Global warming impact on future socioeconomic activities through labor productivity

Ken'ichi Matsumoto*

Abstract

Climate change (global warming) has various impacts on human society and economic activities. One of the important aspects of global warming impacts is labor productivity through temperature increases. Higher temperature negatively affects the efficiency at work. In addition, the impact can vary by region because of differences in the economic structure and the climate conditions. The purpose of this study is to evaluate global warming impact on future economic activities through changes in labor productivity. To evaluate the global warming impact on future economic activities, we used a computable general equilibrium model considering the relationship between temperature and labor productivity. To calculate the future temperature, we used the MAGICC6 (Model for the Assessment of Greenhouse Gas Induced Climate Change version 6). For the future scenarios, we used business-as-usual (BaU) and 2°C scenarios. In the global level, gross domestic product (GDP) was 0.19-0.32% smaller for the BaU scenario when the global warming impact was considered, while the impact on GDP was smaller for the 2°C scenario (around 0.02%). However, the impact differs by region. For primary energy supply, the total supply was 0.33-0.63% smaller for the BaU scenario when the global warming impact was considered, while the impact was slight for the 2 °C scenario (0.01-0.02%). Consequently, CO_2 emissions were also affected. In the BaU scenario, CO_2 emissions from fossil fuels and industrial process were 0.34-1.18% smaller when the global warming impact was considered. These results suggest that larger the temperature increases, the larger the impact. However, although the degree was not large, it is indicated that the socioeconomic impacts to achieve the 2 °C target were smaller than previously believed.

Keywords: climate change, economic activities, GDP, primary energy supply, labor productivity

* Graduate School of Fisheries and Environmental Sciences, Nagasaki University; 1-14 Bunkyo-machi, Nagasaki 852-8521, Japan; kenichimatsu@nagasaki-u.ac.jp; +81(0)95-819-2735

1. Introduction

Reducing carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions is essential for preventing dangerous levels of climate change and the international society has made efforts for mitigation under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. In addition, the Paris Agreement came into effect and countries ratified the agreement will further reduce GHG emissions to achieve the "2°C" target. However, climate change has already happened and it is expected to be severer in the future. Climate change (global warming) has various impacts on human society and economic activities, such as food production, water resources, and health. One of the important aspects of global warming impacts is labor productivity through temperature increases (Kjellström et al., 2009; Roson and Sartori, 2016; Takakura et al., 2017). Higher temperature decreases the efficiency at work. In particular, the impact is larger for agricultural workers than for office workers. In addition, the impact can vary by region because of differences in the economic structure and the climate conditions. The purpose of this study is to evaluate the global warming impact on future economic activities through labor productivity changes.

2. Methods

2.1 Study design

In this study, we analyzed socioeconomic impact of temperature increases through the changes (declines) in labor productivity in the global scale for the business-as-usual (BaU) and 2°C scenarios. Takakura et al. (2017) evaluated the economic impact of climate change through the changes in worktime and labor productivity. In that study, the relationship between climate change and economic impact was one way, meaning that the interactive relationship was not considered (the economic impact was calculated with given climate conditions). However, in reality, there exist interactions between socioeconomic activities and climate conditions. To be more precise, if climate change affects socioeconomic conditions, GHG emissions are also affected and the degree of climate change is also affected as a result. Therefore, by modeling a component of a global warming impact such as labor productivity in an economic model, the level of global warming will be different from the level initially assumed. Thus, such an important interaction between socioeconomic conditions and climate conditions is considered in this analysis.

We used two models for the analysis: a CGE model for socioeconomic analysis and the MAGICC6 (Model for the Assessment of Greenhouse Gas Induced Climate Change version 6) for climate change analysis (Fig. 1). First, the CGE model was used to calculate economic activity levels, including GHG emissions, under the assumed scenarios (see section 2.3). The MAGICC6 was then applied to calculate climate conditions with the GHG emissions obtained from the CGE model. The calculated temperature increases were input to the CGE model. The CGE model is run with about 10-year time steps (2001, 2005, 2010, 2020, … 2100). The MAGICC6 can be run using multi-model-ensemble emulations for climate parameters and carbon cycle settings (171 in total). Thus, we used the outputs of 17, 50, and 83 percentiles for the analysis. Although the future temperature increases will be different by region, this study used the identical temperature increases for all regions because of the limitation of the MAGICC6, which calculates global mean temperatures. Therefore, the changes in labor productivity might be underestimated in high-latitude regions and overestimated in low-latitude regions.

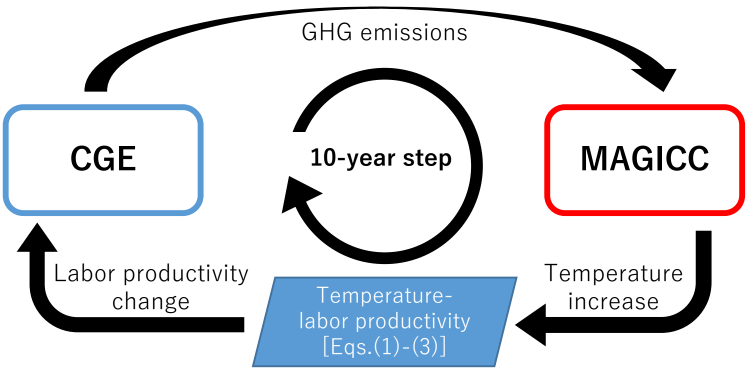

Fig 1. Framework of this study.

The details of the CGE model are explained in section 2.2 and those of the MACICC6 are in Meinshausen et al. (2011)[1].

2.2 CGE model

We used an economic model to analyze future scenarios from various socioeconomic perspectives. This model is a multi-regional/multi-sectoral recursive dynamic CGE model on a global scale, with energy and environmental (GHG emissions) components. The model is based on works such as Masui et al. (2011), Matsumoto (2013), Matsumoto and Masui (2009, 2011), and Okagawa et al (2012). As full model details are described in our previous studies, such as those of Matsumoto and Andriosopoulos (2016) and Matsumoto et al. (2016), only the major features of the model are presented here.

The model disaggregates the world into 24 geographical regions, each of which has 21 industrial sectors and a final demand sector (Table 1). In the electric power sector, a diversity of technologies, including thermal, hydroelectric, nuclear, and several types of renewable energy (Table 1), is explicitly assumed. In addition, CCS technology can be selected as an advanced technology for thermal and biomass power generation. Future energy efficiency improvement is included as an exogenous parameters as autonomous energy efficiency improvement (AEEI) as often used in this kind of model. Each industrial sector is represented by a nested constant elasticity of substitution (CES) production function, in which substitution is considered for production factors, energy sources, and intermediate inputs based on relative prices and elasticity parameters. The detailed structures are explained in Matsumoto and Andriosopoulos (2016) and Matsumoto et al. (2016). Each industrial sector produces products/services delivered for international and/or domestic markets. In each domestic market, the supplied products/services are consumed as final consumption, investment, and/or intermediate inputs. For each period, the total investment demand is set exogenously to meet an assumed future economic growth rate.

The final demand sector in each region owns all production factors (capital, labor, land, and resources) and supplies them to the industrial sectors to earn income for final consumption and savings. The final demand for each product/service is determined to maximize the utility represented by a CES function.

From the activities of industrial sectors (i.e., production) and the final demand sector (i.e., final consumption) in each region, GHGs, including CO_2, are emitted. The model is run to simulate global emission pathways

[1] Please also see http://www.magicc.org/ for the MAGICC6.

between the base year (2001) and 2100 for the 2°C scenarios, while such constraints are not applied to the BaU scenario. In the model, global emissions trading is taken into account when reducing emissions. The total annual global emission allowances are equal to the global emission level in each year of the target emission pathway. Emission allowances are allocated to each region, in proportion to their projected population from the year 2050 onwards. Between the base year and 2050, regional emission allowances are set using linear interpolation between the observed emissions in the base year and the assigned emission allowances for 2050.

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

Code	Region	Code	Commodities/sectors
AUS	Australia	[Energy]	
NZL	New Zealand	COA	Coal
JPN	Japan	OIL	Crude oil
CAN	Canada	GAS	Natural gas
USA	United States	P_C	Petroleum products
E15	Western EU countries	GDT	Gas manufacture and distribution
RUS	Russia	ELY	Electric power [a]
E10	Eastern EU countries	[Non-energy]	
XRE	Other Europe (e.g., Bulgaria)	AGR	Agriculture (e.g., rice)
KOR	Korea	LVK	Livestock (e.g., bovine cattle)
CHN	China and Hong Kong	FRS	Forestry
XRA	Other Asia-Pacific (e.g., Mongolia)	FSH	Fishery
IDN	Indonesia	EIS	Energy-intensive industries (e.g., chemical products)
THA	Thailand		
XSE	Other Southeast Asia (e.g., Malaysia)	OMN	Other mineral mining
IND	India	M_M	Metals and manufacturing (e.g., motor vehicles)
XSA	Other South Asia (e.g., Bangladesh)	FOD	Food processing (e.g., food products)
MEX	Mexico	OMF	Other manufacturing (e.g., textiles)
ARG	Argentina	CNS	Construction
BRA	Brazil	TRT	Transportation (e.g., air transportation)
XLM	Other Latin America (e.g., Chile)	CMN	Communication
XME	The Middle East (e.g., Saudi Arabia)	WTR	Water
ZAF	South Africa	OSG	Governmental services (e.g., education)
XAF	Other Africa (e.g., Egypt)	SER	Other services (e.g., insurance)

[a] The electric power sector consists of thermal power (i.e., coal-, oil-, and gas-fired), hydropower, nuclear power, solar power, wind power, geothermal power, biomass power, waste power, and other renewable energy. In addition, thermal power and biomass power with CCS technology are available.
Reference: This table is created based on Matsumoto et al. (2016).

In order to consider the impact of temperature increases on labor productivity in the CGE model, we introduced the relationship obtained from Kjellström et al. (2009) and Roson and Sartori (2016) (eqs.(1)-(3)) in the original CGE model. These equations are defined by three parts: a minimum threshold, below which no temperature effects appear; (b) linear decline of labor productivity; and (c) a minimum level of labor productivity (25%). The shape of equations is same for all sectors, but the minimum and maximum thresholds are different by sector.

$$\begin{cases} lab_{agr} = 1.0 \quad (temp \leq 26) \\ lab_{agr} = 1.0 - \dfrac{1.0 - 0.25}{36 - 26} * (temp - 26) \quad (26 \leq temp \leq 36) \\ lab_{agr} = 0.25 \quad (temp \geq 36) \end{cases} \tag{1}$$

$$\begin{cases} lab_{man} = 1.0 \quad (temp \leq 28) \\ lab_{man} = 1.0 - \dfrac{1.0 - 0.25}{43 - 28} * (temp - 28) \quad (28 \leq temp \leq 43) \\ lab_{man} = 0.25 \quad (temp \geq 43) \end{cases} \tag{2}$$

$$\begin{cases} lab_{ser} = 1.0 \quad (temp \leq 30) \\ lab_{ser} = 1.0 - \dfrac{1.0 - 0.25}{43 - 28} * (temp - 28) \quad (30 \leq temp \leq 50) \\ lab_{ser} = 0.25 \quad (temp \geq 50) \end{cases} \tag{3}$$

where *lab*: labor productivity change, *temp*: temperature, *agr*: agricultural sector, *man*: manufacturing sector, *ser*: service sector.

The model is calibrated to reproduce economic activity and energy levels in the base year, using various published data: The Global Trade Analysis Project (GTAP) 6 database (Dimaranan, 2006) for economic activity levels, the Emission Database for Global Atmospheric Research v4.2 (European Commission Joint Research Centre 2011) for GHG emissions, and the International Energy Agency (IEA) energy balance tables (IEA 2009a, b) for energy. In addition, the initial temperature in each region was obtained from Roson and Sartori (2016).

By running the model, with the above data and the scenarios (section 2.3), we get the outputs such as economic activities, energy supply, and emissions. The model was developed with the GAMS (General Algebraic Modeling System) software using the MPSGE (mathematical programming system for general equilibrium analysis) modeling framework.

2.3 Future scenarios

Using the CGE model, the BaU scenario and the 2°C scenario were analyzed. With the BaU scenario, we analyzed the impact of global warming on socioeconomic conditions through labor productivity when no climate policies were considered. With the 2°C scenario, we analyzed the impact when mitigation policies were introduced.

First, we developed a BaU scenario. The BaU scenario assumes that no policies and measures that aim to control GHG emissions are introduced. Assumptions in the BaU scenario are shown in Fig. 2. The details of the scenario are described in Matsumoto and Andriosopoulos (2016) and Matsumoto et al. (2016). We assumed that the global population will grow from about 6 billion in the base year to 10 billion in 2100 (Fig. 2a). Global GDP reaches around 230 trillion US dollars (USD, Fig. 2b), and global primary energy supply will reach approximately 1180 EJ by 2100 (Figs. 2d and 2e). Globally, fossil fuel supply, particularly for coal, increases continuously during this century because of its relatively low cost (Fig. 2e). Consequently, total CO_2 emissions increase to 25.1 GtC/year by 2100 (Fig. 2c). As a result, the global mean temperature rises around 3.9 °C from the pre-industrial level.

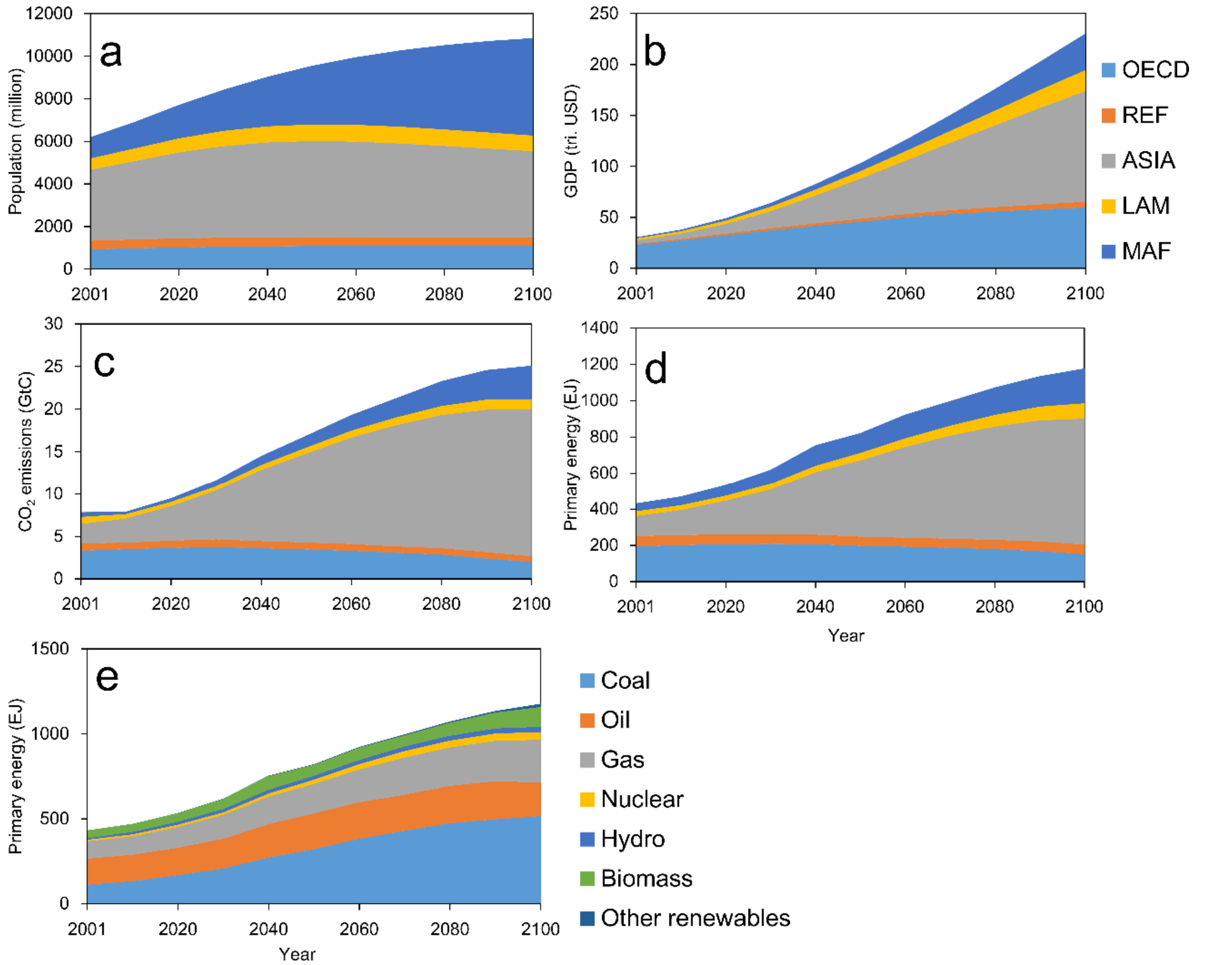

Fig. 2 Properties of the BaU scenario from the base year to 2100: (a) population, (b) GDP, (c) total CO_2 emissions, (d) primary energy supply by region, and (e) primary energy supply by fuel type. Five regions are defined: OECD: member states of the Organisation for Economic Cooperation and Development as of 1990, REF: countries from the reforming economies of Eastern Europe and the former Soviet Union, ASIA: most Asia-Pacific countries excluding the Middle East and OECD countries, LAM: Latin American and Caribbean countries, and MAF: Middle Eastern and African countries.

The 2°C scenario is an emission constraint scenario, which control GHG emissions so that temperature rise will not exceed 2°C from the pre-industrial level in 2100.

Because we run the models for two scenarios for three climate change results (and also the case not considering the global warming impact), there are called BaU-wo, BaU-q17, BaU-q50, and BaU-q83 for the

BaU scenario, and 2C-wo, 2C-q17, 2C-q50, and 2C-q83 for the 2°C scenario[2].

3. Results and discussion

Figure 3 shows the GDP level in both scenarios relative to the BaU-wo case (BaU scenario not considering global warming impact through labor productivity) and Table 2 shows the regional GDP relative to either BaU-wo or 2C-wo in 2100. In the BaU scenario, GDP was 0.19-0.32% lower in the global level in 2100 when the global warming impact was considered. As the global warming became severe, the impact on GDP tended to be larger. However, the impact differed by region. In the BaU scenario, for example, GDP was 1.65% lower in Indonesia, while it was 0.52% higher in Russia, when the global warming impact was considered (BaU-q50; Table 2). The global warming impact is usually larger in the warm regions than in the cold regions. Therefore, decline in production in warm regions were partly compensated by the increase in production in cold regions. As a result, the warm regions such as Indonesia suffered negative impact, while the cold regions such as Russia received positive effect.

For the 2°C scenario, global GDP was lower than the BaU scenario (-6.43--6.46% in 2100; Fig. 3b), but the global warming impact observed within the 2°C cases was not large compared with that observed in the BaU cases. In 2100, GDP was 0.02% smaller in the 2C-q17, 2C-q50, and 2C-q83 cases than the 2C-wo.

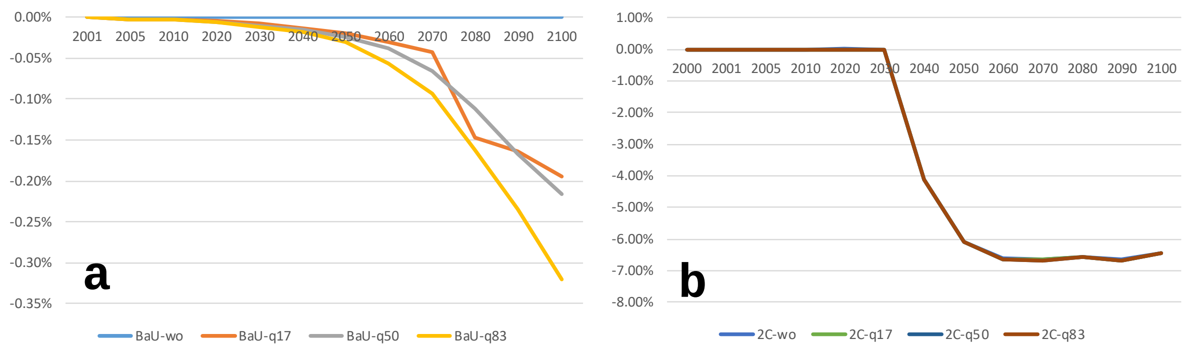

Fig. 3 Global GDP levels relative to the BaU-wo case. (a) BaU scenario, (b) 2°C scenario.

---

[2] "BaU" and "2C" are the BaU and 2°C scenarios, respectively. "wo", "q17", "q50," and "q83" show no impact of temperature increases, 17 percentiles, 50 percentiles, and 83 percentiles, respectively.

Table 2 GDP levels relative to the scenarios not considering global warming impact in 2100.

	BaU-q17	BaU-q50	BaU-q83	2C-q17	2C-q50	2C-q83
AUS	-0.18%	-0.25%	-0.30%	-0.03%	-0.04%	-0.05%
NZL	-0.16%	-0.19%	-0.30%	-0.02%	-0.02%	-0.02%
CHN	-0.09%	-0.16%	-0.21%	-0.02%	-0.03%	-0.04%
JPN	-2.79%	-0.38%	0.24%	0.00%	0.00%	0.01%
KOR	0.30%	-0.02%	-0.09%	0.00%	0.00%	0.00%
IDN	-1.47%	-1.65%	-2.05%	-0.29%	-0.37%	-0.51%
THA	-0.50%	-0.59%	-1.10%	-0.31%	-0.34%	-0.38%
XSE	-0.19%	-0.22%	-0.22%	-0.03%	-0.04%	-0.06%
IND	-0.35%	-0.56%	-0.84%	-0.02%	-0.02%	-0.03%
XSA	-0.04%	-0.08%	-0.13%	-0.01%	-0.01%	-0.01%
CAN	-0.04%	-0.08%	-0.12%	0.00%	0.00%	0.00%
USA	0.25%	0.00%	-0.03%	0.00%	0.00%	0.00%
MEX	-0.05%	-0.04%	0.07%	0.00%	0.00%	0.00%
ARG	-0.12%	-0.13%	-0.14%	0.00%	0.01%	0.01%
BRA	-0.10%	-0.19%	-0.28%	0.01%	0.01%	0.02%
RUS	0.54%	0.52%	0.42%	-0.01%	0.00%	0.00%
XME	0.02%	0.10%	0.10%	0.00%	0.01%	0.01%
ZAF	1.05%	0.28%	0.68%	0.17%	0.23%	0.35%
XRA	-0.19%	-0.21%	-0.27%	-0.01%	-0.02%	-0.02%
XE15	-0.08%	-0.02%	-0.04%	0.01%	0.01%	0.02%
XE10	-0.06%	-0.02%	-0.06%	0.00%	0.00%	0.01%
XRE	-2.95%	-0.20%	-0.18%	0.01%	0.01%	0.02%
XLM	-0.15%	-0.31%	-0.48%	0.00%	0.00%	0.00%
XAF	0.00%	-0.29%	-0.68%	0.00%	0.00%	0.00%
World	-0.19%	-0.22%	-0.32%	-0.02%	-0.02%	-0.02%

Note: The BaU (2°C) cases were compared with the BaU (2°C) scenario not considering global warming impact.

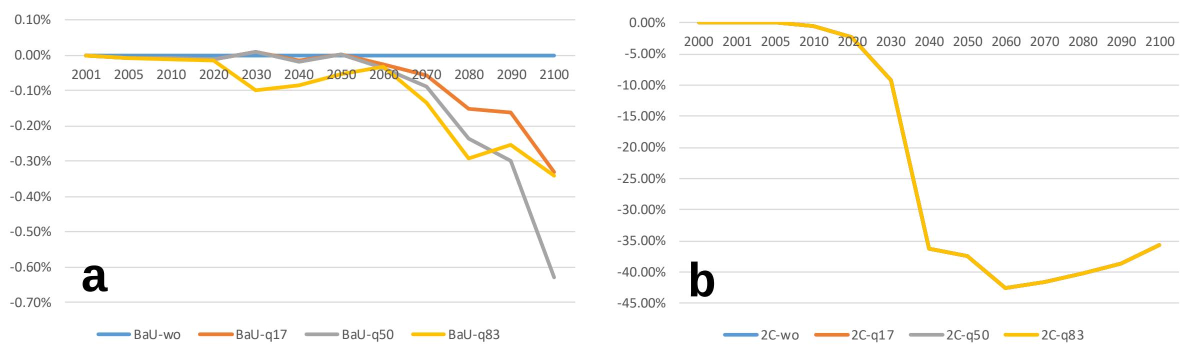

Fig. 4 Total primary energy supply in the world relative to the BaU-wo case. (a) BaU scenario, (b) 2°C scenario.

Figure 4 shows the total primary energy supply in the world compared with the BaU-wo case. Similar to the trends seen in GDP, the total primary energy supply was lower in the cases global warming impact was considered (-0.33--0.63%). However, different from GDP, the BaU-q50 was the lowest among the three cases after 2090. The total primary energy supply is the sum of various types of energy sources and the energy sources supplied are different by region. In addition, the global warming impact on economic activities differ by region as abovementioned. This may cause the fact that the total primary energy supply for the BaU-q50 was lower than the BaU-q83.

For the 2°C scenario, the total primary energy supply was lower than the BaU scenario (-35.64--35.65% in 2100; Fig. 4b), but the global warming impact observed within the 2°C cases was not large compared with that observed in the BaU cases similar to GDP. In 2100, the total primary energy supply was 0.01-0.02% smaller in the 2C-q17, 2C-q50, and 2C-q83 cases than the 2C-wo.

Figure 5 shows the primary energy supply by source relative to the cases not considering the global warming impact. Because Similar tendencies ware shown for the other cases, here we only showed the BaU-q83 and 2C-q83 cases. Overall, the impact was larger for the reference case. In the reference case, biomass energy increased compared with the BaU-wo case, while oil, gas and wind energy decreased, particularly the impact on the wind energy was large. In the 2°C case, fossil fuels decreased compared with the 2C-wo case in 2100, while wind and biomass energy increased. However, no similarities were observed between the BaU and 2°C scenarios, because of the differences in the energy structure between the scenarios.

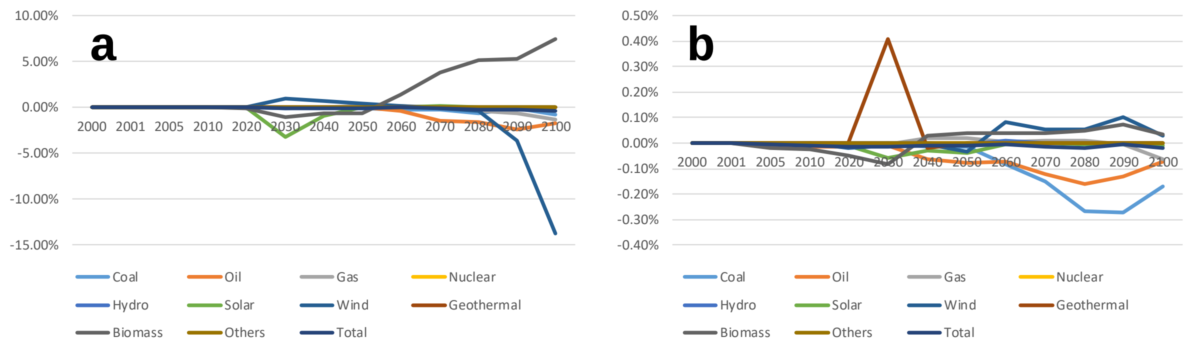

Fig. 5 Primary energy supply in the world by source relative to the cases not considering the global warming impact. (a) BaU-q83 relative to BaU-wo, (b) 2C-q83 relative to 2C-wo.

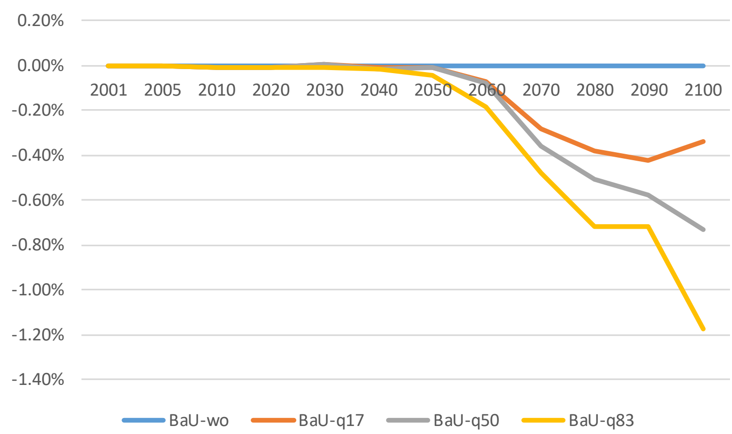

Fig. 6 Total CO_2 emissions in the world relative to the BaU-wo case. The figure only shows the results for the reference scenario, because emissions are given for the 2°C scenario when running the CGE model.

As a result of these changes due to the global warming impact, GHG emissions were also affected. Figure 6 shows global CO_2 emissions in the BaU scenario compared with the BaU-wo case. Again, the emissions were lower in the in the cases global warming impact was considered (-0.34--1.18%) and the higher percentile cases show lower emissions because of the higher global warming impact. As a results, the temperature increases were slightly slowed down (Table 3).

Table 3 Temperature increases from the pre-industrial level in the BaU scenario.

Year	BaU-no (q17)	BaU-q17	BaU-no (q50)	BaU-q50	BaU-no (q83)	BaU-q83
2000	0.71	0.71	0.74	0.74	0.77	0.77
2010	0.89	0.89	0.96	0.96	1.02	1.02
2020	1.06	1.06	1.18	1.18	1.29	1.29
2030	1.27	1.27	1.43	1.43	1.59	1.59
2040	1.52	1.52	1.73	1.73	1.96	1.96
2050	1.80	1.80	2.08	2.08	2.37	2.37
2060	2.09	2.09	2.42	2.42	2.79	2.79
2070	2.39	2.39	2.81	2.80	3.24	3.23
2080	2.70	2.70	3.20	3.20	3.72	3.71
2090	3.04	3.03	3.59	3.58	4.17	4.16
2100	3.38	3.37	3.97	3.95	4.60	4.58

Note: BaU-no (q17), BaU-no (q50), and BaU-no (q83) respectively show 17, 50, and 83 percentiles of the temperature changes for the BaU scenario not considering the global warming impact.

Compared with the impact on CO_2 emissions, the impact on the total primary energy supply and GDP was small. This may be due to substitution mechanisms among production factors, energy sources, and intermediate inputs, which were taken into account in the CES production functions (Matsumoto et al. 2016 Fig. A1). Thus, the impact on economic activities was eased compared with the emissions.

4. Conclusion and policy implications

In this study, we evaluated global warming impact on future economic activities through changes in labor productivity using the combination of the CGE model and the MAGICC6. We found that economic activities would be negatively affected when the relationship between global warming and labor productivity is considered in the economic model. Although such impacts are larger in the BaU scenario, they are negligible in the 2°C scenario. These results suggest that larger the temperature increases, the larger the socioeconomic impact. However, it is indicated that the socioeconomic impacts to achieve the 2°C target are smaller than previously believed, although the degree is not large.

Climate mitigation is considered to affect economy negatively and this study also showed the same results. However, the socioeconomic impact will be smaller by considering impact of climate change. This study analyzed only labor productivity, but impact or damage caused by climate change varies as mentioned in section 1; thus the impact will be severer than expected. Therefore, the cost of climate change will be much less than previously thought and climate mitigation measures should be kept implementing.

Although climate mitigation is essential to solve the climate change issue, adaptation to climate change is also necessary to prevent or minimize the damage caused by climate change. In terms of labor productivity, the necessity for the adaptation will increase as the emissions and the impact are larger. Therefore, adaptation such as cooling workplaces and shifting worktime. From this point, it is necessary to evaluate the cost of the mitigation, impact, and adaptation simultaneously.

Acknowledgements

This research was supported by JSPS KAKENHI grant number 15K16161 and the Integrated Research Program for Advancing Climate Models (TOUGOU program) from the Ministry of Education, Culture, Sports, Science and Technology.

References

Dimaranan, B.V. (2006) Global trade, assistance, and production: the GTAP 6 data base. Center for Global Trade Analysis, Purdue University: West Lafayette.

European Commission Joint Research Centre (2011) Emission Database for Global Atmospheric Research (EDGAR). http://edgar.jrc.ec.europa.eu/. Accessed Nov 11, 2013.

International Energy Agency (IEA) (2009a) Energy balances of OECD countries: 2009 edition. IEA Publications: Paris.

International Energy Agency (IEA) (2009b) Energy balances of non-OECD countries: 2009 edition. IEA Publications: Paris.

Kjellstrom, T., Kovats, R. S., Lloyd, S. J., Holt, T. & Tol, R. S. J. (2009) The Direct impact of climate change on regional labor productivity. *Arch. Environ. Occup. Health* 64, 217–227.

Masui, T., Matsumoto, K., Hijioka, Y., Kinoshita, T., Nozawa, T., Ishiwatari, S., Kato, E., Shukla, P. R., Yamagata, Y. & Kainuma, M. (2011) An emission pathway for stabilization at 6 Wm‾2 radiative forcing. *Clim. Change* 109, 59–76.

Matsumoto K (2013) Change in energy structure and energy security under climate mitigation scenarios. In: Leal, W. & Voudouris, V. (eds) Global energy policy and security. Springer: London.

Matsumoto, K. & Andriosopoulos, K. (2016) Energy security in East Asia under climate mitigation scenarios in the 21st century. *Omega* 59, 60–71.

Matsumoto, K. & Masui, T. (2009) Mid-term dynamic effects of carbon tax based on the imputed price of carbon. *Environ Sci* 22, 391–400.

Matsumoto, K. & Masui, T. (2011) Analyzing long-term impacts of carbon tax based on the imputed price, applying the AIM/CGE model. *Manag. Environ. Qual. An Int. J.* 22, 33–47.

Matsumoto, K., Tachiiri, K. & Kawamiya, M. (2016) Impact of climate model uncertainties on socioeconomics: A case study with a medium mitigation scenario. *Comput. Oper. Res.* 66, 374–383.

Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. (2011) Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: Model description and calibration. *Atmos. Chem. Phys.* 11, 1417–1456.

Okagawa, A., Masui, T., Akashi, O., Hijioka, Y., Matsumoto, K. & Kainuma, M. (2012) Assessment of GHG emission reduction pathways in a society without carbon capture and nuclear technologies. *Energy Econ.* 34, S391–S398.

Roson, R. & Sartori, M. (2015) Estimation of climate change damage functions for 140 regions in the GTAP9 database. 1, 1–39.

Takakura, J., Fujimori, S., Takahashi, K., Hijioka, Y., Hasegawa, T., Honda, Y. & Masui, T. (2017) Cost of preventing workplace heat-related illness through worker breaks and the benefit of climate-change mitigation. *Environ. Res. Lett.* 12, 64010.