−4.32%	−6.00%	−1.75%	−7.06%
AFR	−4.48%	−5.04%	−5.18%	−5.59%	−6.15%	−4.86%
MES	−7.30%	−4.24%	−5.27%	−6.66%	−9.57%	−5.80%
LAM	−0.43%	0.17%	0.11%	−0.82%	−3.83%	−0.06%
REA	−19.48%	−14.46%	−16.29%	−17.55%	−19.43%	−17.74%
KOR	−3.29%	−1.22%	−1.34%	−3.28%	−5.69%	−2.18%
IDZ	−29.41%	−23.77%	−25.46%	−24.02%	−11.76%	−27.47%

Note: Similar trends can be seen for the S45 (table S1) and S2 (table S2) scenarios.

considerably affected, while those of imports were negatively but relatively weakly, or even positively, affected. Similar trends were observed for the mitigation scenarios (figures S6–S7 for the S45 and S2 scenarios, respectively), although the impacts were smaller with increased mitigation efforts.

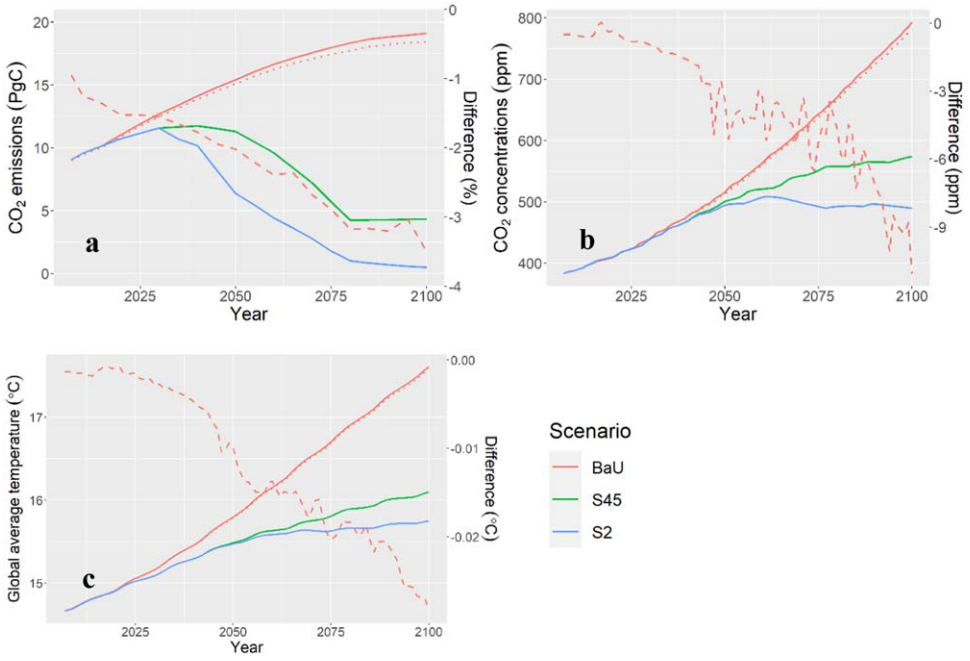

Figure 4. Global (a) CO_2 emissions, (b) CO_2 concentrations, and (c) average temperature. Red-dotted lines show BaU with impacts of climate change, and the red-dashed line shows the difference between cases with and without impacts (right axis).

Due to such reduction in economic activity, CO_2 emissions in the BaU scenario decreased slightly compared to the no-impact case (figure 4(a)), with a generally expanding difference between the two cases over time reaching a 3.6% decline by 2100. These differences were due to the degradation of economic activity caused by the impact on labor productivity, which reduces fossil fuel use. This reduction in CO_2 emissions also caused a difference in global CO_2 concentrations between the two cases (with and without climate change impacts; figure 4(b)). Although the difference in the concentrations was small, it expanded with time (as with CO_2 emissions), reaching an 11.6 ppm or 1.5% decline by 2100. These reductions in emissions and concentrations in BaU affected the global average temperature slightly (figure 4(c)). With the expansion of the difference between the two cases shown in CO_2 concentrations, the temperature difference also expanded and reached 0.030°C in 2100.

Regarding the mitigation scenarios, since the emission levels shown in figure S2 were applied as model constraints, the emissions and concentrations, as well as average temperatures, remained at the same level across the global scale for both no-impact and impact cases.

When considering the climate change impacts compared with the no-impact case, on the regional scale, CO_2 emissions decreased in some regions, while they increased in others (figure 5). In particular, emission reduction was the largest for IND, followed by IDZ. As shown in figure 3 and table 2, these regions experienced the largest decline in GDP, corresponding to a large emission reduction. Such directional tendencies were similar across the three scenarios, although the degrees of change varied.

Regarding the BaU scenario, the emission changes expanded with time, and the total negative impacts increased with the decrease in labor productivity. As for the mitigation scenarios, regional emission changes expanded until the middle of the century, stabilizing thereafter for S45, and shrinking for S2, although the totals were not affected for the mitigation scenarios. Note that because emissions reduction targets were not set from 2007 to 2015 for the mitigation scenarios (i.e., the same emission pathway with the BaU scenario was applied), the impacts on total emissions were identical across all scenarios in these years.

4. Discussion

This study represents the first attempt to quantitatively evaluate the impacts of heat-induced labor productivity changes promoted by future climate change via a coupled modeling framework with a CGE model and an EMIC. The results indicated that the changes in labor productivity due to heat stress non-negligibly affected economic conditions, particularly in hot and humid regions, although its impacts on global average temperatures, as well as CO_2 emissions and concentrations, were limited. Labor productivity in the agricultural sector was affected more than in the manufacturing and service sectors because of the difference in corresponding working

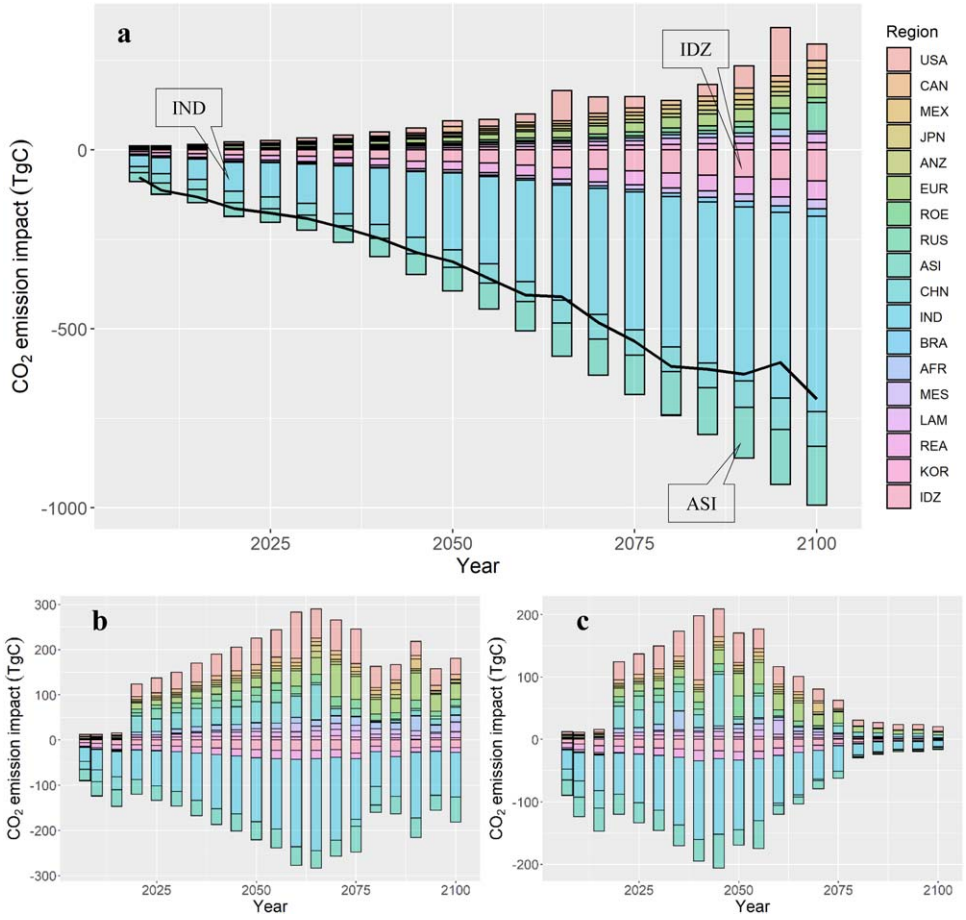

Figure 5. Climate change impacts on the regional CO_2 emissions relative to the no-impact case: (a) BaU, (b) S45, and (c) S2. Black line in (a) indicates the total global impact.

conditions. Since the agricultural sector is neither carbon- nor energy-intensive, impacts on CO_2 emissions and concentrations at the global scale were less than the economic impacts (GDP $=$ 5.7% versus CO_2 emissions $=$ 3.6% by 2100 under BaU). Regionally, however, hot and humid areas experienced significant decreases in CO_2 emissions induced by their large economic losses. As these regions primarily comprise developing countries with already low emissions, the economic and emission disparities between developed and developing nations is set to widen further. Therefore, adaptation to climate change and intensive aid to realize adaptation measures are essential, particularly in these regions, to compensate for their socioeconomic losses.

In this study, we also elucidated that some high-latitude regions experienced positive economic impacts because of small or non-existent impact of climate change on labor productivity. However, some studies in Europe using high-resolution models found some negative economic impacts of heatwaves (Orlov *et al* 2019, García-León *et al* 2021). These contradictory results partly arose from the resolution of the analysis, and the sparse spatiotemporal resolution of the CGE model is a limitation of this study.

Climate change mitigation can reduce both global and regional economic impacts due to heat-induced labor productivity changes, as increasing temperatures are limited compared to the BaU scenario. However, the future economic losses caused by climate change mitigation could be larger than that caused by climate change impacts (i.e., heat-induced labor productivity). For example, in 2100, total global GDP loss was 7.5% for the S45 mitigation scenario compared with BaU (total global GDP in 2100: USD 423.7 trillion for BaU and USD 391.8 trillion for S45), while the losses due to heat-induced labor productivity for BaU and S45 were 5.7% and 3.4% (figure 3), respectively. Therefore, mitigation of climate change impacts may not adequately offset the GDP losses associated with climate change impacts.

Our findings are consistent with the findings of Matsumoto (2019) and Takakura *et al* (2017). As indicated by Matsumoto (2019), considering the interactions between socioeconomic and climate systems has critical impacts on economic conditions (e.g., GDP) and CO_2 emissions, supporting the importance of developing coupled models to evaluate the future economic impacts of climate change. Compared to Matsumoto (2019), who used a similar framework as this study but a simple climate model for the climate system instead of an EMIC, annual labor productivity was more strongly affected (i.e., decreased labor productivity) in our study (e.g., around 75% in

Matsumoto (2019) versus 48.0% in this study in the agricultural sector of IDZ for 2100 under the BaU scenario). This is perhaps because daytime and monthly average climate conditions and changes were considered in this study, reflecting the greater impacts of the hot seasons and removing the nighttime impacts when temperatures are lower and fewer people are working. Accordingly, although the impact on global GDP was similar across the two studies, the regional impacts, particularly the negative ones, were larger in this study, as were the impacts on CO_2 emissions. As the climate model and data used in this study were more reasonable than Matsumoto (2019), the feedback effects can be considered more significant than those in the literature.

Other studies, such as Takakura *et al* (2017), also evaluated economy-wide impacts due to climate-change-induced labor productivity using CGE models. Compared with Takakura *et al* (2017), although a direct comparison is difficult because of the differences in the CGE models and the scenarios, the GDP loss observed in the present study was within a similar range for both the BaU and mitigation scenarios. For example, Takakura *et al* (2017) showed ~1.7%–5.4% GDP loss for RCP 8.5 (similar to BaU in the current study in the sense that both are non-mitigation scenarios), and ~0.4%–1.2% loss for RCP 2.6 (similar to S2 in the current study).

This study has some limitations. First, homogeneous assumptions were applied to the relationship between labor productivity and WBGT across regions and sub-sectors; whereas in reality, tolerance to heat may differ by region; people living in hot and humid areas may have a higher heat-tolerance than those living in cool/cold areas. However, such a claim lacks quantitative evidence, and further research is needed to substantiate it. Second, the spatiotemporal resolutions of the CGE model were not as high as those of the EMIC, and these lower resolutions may have underestimated the impacts of heat stress through averaging. However, it is difficult to develop a high-resolution economic model like the EMIC due to limited data availability. Finally, this study did not consider adaptation measures to heat stress, such as work time adjustments and the installation of additional air-conditioning units, although such measures can help maintain labor productivity and reduce the economic impacts (Takakura *et al* 2018). Although it is important to consider the effects of adaptation measures, this study contributed to the literature by evaluating the worst-case scenarios (i.e., socioeconomic impacts without climate change adaptation) using the novel modeling framework. However, evaluating the effect of adaptation measures considering their costs remains a topic for future research.

5. Conclusion

This study evaluated the impacts of climate change through labor productivity changes by applying a new modeling framework, coupling a CGE model and an EMIC to consider the interactions between socioeconomic and climate systems. The results suggested that with continuing climate change, labor productivity will decrease in most regions, and GDP will be negatively affected. The negative impact was particularly considerable in South and Southeast Asia, where labor productivity declined largely because of their hot and humid conditions, and other regions where climate change did not largely affect labor productivity saw an increased GDP due to their comparative advantage. The impact on global CO_2 emissions, CO_2 concentrations, and temperatures by coupling socioeconomic and climate systems was negative but limited, although some regional differences in relation to GDP loss were observed.

The following are some methodological and practical implications of this study. This study identified some advantages of using a coupled model across different disciplines in climate change research, for both social and natural scientists, even though such a modeling framework has been used rarely. These approaches are desirable for further evaluation to assist with understanding the consequences of future climate change, and identifying any relevant measures, which can contribute to achieving low-carbon societies and sustainable development. From a practical perspective, this study elucidated that mitigating climate change will reduce the socioeconomic impacts of climate change, implying that early actions related to emission reduction are essential to controlling these impacts. However, deleterious effects will occur even with sufficient efforts to achieve a low-carbon society, particularly in the hottest and humid regions. As such regions are often found in developing countries, or least developed countries, domestic as well as international efforts for adapting to climate change, such as diffusion of air conditioners and mechanization in agricultural sectors, are essential to mitigating the impacts of climate change.

Further studies are required to address the following points. First, from an analysis perspective, evaluating the impacts of climate change, mitigation, and adaptation simultaneously is essential to achieving a 2°C target, or low-carbon society. Furthermore, understanding the socioeconomic consequences of extreme weather events is an important topic to be addressed (e.g., labor endowment and heatwaves). From the perspective of model development, since there are numerous interaction channels between socioeconomic and climate systems (Tachiiri *et al* 2021), various aspects related to heat stress and labor productivity, as well as land use, ecosystem services, diseases, and disasters, should be incorporated in the model on priority. Further, more sophisticated climate models, such as the Earth system model, should be incorporated for a more precise analysis including the impact of extreme weather events, considering spatiotemporal resolution.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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