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LETTER

Avoided economic impacts of energy demand changes by 1.5 and 2 °C climate stabilization

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Abstract

Energy demand associated with space heating and cooling is expected to be affected by climate change. There are several global projections of space heating and cooling use that take into consideration climate change, but a comprehensive uncertainty of socioeconomic and climate conditions, including a 1.5 °C global mean temperature change, has never been assessed. This paper shows the economic impact of changes in energy demand for space heating and cooling under multiple socioeconomic and climatic conditions. We use three shared socioeconomic pathways as socioeconomic conditions. For climate conditions, we use two representative concentration pathways that correspond to 4.0 °C and 2.0 °C scenarios, and a 1.5 °C scenario driven from the 2.0 °C scenario with assumption in conjunction with five general circulation models. We find that the economic impacts of climate change are largely affected by socioeconomic assumptions, and global GDP change rates range from +0.21% to −2.01% in 2100 under the 4.0 °C scenario, depending on the socioeconomic condition. Sensitivity analysis that differentiates the thresholds of heating and cooling degree days clarifies that the threshold is a strong factor that generates these differences. Meanwhile, the impact of the 1.5 °C is small regardless of socioeconomic assumptions (−0.02% to −0.06%). The economic loss caused by differences in socioeconomic assumption under the 1.5 °C scenario is much smaller than that under the 2 °C scenario, which implies that stringent climate mitigation can work as a risk hedge to socioeconomic development diversity.

1. Introduction

Understanding the costs and benefits of climate policies is important, since large investments and lifestyle changes could be required for both mitigation and adaptation actions that aim to reduce the adverse effects of climate change. The energy use for space heating and cooling is closely related to climate policy. Changing this energy use is one of the key solutions to adapt to altered intensity and frequency of heat and cold waves due to climate change. Reduction in energy use in buildings can thus be a mitigation option.

Energy use in buildings is strongly affected by climate conditions; the use of air conditioners due to high temperature can be interpreted as an adaptation to climate change. Moreover, mitigation options, such as reducing the use of air conditioners, reduce greenhouse gas emissions and suppress climate change, leading to lower air conditioner use. The energy system may potentially be one of the sectors of the economy most affected by climate change (Mideksa and Kallbekken 2010). Therefore, evaluating mitigation benefits, adaptation costs to adapt to changes in heating and cooling demand, and remaining impacts

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from climate change would enable us to derive a better strategy to overcome climate change.

Regarding climate mitigation in the building sector, earlier studies have shown the contribution of energy-saving technologies (e.g. high-efficient air conditioners and thermal insulation (Serrano *et al* 2017, Waite *et al* 2017a, Hanaoka *et al* 2014). The contribution of human behavioral change to energy demand, such as refraining from excessive use of air conditioners, has also been assessed (Fujimori *et al* 2014a). Fujimori *et al* (2014a) argued that technological and/or behavioral energy savings in the building sector could contribute significantly to reducing economic losses due to climate mitigation. As for climate change adaptation related to energy use for heating and cooling, health impact cost studies have estimated societal costs, including, for example, the costs of labor productivity loss due to heat-related illness prevention (Takakura *et al* 2017). The principle objective of these studies is to provide aggregated economic impact numbers, which will allow for an assessment of importance over time, such as comparing changes in the gross domestic product (GDP), as well as providing a comparison of economic impacts in monetary terms across sectors based on which policymakers can prioritize sectors where adaptive measures are most needed.

With respect to economic impact due to changes in energy consumption and large investments, climate change is likely to increase summer electricity use for space cooling in most regions, and decrease space warming energy use in winter. As heating and cooling changes tend to offset each other, most studies agree that the effect of climate-induced changes in heating and cooling demand on the global economy is minuscule (Zhou *et al* 2014, Eom *et al* 2012, Isaac and van Vuuren 2009, Mima and Criqui 2009, Bosello *et al* 2006). Meanwhile, considering technology costs, earlier studies have pointed out that meeting the high cooling demand caused by climate change could require incremental investments for air conditioning (Waite *et al* 2017b, Hasegawa *et al* 2016, Davis and Gertler 2015, Jenner and Lamadrid 2013, Labriet *et al* 2013, Tol 2013, Roson and Mensbrugghe 2012, Eboli *et al* 2010, Isaac and van Vuuren 2009, McNeil *et al* 2008). However, the limited impact of climate change on global energy may have a much greater effect on the economy because the economic impact of fluctuations in energy use depends on energy systems and/or industrial structures (Hasegawa *et al* 2016).

As indicated above, the link between climatic variables and energy use has been widely documented and utilized to explain future energy consumption changes on a regional (Fazeli *et al* 2016, Eom *et al* 2012, Yu *et al* 2014, Zhou *et al* 2014, Chaturvedi *et al* 2014, Shorr *et al* 2009, Amato *et al* 2005, Frank 2005, Sailor and Pavlova 2003) and global (De Cian and Sue Wing 2017, Riahi *et al.* 2017, Bosello *et al* 2013, De Cian *et al* 2012, Roson and Mensbrugghe 2012, Eskeland and Mideksa 2010, Isaac and van Vuuren 2009) scale in consideration of the timescale of meteorological drivers, which covers the annual average, seasonal basis, and temporal exposure to different intervals of temperature.

Despite the rich accumulation of relevant past studies, further assessment of economic impacts associated with climate change on energy demand for space heating and cooling is necessary due to the following reasons.

First, the Paris Agreement defines a long-term temperature goal for international climate policy as holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels (UNFCCC 2015).

Quantified mitigation benefits from avoiding investments in new devices for meeting the cooling demand is an important aspect in global negotiations. There is no literature that explicitly discusses the 1.5 °C change in global scale in the context of the macro economy. Second, earlier studies have not considered uncertainty in the different shared socioeconomic pathways (SSPs) that shows different adaptation approaches to climate change regarding energy use for heating and cooling. Moreover, newly developed SSPs developed by Riahi *et al* (2017) can be used to carry out the most up-to-date assessment. Hasegawa *et al* (2016) is a pioneering study in this context, although they only considered GDP and population variations for the SSPs. In principle, SSPs should include autonomous adaptation that can reflect future social practices against climate change in the assessment. We thus differentiate base temperature for heating and cooling among SSPs. Third, future energy systems and energy consumption may differ by investment cost of specific technologies; hence, it is worth exploring future changes with detailed end-use services and devices.

In this context, this paper aims to facilitate better understanding of economic impacts associated with changes in energy use in the building sector with respect to future climate conditions, while considering different socioeconomic development pathway. Moreover, we analyze the 1.5 °C temperature change scenarios, and discuss its implications from the perspective of 2 °C temperature stabilization.

2. Methods

2.1. Overview

A scenario analysis, explained in 2.4., was executed using an economic model (Asia-Pacific Integrated Model/Computable General Equilibrium [AIM/CGE]) coupled with an end-use model (Fujimori *et al* 2012) to quantify the economic impacts of changes in energy demand for space heating and cooling systems, and describe energy consumption changes under varying climatic scenarios and SSP frameworks. We changed the energy service demand of building sector with

information on socioeconomic assumptions, technology, and climate change. We finalized simulation results data into five regions (ASIA: Asia, except for OECD90 countries; MAF: The Middle East and Africa; LAM: Latin America; OECD90: United Nations Framework Convention on Climate Change [UNFCCC] Annex I countries; and REF: Eastern Europe and the Former Soviet Union) to discuss our results.

2.2. The AIM/CGE model

The AIM/CGE model is a one-year-step, recursive, dynamic CGE model combined with the AIM/Enduse model, which is an energy end-use model based on previous work (Fujimori *et al* 2012). This approach integrates detailed information regarding energy end-use technologies, such as stock changes in air conditioning technologies over time and their associated costs, whereas the conventional method only incorporates aggregated energy demand (see Fujimori *et al* (2012) for details of the model structure and mathematical formulas). When considering the selection of end-use technologies and stock changes with respect to space heating and cooling demand, we assume that the household and commercial sectors require several energy services (heating, cooling, cooking, lighting, etc.) and a variety of technologies to meet demand.

They key driver to quantify economic impacts is the changes in energy service demand for heating and cooling. The service demand is fulfilled by multiple devices that have different energy efficiencies, annualized investment costs, operation costs, and management costs, as shown in supplementary information tables 2 and 3. The selection of an energy technology is determined by the distribution of its share of all the energy devices within a logit function, where one endogenously determined variable and two parameters for each device are associated. The former variable is the total cost of device that includes both of initial investment and operation and management (O&M) costs. One parameter is the exponent for the cost, and the other parameters represent the factors other than cost. The base year parameters and annualized investment cost were calibrated by Akashi and Hanaoka (2012). We differentiated the energy fuel efficiency and cost by fuel inputs. The fuel-wise device shares are calibrated from the base year information, and in that sense, the regional characteristics are reflected in the calibrated parameters. We assumed that future technologies that are not currently used have uniform cost and efficiency information globally. We did not explicitly model learning curve for heating, ventilation, air conditioning devices (HVACs). We assumed that the technological improvement be achieved by energy device producers' efforts, such as R&D, according to the assumption that is consistent with the SSP's world view. In Fujimori *et al* (2016), this was already tested with our SSP2 assumptions against historical observations. However, this may not be in the case of sectoral breakdown. Regarding the assumptions for SSP1 and SSP3, they are no longer the scenarios to reproduce historical period, but they would be generated to show future uncertainty under specific assumptions.

The energy balance was calculated by those expenditure changes for heating and cooling. This energy balance and disposable income provides impacts on both power generation and production sectors. There are several power-generation sectors, and the output of power generation from several energy sources was combined with a logit function. This method was adopted to account for the energy balance, as the constant elasticity substitution (CES) function does not guarantee a material balance. The production sectors maximize profits under multi-nested CES functions and individual input prices.

2.3. Energy service demand

The energy service demands for space heating and cooling were determined using the method from Schipper and Meyers (1992), while other demands were determined using the method from Fujimori *et al* (2014b). We changed energy service demand due to changes in heating degree days/cooling degree days (HDD/CDD), as well as socioeconomic drivers. The cooling service demand in the sector is a function of the output of commercial sector formulated by labor force, floor space, cooling degree days, and device penetration rates. Labor force is endogenously determined in the conventional CES production function, and the floor area per capita was expressed as a function of income, as per Mcneil and Letschert (2007). The cooling degree days are processed by General Circulation Models (GCM) outcomes, while the device penetration rates are the function of GDP/cap adapted from Isaac and van Vuuren (2009). Climate condition and SSPs assumption give different device penetration rate. A similar concept is adopted for the heating service demand. Furthermore, the household sector also uses the same concept with population information, than labor force variable (see supplementary annex for a more detailed description).

2.4. Scenario settings and data

There are two types of scenarios that we simulate in this study—the core and sensitivity scenarios. The former consists of two dimensions, climate and socioeconomic conditions. In climate conditions, four climate scenarios were used to see how the 1.5 °C scenario differs from the 2 °C and 4 °C scenarios. Two scenarios were directly taken from the Representative Concentration Pathway (RCP) of RCP2.6 (2 °C) and RCP8.5 (4 °C). A third scenario, 1.5 °C, is where the climate condition after 2020 is constant at the level of RCP2.6. We acknowledge that there could be other approaches to investigate 1.5 °C and 2 °C temperature changes (e.g. Schleussner *et al* 2016), but in this paper, we adopt this approach to necessarily consider socioeconomic dynamics over a certain period (time slice experiments do not work). We will discuss

Table 1. Literature on thresholds for heating and cooling degree days (°C).

Author/Year	Location	HDD threshold	CDD threshold
Moustris *et al* 2015	Athens, Greece	18	26
Psiloglou *et al* 2009	Athens, Greece	20	20
Reiss and White 2005	California	15.5	21.1
Eom *et al* 2012	China	18	18
Zhang *et al* 2006	China	20	25
Zhang *et al* 2001	China	20	26
Dowling 2013	European	15	18
Eskeland and Mideksa 2010	European	18	22
Isaac and van Vuuren 2009	Global	18	18
Sakamoto *et al* 2014	Japan	18	24
MLIT 2017	Japan	14	24
Lee *et al* 2014	Korea	15	20
Psiloglou *et al* 2009	London	16	16
Beccali *et al* 2008	Palermo	18.7	22
Holmes 2016	Scotland, UK	15.5	22
Pardo *et al* 2002	Spain	18	18
Valor *et al* 2001	Spain	18	18
Labandeira *et al* 2012	Spain	13	23
UK Climate Projections 2014	UK	15.5	22
Jaglom *et al* 2014	USA	18	18
Petri and Caldeira 2015	USA	18.3	18.3
Mishra and Lettenmaier 2011	USA	18.3	23.9
Hamlet *et al* 2010	USA	18.3	23.9
Sailor 1997	USA	18.3	18.3
Alberini and Filippini 2011	USA	18.3	18.3
Shorr *et al* 2009	USA, Northeast area	18.3	18.3

this point further in later sections of this paper. In addition to those three scenarios with climate change, a no climate change (NoCC) scenario is also used as the baseline scenario.

The socioeconomic dimension consists of three SSPs (SSP1: sustainability; SSP2: middle of the road; and SSP3: regional rivalry) to compare the economic implications due to different socioeconomic assumptions (O'Neill *et al* 2017). SSPs estimates were used for population and GDP (IIASA 2012). One of the novelties of this study is that it considers two additional socioeconomic features beyond population and GDP. First, the threshold of heating and cooling demand temperature is differentiated across SSPs. Second, different level of autonomous energy efficiency improvement is assumed across SSPs.

In order to determine the base temperature for heating and cooling demand, we collected relevant information as much as possible from worldwide literature, as summarized in table 1, mainly covering the temperate zone. We assume that all base temperatures cover the SSPs condition. First, we took the median from the all literature for the SSP2 assumption which is characterized as a sort of historical extension scenario. We set the base temperature as 18 °C for heating and 22 °C for cooling demand, respectively, for SSP2. Second, the quantile in table 1 is used for the SSP1 and SSP3 to reflect different energy demands by social movement. SSP1 is represented by more rapid technological improvement (e.g. buildings are more thermally-insulated) and a more pro-environmental society (e.g. people refrain from excessive use of air conditioner). Thus, energy demand for heating and cooling would be lower. To represent such lower energy demand, a 4 °C higher temperature threshold for cooling demand and 2 °C lower temperature threshold for heating demand are assumed in SSP1, than SSP2. The opposite assumption is applied to SSP3 (table 3). Autonomous energy efficiency improvement is assumed to be high, middle, and low for SSP1, SSP2, and SSP3, respectively, according to the different level of mitigation challenges (table 3).

We point out two caveats—SSP3 is unlikely to achieve a 1.5 °C or 2 °C stabilization (Fujimori *et al* 2017), and none of these three SSPs will reach over 8.5 W m^{-2}. However, our goal is to examine the socioeconomic and climatic conditions systematically, and thus, we continue to use these scenarios nevertheless. We use three different heating/cooling degree day (HDD and CDD, respectively) threshold conditions to see the sensitivity of the adaptive level to climate change for heating and cooling.

In this analysis, HDD and CDD refer to the sum of positive or negative deviations in the actual temperature from the base temperature over a given period. The base temperature is defined as the temperature level where there is no need for either heating or cooling (Mideksa and Kallbekken 2010). Changes in HDD and CDD corresponding to temperature changes are computed on a half-degree grid cell scale by utilizing the output of GCMs (Hempel *et al* 2013). Then, they were aggregated according to AIM/CGE regions using a population density map (Center for International Earth Science Information Network–CIESIN–Columbia University and Centro Internacional de Agricultura Tropical–CIAT 2005) as a weighting parameter. These values were then fed into the economic model as drivers of the associated energy consumption.

Table 2. Simulation framework.

Simulation objective	SSPs	Climate condition
Climate impact and 1.5 °C scenario	SSP2	1.5 °C/2.0 °C/4.0 °C/ No climate change
The effect of socioeconomic assumptions	SSP1/SSP2/SSP3	1.5 °C/2.0 °C/4.0 °C/ No climate change
Sensitivity of adaptive level to climate change for heating and cooling	SSP2(3 different HDD/CDD threshold condition)	

Table 3. List of parameters and their assumptions for socioeconomic conditions.

Parameter	Population and GDP assumption	HDD(H)/CDD(C) threshold (°C)	Autonomous energy efficiency improvement
SSP1	SSP1 database (Low population growth and high economic growth)	15/26	0.1%
SSP2	SSP2 database (Sustainable population and economic growth)	18/22	0.05%
SSP3	SSP3 database (High population growth and low economic growth)	20/18	0.025%

3. Results

3.1. Energy consumption change of building sector

We found that the building sector, against other sectors, shows extreme change of energy consumption in 2100 compared to the no climate change scenario. Increased energy consumption of electricity prevails in all regions with the 4.0 °C scenario, while reduced energy use of oil and coal prevails in all regions in 2100. The maximum change occurs in the SSP2 and 4.0 °C scenarios. In order to adapt to hotter days, electricity consumption increases drastically in the 4.0 °C scenario. Compared to the current energy system, the global final energy mix in the building sector is slightly more skewed toward electricity and natural gas due to cooling energy demand. The pattern is accentuated under rapid warming with more widespread regions. Changes in the heating degree days interact with reducing heating energy sources, such as coal, oil, and natural gas. Furthermore, the impact on natural gas use increases with cooling degree days, which is related to the building of cooling systems that use natural gas. Energy consumption in the SSP2 and less than 2.0 °C increase scenarios shows energy use reduction compared to the no climate change scenario due to larger heating, than cooling, demand change. The ultimate effect on energy consumption is related to the region's income situation and degree days change. OECD90 and LAM regions have slightly larger impact than other regions in energy consumption change due to heating and cooling degree day change.

3.2. Climate Impact and the 1.5 °C Scenario

Figure 2 shows GDP changes associated with changes in space heating and cooling demand at the global level in SSP2 compared to no climate change case. The GDP's negative impacts in 2100 are highest (median: −0.94%) in the 4 °C scenario, whereas the 1.5 °C scenario maintains a low GDP change (median: −0.05%). These range and median values are slightly different from previous estimates (Hasegawa *et al* 2016) mainly due to different HDD and CDD threshold assumptions. The gap between the 1.5 °C and 4 °C scenarios is 0.31% in 2050, and grows larger in the latter half of the century, reaching 0.79% in 2100. The median of the 2 °C scenario shows 0.19% GDP loss in 2100. The gap between the 2 °C and 4 °C scenarios is much higher than that between the 2 °C and 1.5 °C scenarios. GDP losses in the latter half of this century are accelerated in the 4 °C scenario compared to the 1.5 °C or the 2 °C scenarios.

Table 4. List of parameters and their assumptions for climatic conditions.

Parameter	Climate condition in 2100 (GCMs)
1.5 °C	+1.5 (compared to pre-industrial level)
2.0 °C	RCP2.6
4.0 °C	RCP8.5
No climate change	+0

Figure 3 shows global temperature change has a linear impact on GDP loss globally. There is a strong negative correlation between global GDP losses and temperature increase. However, the relationship between these two variables in the low-temperature increase area is relatively unclear because of regional variation of climate change and its impact threshold. The differences between the 1.5 °C and 2 °C scenarios are less than −0.2% in terms of change in GDP.

3.3. Sensitivity analysis

Figure 4 shows GDP changes relative to the level of no climate change (No CC) for 1.5 °C, 2 °C, and 4 °C in 2100 at the global and five aggregated regions with different SSPs. The effects of changes in HDD and CDD threshold differ across regions and SSPs. For instance, in the case of SSP1 (Sustainability), climate change causes less change in GDP compared to other SSP scenarios. This SSP variety could be due to a mixture of two reasons. One is basic economic (GDP) and demographic assumptions differences. The other is HDD/CDD threshold and technological annualized investment cost assumption differences. Therefore, to identify the primary factor, we conduct a sensitivity

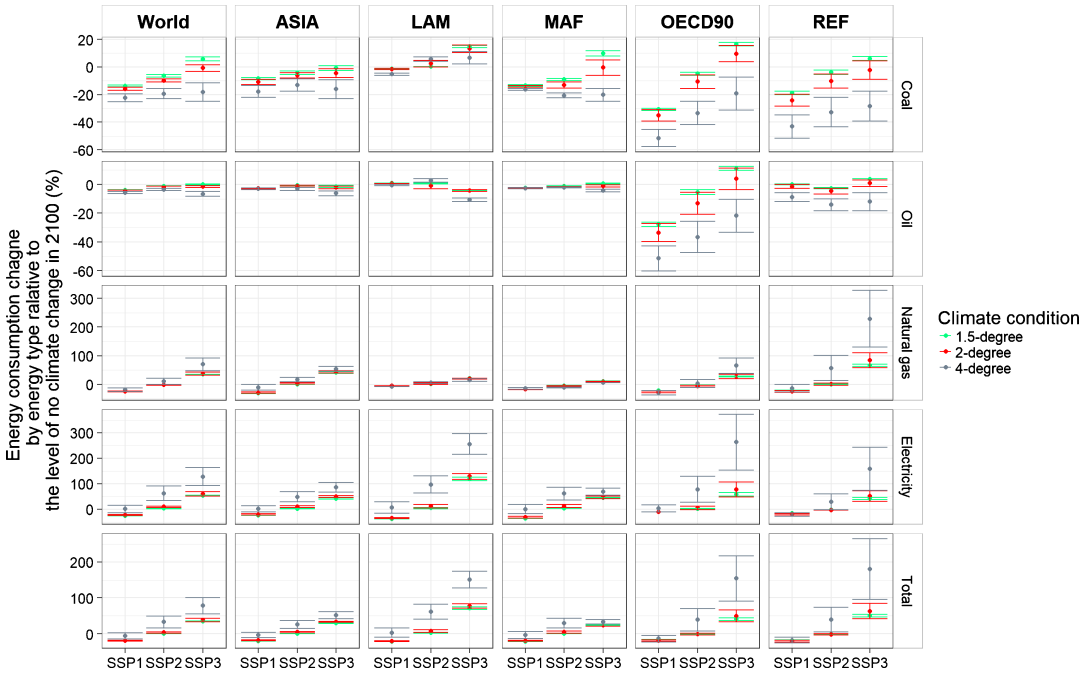

Figure 1. Energy consumption change of the building sector relative to no climate change for each SSP (SSP1, SSP2, and SSP3) with different climatic scenarios (1.5 °C, 2 °C, and 4 °C) in 2100. Error bars represent 95% confidence interval of the mean across the five GCMs (ASIA: Asia, except for OECD90 countries; MAF: The Middle East and Africa; LAM: Latin America; OECD90: United Nations Framework Convention on Climate Change [UNFCCC] Annex I countries; and REF: Eastern Europe and the Former Soviet Union).

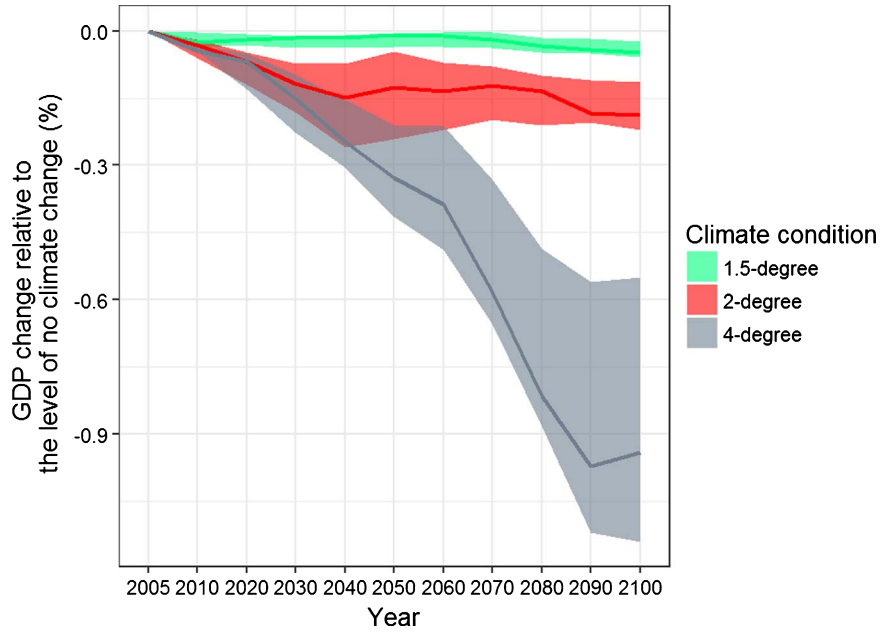

Figure 2. Changes in GDP due to changes in demand for space heating and cooling under different climatic conditions in SSP2. GDP changes are shown as changes from the level without any climate change. The lines show median values, and the ranges represent the uncertainty ranges of the General Circulation Models (GCMs). See supplementary information for regional GDP changes.

analysis that suggests that the latter factor (threshold assumption) is larger (see the section on decomposing of heating and cooling impact written in the source of economic loss and supplementary information available at stacks.iop.org/ERL/13/045010/mmedia). Regarding regional variety, SSP3 shows large regional differences across climate conditions. For example, Reforming Regions (REF; mostly Former Soviet Union) and Latin America (LAM) show high impact, while OECD (OECD90), Asia, and the Middle East and Africa (MAF) are relatively small in the 4 °C scenario. In the 4 °C climatic condition scenario, REF and LAM show large uncertainty across GCMs. We found significant differences among different climatic

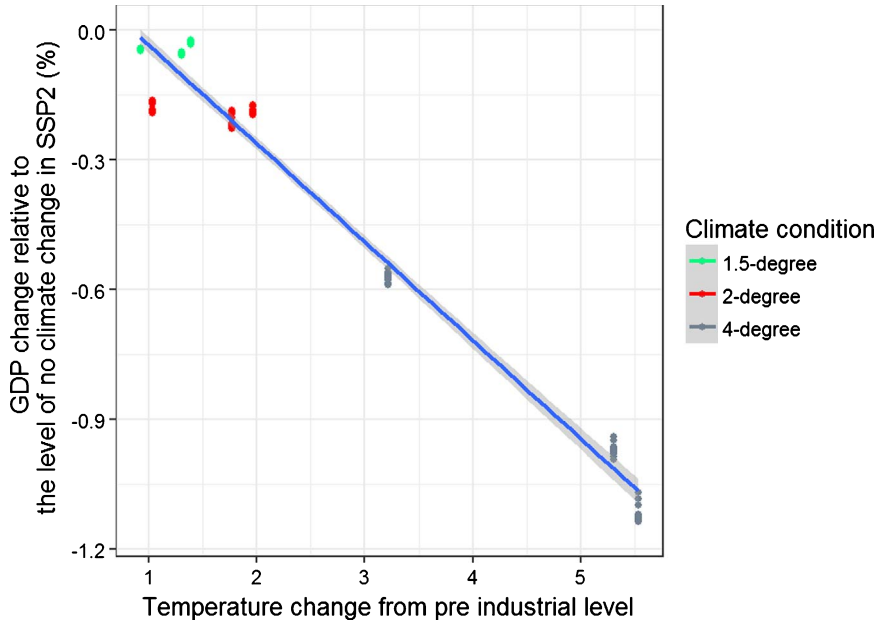

Figure 3. Relationship between temperature change and GDP loss in the 2090s (2091–2100). Each shape represents a different scenario of temperature change from RCP8.5, RCP2.6, and a modified version for a 1.5 °C scenario in SSP2. The blue line is the regression line, and the gray color shows the 95% confidence interval.

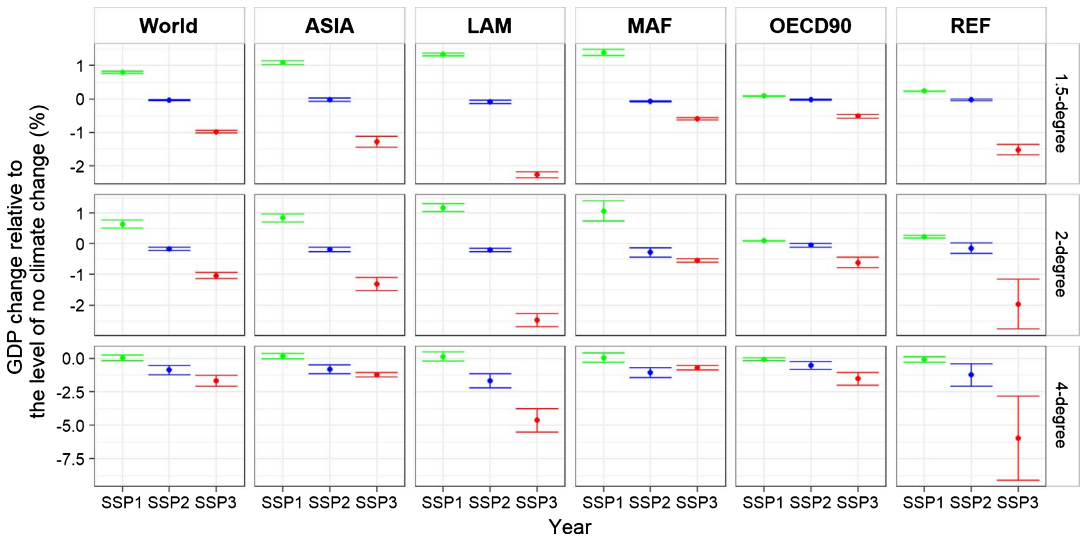

Figure 4. GDP change relative to the each SSP (SSP1, SSP2, and SSP3) with different climatic scenario (1.5 °C, 2 °C, and 4 °C) in 2100. Error bars represent 95% confidence interval of the mean across the five GCMs (ASIA: Asia, except for OECD90 countries; MAF: The Middle East and Africa; LAM: Latin America; OECD90: United Nations Framework Convention on Climate Change [UNFCCC] Annex I countries; and REF: Eastern Europe and the Former Soviet Union).

condition. The 4 °C case shows greater impact than those in the 1.5 °C and 2 °C scenarios in all regions in all SSPs scenarios that were used in this study. Interestingly, the 1.5 °C scenario can reduce GDP loss inequality among regions in all SSPs. GDP loss gaps among SSPs at 2 °C are significantly more severe than at the 1.5 °C scenario in SSPs, and socioeconomic assumptions amplify the regional variety.

Since extant literature on the threshold HDD and CDD does not cover all regions, we carried out a sensitivity analysis on the impact of different low and high threshold cases for SSP2. In this study, we changed the CDD threshold from 22 °C–18 °C or 26 °C. In our benchmark estimate, the CDD threshold change had significant effects. These threshold changes may result in substantial GDP loss in REF and LAM, at around 4%, in cooling degree days, with the 18 °C threshold, compared to the no climate change case in 2100. As the use of air conditioners increases, we can avoid approximately 1% (22 °C) or 2% (26 °C) economic loss globally. This means that people's adaptive lifestyle can mitigate global economic loss. Heating is not as sensitive as cooling, since most of economic impacts come from cooling demand.

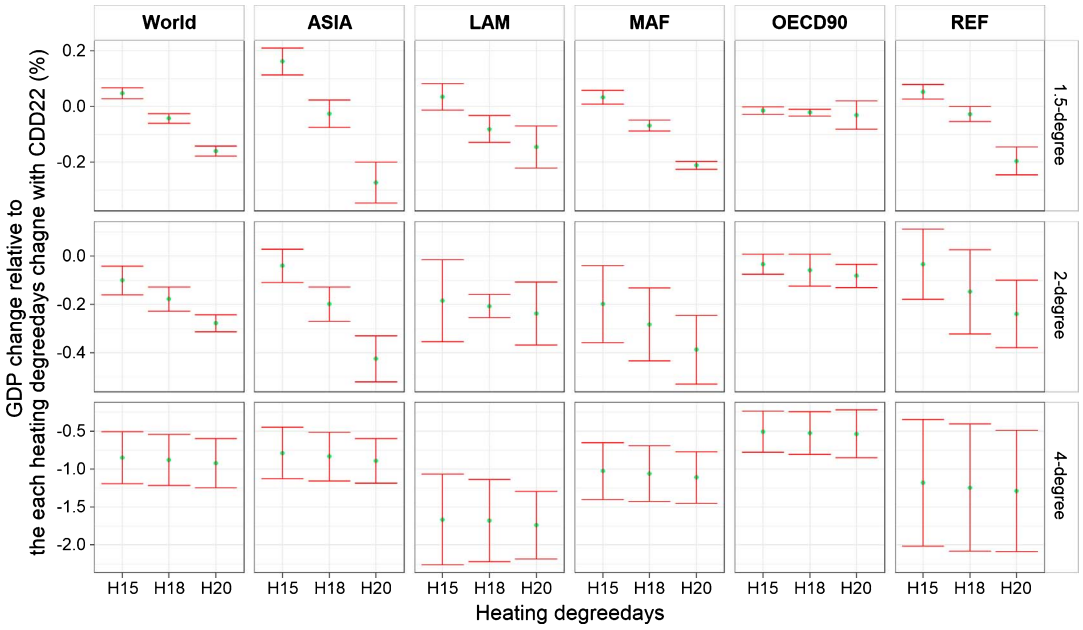

Figure 5. Impact of change in heating demand on GDP changes with different challenges to adaptation in SSP2 at the global level and across the five regions. Error bars represent 95% confidence interval of the mean across the five GCMs (ASIA: Asia, except for OECD90 countries; MAF: The Middle East and Africa; LAM: Latin America; OECD90: United Nations Framework Convention on Climate Change [UNFCCC] Annex I countries; and REF: Eastern Europe and the Former Soviet Union).

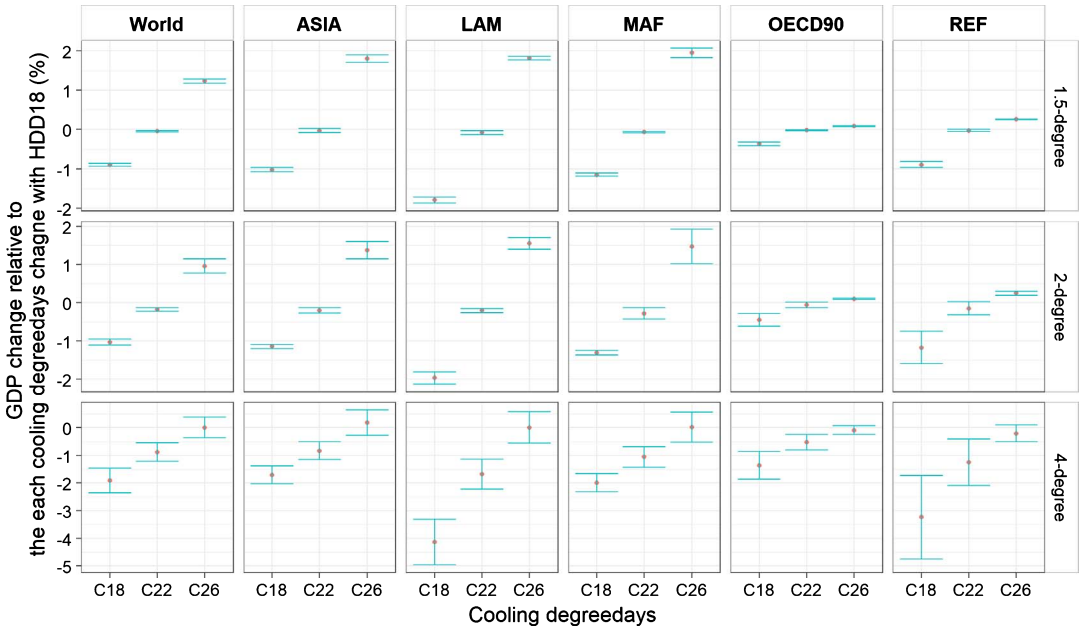

Figure 6. Impact of change in cooling demand on GDP changes with different challenges to adaptation in SSP2 at the global level and across the five regions. Error bars represent 95% confidence interval of the mean across the five GCMs (ASIA: Asia except, for OECD90 countries; MAF: The Middle East and Africa; LAM: Latin America; OECD90: United Nations Framework Convention on Climate Change [UNFCCC] Annex I countries; and REF: Eastern Europe and the Former Soviet Union).

4. Discussions

We have examined the economic implications of changes in space heating and cooling energy demand due to changes in its use. A 1.5 °C temperature change results in an economic loss of 0.31% in 2050, and 0.89% in 2100, globally, compared to a 4 °C climate change scenario. Compared to a 2 °C climate change scenario, there are still noticeable reductions in economic loss of 0.14% under the 1.5 °C climate change scenario in 2100. The effort of limiting global temperature rise below 1.5 °C shows small GDP losses in all regions. Furthermore, this economic loss is negligible regardless of the SSPs. In contrast, the 4 °C climate change scenario shows us that there will be an associated economic cost, and its magnitude depends on the degree

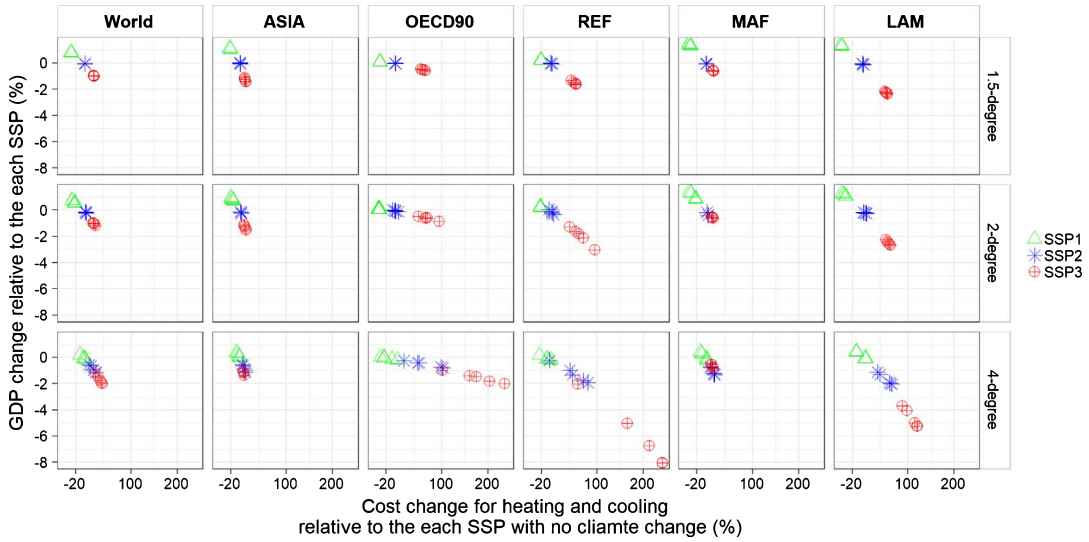

Figure 7. Relationship between GDP change and annualized additional investment cost change for heating and cooling in all SSPs and climatic conditions. Points refer to data of each SSP and climatic condition, including 5GCMs in 2100 (ASIA: Asia, except for OECD90 countries; MAF: The Middle East and Africa; LAM: Latin America; OECD90: United Nations Framework Convention on Climate Change [UNFCCC] Annex I countries; and REF: Eastern Europe and the Former Soviet Union).

of socioeconomic development. In the worst-case scenario, like the SSP3, economic loss is considerably high. From this observation, we emphasize the importance of socioeconomic development. Another possible interpretation of our results would be that mitigating climate change can be a risk hedge to worse socioeconomic development (e.g. low economic growth and low adaptive capacity). Our results show global increase in energy consumption due to an increase in cooling demand. In some scenarios, energy consumption for the building sector reduced, but it does not lead to changes in the energy consumption of other sectors (see supplementary figure 8). Other simulation shows that reduced heating demand is offset by increases in agriculture, transportation, industrial, and commerce energy demand (De Cian and Sue Wing 2017). We hypothesize that the incremental costs of using heating and cooling technologies is the main factor that generates GDP loss, and we found that GDP loss and annualized investment costs for additional devices are correlated, although with high variation in different regions (figure 7). A reduction of utility in the energy system can be driven by higher energy prices and higher energy related cost, such as purchasing equipment for heating and cooling, and investment of building insulation. Our assumption of technology cost and efficiency information for the future is globally the same; it may cause uncertainty of the SSPs results. The additional cost implies reduction of spending for non-energy purposes. To maximize overall utility, the consumer tends to reduce the part of utility associated with energy; thus, the consumer reduces lighting and other services (Hamamoto 2013), creating GDP losses in the region. In some regions, trade must keep overall demand change, and thus, GDP losses are larger than other regions, since the demand change does not generate industrial activities. Developed countries, like those belonging to the OECD90, have relatively less impact from annualized additional cost increase for cooling and heating than other regions. Current OECD regions are geographically located in a temperate climate zone where the cooling demand would not increase compared to tropical zones. Furthermore, the scale of GDP itself is larger than that of developing countries, which makes the relative economic damage to total macro economy small. Additionally, they have industries related to heating and cooling devices. The opposite trend can be observed in Asia, Africa, and Latin America.

We found strong evidence of a relationship between investment costs of air conditioners and economic losses (table 5). Most additional costs come from using air conditioners. The penetration of air conditioners is driven by income, and maximum climate saturation is driven by climate. In addition to climate change, the increase in cooling demand is due to income growth in high-potential developing regions, which was not highlighted in previous studies. Boosting air conditioner sales can thus have positive impact on enterprises that manufacture air conditioners and its components, and deal with its sales. On the other hand, this investment from the consumer side will reduce different kinds of expenditures, since air conditioners are relatively expensive compared to other building devices. Therefore, it leaves consumers with less money to buy other devices. Finally, the reduced purchasing power has a negative impact on investments in other businesses, and eventually total utility will decline. This similarity is also reported in Isaac and van Vuuren (2009). There is a positive impact on human health from sustaining working hours in businesses to reducing medical expenses when we purchase and use

Table 5. Correlation between the device penetration ratio of air-conditioner and annualized additional investment cost of each region in all SSPs and climatic conditions in 2090s (2091–2100) (each region ($N = 450$)).

	Annualized additional investment cost				
OECD90	REF	Asia	MAF	LAM	
Device penetration of air-conditioner	0.990[a]	0.991[a]	0.977[a]	0.971[a]	0.992[a]

[a] $p < .05$

air conditioners. Therefore, we must combine these two factors to find a reliable estimate for a complete decision-making process.

The GDP change is very sensitive to the threshold change of heating and cooling assumptions. Sensitivity analysis reveals that assumptions can be made in which the overall net effect is either positive or negative. Additionally, climate change-related GDP change can be differentiated due to the fundamental economic structure, social acceptance of new technology, study model, and autonomous adaptation to climate change that mostly relates to cultural background. In our simulation, the power generation mix changes across the SSPs and climate change until its capacity. This is because of completeness change by energy price. However, we did not explore people's behavioral change, wherein they adopt renewables across SSPs. Social acceptance of renewables can differ among regions and SSPs, since it requires large land and emits excessive noise, which is one of our limitations. It is considerably difficult to see the historical evidence for all regions due to lack of energy consumption data by energy service and stock changes that decrease energy consumption by technology improvement. Hence, we adopted an engineering approach, so our projections of climate change impacts depend fundamentally on the engineering calculation method, which was calculated as the product of changes in population, floor area per capita, heating and cooling demand per area, and device penetration ratio. Sensitivity has been sufficiently explored, except toward floor space area, which is related to population and economic growth. We thus hypothesize that all increments of floor space will affect energy consumption. In reality, floor space area and share of total area heated (or cooled) in year t will differ among SSPs because of cultural use of space. The general equilibrium (GE) model used in our study tends to show higher costs as it captures economy-wide interactions and distortions. On the other hand, partial equilibrium models tend to show lower costs, since they represent only direct costs, and usually neglect costs imposed on other sectors of the economy and other distortions (Paltsev and Capros 2013). As definitions of costs differ among the models, we do not report them here, since they are not directly comparable. Unobservable factors that we did not account for also cannot be considered, as these omitted variables may cause bias. One of our biases may arise from the homogeneity threshold temperature for heating and cooling. It would thus be preferable to have region-specific threshold temperature for cooling and heating. Additionally, the response function curve for temperature may differ by people's capacity to endure temperature change. Our primary focus point was to ascertain the global overall trend and the scale of the magnitude, but it may be better to incorporate a comfortable temperature range for people in different regions, housing types, and building insulation standards if local policymaking is the goal.

5. Conclusions

We quantified the economic implication of the building sector for limiting global temperature rise at 1.5 °C, including climate models (RCPs and GCMs), and population, income, behavioral adaption, and technical improvement uncertainty (SSPs). We found significant differences among different climatic condition, and more specifically, large benefits to hold warming below 1.5 °C exist. The 1.5 °C scenario results in a low GDP change (median: −0.05%), but has the highest negative impact on GDP in 2100 (median: −0.94%) in the 4 °C scenario. This tendency can be observed across regions and heterogeneous socioeconomic developments. Interestingly, 1.5 °C climate stabilization can reduce GDP loss inequality among regions in all SSPs, which would provide a critical message for the debate on economic development and climate.

Here, we also identified that economic impacts are sensitive to assumptions on the threshold of heating and cooling degree day accounts by SSPs. This suggests that region-specific assumptions may be needed in future research to account for differences based on region and more specific climatic condition, such as lifestyle, humidity, wind, and so on. The other point that should be noted here is that temperature overshoot has not yet been taken into account for the 1.5 °C scenario, while the overshoot would be inevitable in such stringent climate mitigation (Rogelj *et al* 2015). Thus, the result of climate projection consistent with the 1.5 °C emission pathway, which is just under development, would improve this limitation (Riahi *et al* 2017).

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