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Carbon Dioxide Emissions Control Policy under Uncertainties of the Probability and Impact of Abrupt Climate Change Event

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Abstract. This study discusses the target level of industrial carbon dioxide (CO_2) emissions in terms of a cost benefit analysis of climate change, using a so-called integrated assessment model (IAM). In the analysis, special attention is paid to an abrupt climate change event, sometimes called an irreversible dangerous climate change event or a catastrophe, which might occur because of long term global warming. Taking the characteristics of such an event into consideration, an IAM is extended to contain a hazard function that connects the rise in air temperature with the probability of abrupt change. Keeping in mind the large natural scientific and economic uncertainty concerning an abrupt change, this study shows several CO_2 control targets by the mid-21st century, graphically indicating the combination of major uncertain factors, i.e., the probability and impact of an abrupt change, for each target. The results imply that if the impact of abrupt change can be assumed at less than around 20% of total consumption, the optimal industrial CO_2 emissions level will be 75% or higher in 2055 relative to that in 2005 even for a high probability of abrupt change, while a very stringent emissions target is required if there is the possibility of an abrupt change exerting a greater impact. In other words, developing adaptation measures to reduce the impact of abrupt change to 20% of total consumption is recommended as well as controlling GHG emissions.

Keywords: Integrated assessment model, Stochastic model, Catastrophe, Climate change, Global warming

1. Introduction

Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) reports that *it is very likely that anthropogenic greenhouse gas increases caused most of the observed increase in global average temperatures since the mid-20th century*, and that *continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century*.

The IPCC report as well as other reports, including the Stern Review on the Economics of Climate Change (Stern, 2007) that warns us of the impact of climate change caused by greenhouse gas (GHG) emissions, further international debates on GHG emissions control after the first commission period of the Kyoto Protocol to the United Nations Framework Convention on Climate Change, 2008-2012. Integrated assessment models (IAMs) that calculate interactions among economies, GHG emissions, and climate change have been used for providing the debaters with reasonable GHG emissions targets in the future.

However, it is difficult to clinch the debates; a major reason for this is that natural scientific information has not yet been sufficiently clarified, especially regarding the impact of climate change due to the rise in atmospheric air temperature, as well as regarding the interaction between airborne GHG concentrations and air temperature. More specifically, for example, climate sensitivity defined as the equilibrium response of global surface temperature to a doubling of equivalent carbon dioxide (CO_2) concentration has not been determined, though its probability distribution has been recently investigated (Royer et al., 2007).

In regard to the impact of climate change, uncertainties exist concerning not only continuous effects related to the extent of warming such as heat-related illness and land submergence by a rise in sea level, but also regarding potential abrupt climate change events which may occur discontinuously due to warming. The latter, also referred to as dangerous irreversible events or catastrophes, includes the shutdown of global-scale thermohaline circulation and the melting of the West Antarctic ice sheet, and should necessarily be incorporated into IAMs since they can have a substantial impact on an optimal GHG emissions path (Wright and Erickson, 2003).

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Many difficulties are involved in incorporating abrupt climate change events, hereafter referred to as abrupt changes, into IAMs. These difficulties originate mainly in the uncertainty concerning the conditions in which abrupt changes occur; these conditions have been gradually clarified over time in many studies, yet they have not been fully understood, and gaining a complete understanding of them will take some time. This means that no GHG emissions target exists that assures zero risk of abrupt change. What we can determine at present is an optimal emissions path based on the balance between the probability and impact of abrupt change and the cost of GHG emissions reduction, which is the primary purpose of this study. We may also consider developing adaptation measures to reduce the impact of abrupt change, which allows the relaxation of an emissions control target.

While Nordhaus has dealt with this issue using his IAM called the DICE model (Dynamic Integrated model of Climate and the Economy) (Nordhaus and Boyer, 2000; Nordhaus, 2007a), the present study extends the model to reflect the characteristics of abrupt changes: the probability of an abrupt change is explicitly introduced as an endogenous variable in the model, following an approach presented by Gjerde et al. (1999). This means that the analysis described in this paper adopts a discontinuous and stochastic modeling technique, which is different from the conventional, continuous, and deterministic technique used in the DICE and other major models. Here, we focus on the control targets of industrial CO_2 emissions, i.e., total anthropogenic CO_2 emissions except those due to land-use change, because they are the most important anthropogenic GHG emissions.

2. The Model

The DICE model (Nordhaus and Boyer, 2000), which is one of the the most well-known integrated assessment model, is modified for application to the present study. The DICE model consists of an economy module based on optimal growth theory and a climate-emissions-damage module representing the relationships among economic activity, GHG emissions, GHG concentrations in the air, and global average air temperature. The model operates in time periods of 10 years with the first period centered on 2005. Since the full specifications including formulations and parameter settings of the latest version of the DICE model, "DICE-2007," are presented by its original modeler (Nordhaus, 2007a), this paper focuses on describing the modifications to the DICE-2007.

This section first describes the model formulation of the continuous and deterministic modeling technique applied in the original DICE-2007. It then presents the modifications of the model formulation necessary for adopting a discontinuous and stochastic technique.

2.1. Continuous and Deterministic Modeling Technique

The objective function W in the DICE model is expressed as follows:

$$W = \int_0^\infty e^{-\rho t} U(t) dt \approx \sum_t e^{-\rho t} U(t), \tag{1}$$

where ρ is the pure rate of social time preference (PRTP), and U the instant utility at the time period t calculated by

$$U(t) = \begin{cases} L(t)\left\{c(t)^{1-\alpha} - 1\right\} \big/ (1-\alpha), & \alpha \neq 1,\ \alpha > 0 \\ L(t)\log\left(c(t)\right), & \alpha = 1 \end{cases}, \tag{2}$$

where $C(t)$: per capita consumption, $L(t)$: population, and α: elasticity of the marginal utility of consumption (EMUC), i.e., relative risk aversion.

Total economic damage due to climate change, denoted by $D(t)$, is expressed by a ratio relative to the gross world product, $Y(t)$, and is given as a quadratic function of the rise in global average air temperature, $T(t)$, as follows:

$$D(t)/Y(t) = aT(t)^2, \tag{3}$$

where a is a parameter. Here $D(t)$ is the total sum of several kinds of global warming damage including the damage caused by abrupt changes. Since we intend to distinguish between continuous, reversible damages and discontinuous, irreversible damages, the former and the latter, denoted respectively by $D_c(t)$ and $D_d(t)$, are separately formulated by the following equations:

$$D_c(t)/Y(t) = a_c T(t)^2, \tag{4}$$

$$D_d(t)/Y(t) = a_d T(t)^2, \tag{5}$$

where a_c and a_d are parameters; $a_c+a_d=a$.

While the total discontinuous, irreversible damage $D_d(t)$ is expressed as a continuous, deterministic function of the rise in air temperature in Equation (5), the damage can be more properly treated by using a discontinuous, stochastic modeling technique, which will be introduced in the next subsection.

2.2. Discontinuous and Stochastic Modeling Technique

The model presented by Gjerde et al. (1999) following Clarke and Reed (1994), in which the instant utility function is considered to discontinuously change at the time of an abrupt change, is adopted in this study. Denoting the time of an abrupt change event by τ and the instant utility functions before and after the event by U and V, respectively, the objective function is now expressed as follows:

$$W = E\left[\int_0^{\tau} e^{-\rho t} U(t)dt + \int_{\tau}^{\infty} e^{-\rho t} V(t)dt\right]. \tag{6}$$

According to Gjerde et al. (1999), Eq. (6) is converted to

$$W = \int_0^{\infty} e^{-\rho t} S(t)U(t)dt + \int_0^{\infty} e^{-\rho t}\left(1 - S(t)\right)V(t)dt \approx \sum_t e^{-\rho t} S(t)U(t) + \sum_t e^{-\rho t}\left(1 - S(t)\right)V(t), \tag{7}$$

where $S(t)$ is a survival function as shown below, expressing the probability that the event does not occur until the time t:

$$S(t) = \exp\left(-\int_0^t h\left(T(s)\right)ds\right) \approx \exp\left(-\sum_{s=2005}^{t} h\left(T(s)\right)\right), \tag{8}$$

where $h(T(t))$ denotes a hazard function that indicates an increase in the probability of the event with a rise in air temperature and is assumed to be expressed by the following equation where the coefficient η is a parameter.

$$h\left(T(t)\right) = \eta \cdot \left(T(t) - T(2005)\right)^2. \tag{9}$$

In this study, the utility function after the event V is assumed to be equivalent to the function U with a consumption drop at a certain rate of Δ as shown below:

$$V(t) = \begin{cases} L(t)\dfrac{\left(1-\Delta\right)c(t)^{1-\alpha} - 1}{1-\alpha}, & \alpha \neq 1, \alpha > 0 \\ L(t)\log\left(\left(1-\Delta\right)c(t)\right), & \alpha = 1 \end{cases}. \tag{10}$$

Instead of introducing Eqs. (6)-(10), Eq. (3) is now replaced by Eq. (4), i.e., Eq. (5) becomes disused.

3. Parameter Setting

Table 1 shows the reference values for the major parameters used in the model, which are set to be basically as same as those used in the DICE-2007 (Nordhaus, 2007a). The parameters newly introduced in this study, i.e., a_c (and a_d), η, and Δ, are set as follows. The parameters a_c and a_d in Eqs. (4) and (5) are divided from the parameter a in Eq. (3) referring to the detailed breakdown of climate change damage given by Nordhaus (2007b). The parameter η is so determined as to have the survival function $S(2095) = 1 - p$ provided an air temperature path reaching a 2.5 ^{o}C rise relative to 1900 by 2095, where p is the probability of an abrupt change when the air temperature rises

Table 1. Major parameter setting.

Parameter	Value
Pure rate of social time preference (RPTP), ρ	1.5%/y [0.1%/y][1]
Elasticity of the marginal utility of consumption (EMUC), i.e., relative risk aversion, α	2.00 [2.87][1]
Asymptotic global population	8,600 million
Growth rate of total factor productivity	0.92%/y
Probability of an abrupt change in the case of 2.5°C rise in 2090, p	1.2% [variable][2]
Continuous damage function parameter, a_c	0.000978
Discontinuous damage function parameter, a_d	0.001861 [variable][2]
Coefficient of hazard function, η	0.000102 [variable][2]
Impact of an abrupt change, Δ	30% [variable]
Equilibrium climate sensitivity (CS)	3.0°C [4.5°C]

Note: Figures outside brackets are reference values while those in brackets are for sensitivity analysis.

[1] For sensitivity analysis, the values of PRTP (ρ) and EMUC (α) are changed simultaneously to 0.1%/y and 2.87, respectively, to maintain the calibration of the rate of return on capital with empirical estimates. PRTP of 0.1%/y refers to an assumption by Stern (2007).

[2] The values of a_d and η are set consistently according to that of p.

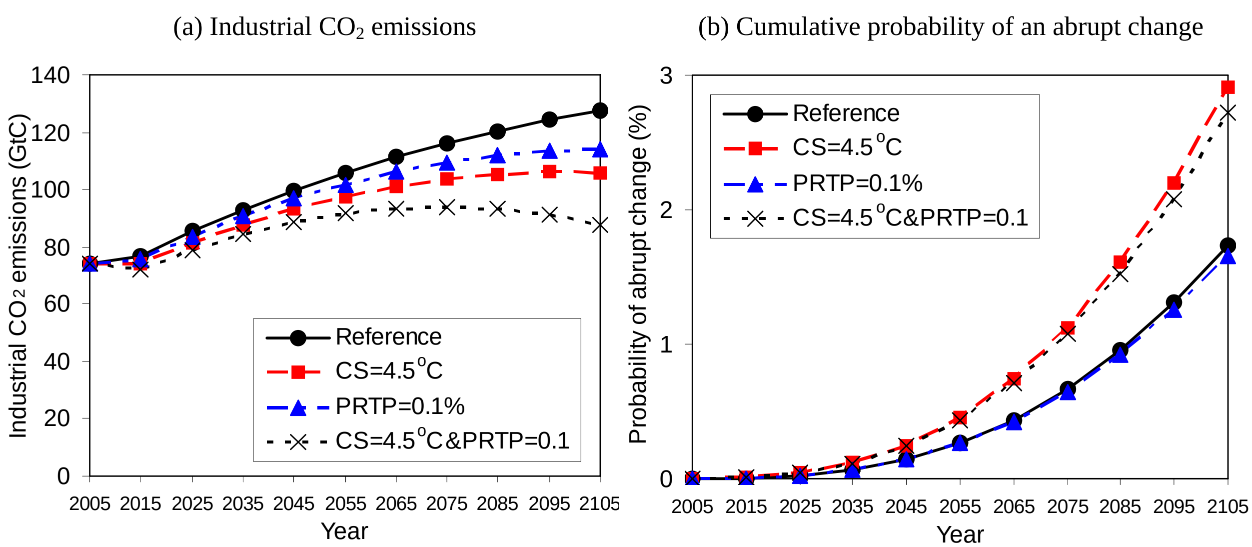


Figure 1. Optimal global industrial CO_2 emissions and corresponding cumulative probabilities of abrupt change.

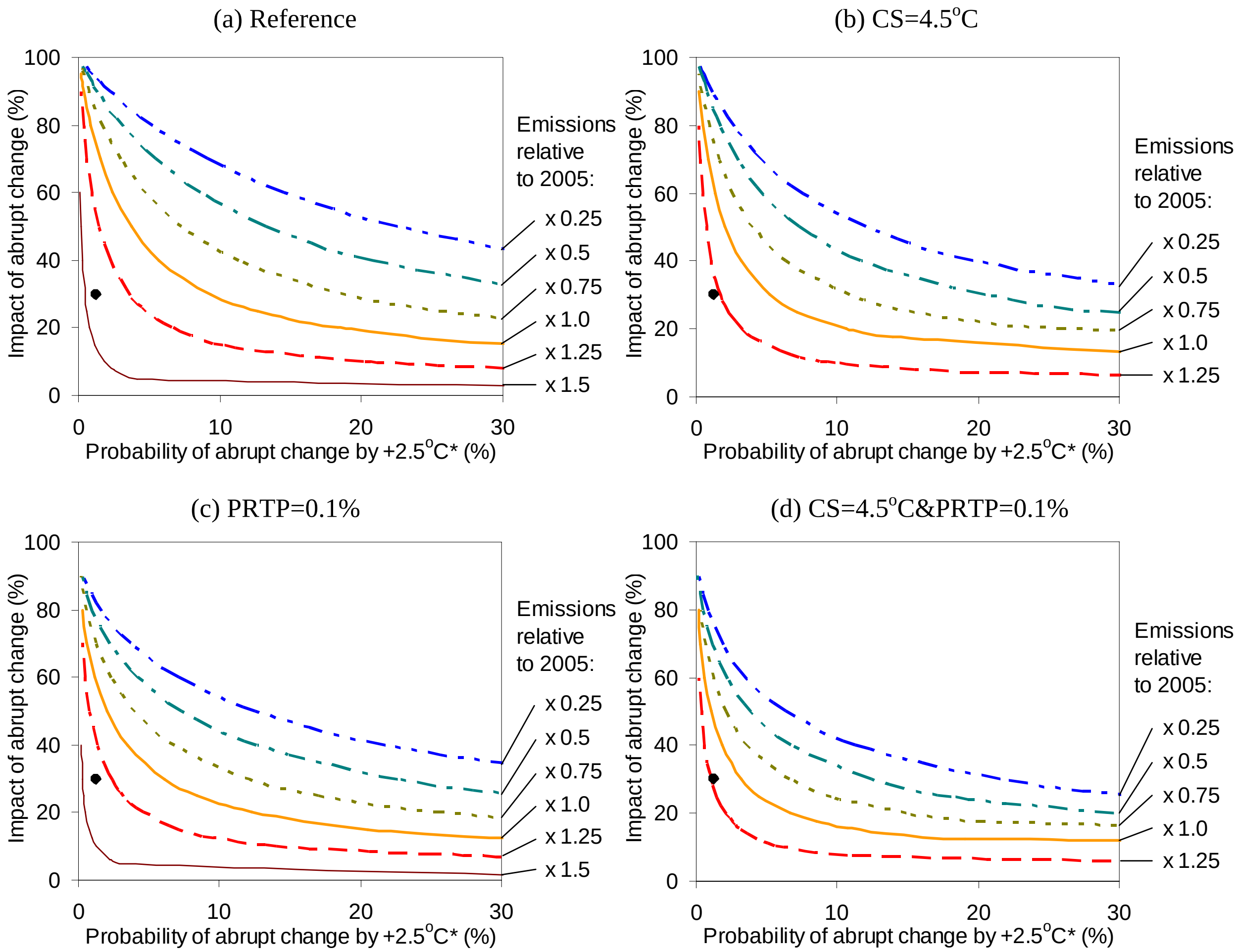
by 2.5 °C relative to 1900 in 2090. The reference values for the parameters p and Δ are set at 1.2% and 30% in reference to their original settings in the DICE (Nordhaus and Boyer, 2000).

In addition to the reference parameter settings, taking into consideration large uncertainty in the parameters p and Δ, corresponding to the probability and impact of an abrupt change, and the climate sensitivity (CS) as addressed earlier, a sensitivity analysis will be performed by treating these parameters as variables. Referring to IPCC (2007), which indicates that CS is likely to be in the range 2 °C to 4.5 °C with a best estimate of about 3 °C, the value for CS is increased to 4.5 °C for the sensitivity analysis from its reference value of 3.0 °C. The parameter related to people's risk aversion α together with the parameter PRTP (ρ) will also be changed for the sensitivity analysis as shown in Table 1.

4. Results

4.1. Basic Analysis

The optimal path of the total world industrial CO_2 emissions are shown in Figure 1 (a), while Figure 1 (b) indicates the cumulative probability of an abrupt change that corresponds to $1 - S(t)$. Note that the model takes into



Note: The black dot in each figure corresponds to the reference parameter setting adopted in the original DICE.
* Probability corresponds to that of abrupt change in the case of a 2.5 °C rise in 2090 relative to 1900.

Figure 2. Conditions for optimal global industrial CO_2 emission levels in 2055 for each case of CS and PRTP.

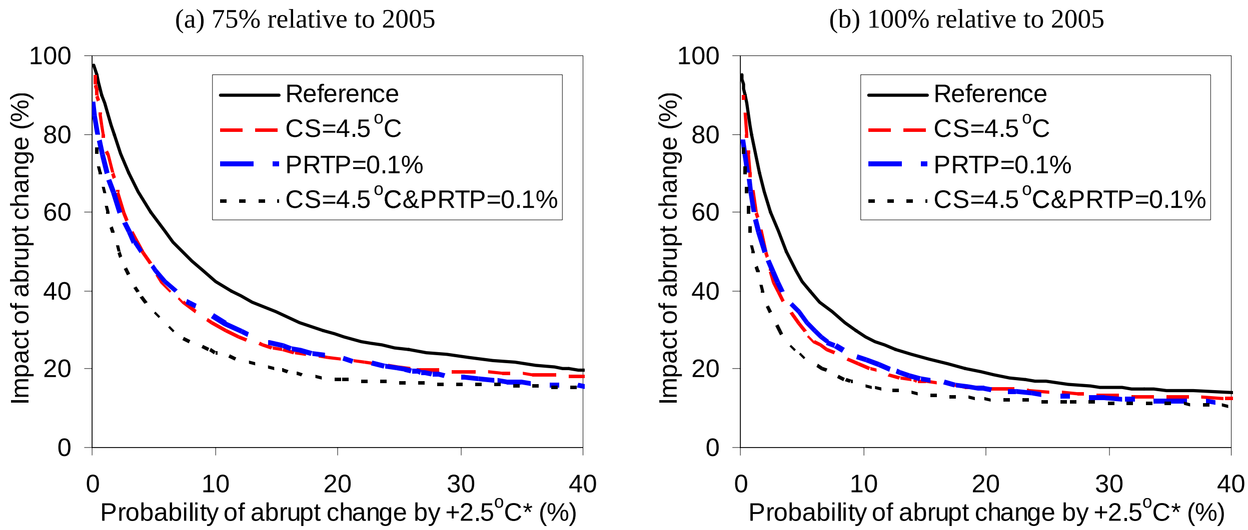
consideration the regulation of CO_2 emissions by the Kyoto Protocol for the second simulation period, i.e., $t = 2015$.

For the reference case, the optimal industrial CO_2 emissions increase to 106 and 123 Giga tons of carbon equivalent (GtC) in 2055 and 2105, respectively. These are respectively 1.42 and 1.71 times larger than 74.3 GtC, the emissions in 2005. The cumulative probability of an abrupt change also increases to 0.27% and 1.73% in 2055 and 2105, respectively.

When we assume that people have a higher risk aversion, i.e., a higher EMUC of 2.87 and accordingly a lower PRTP of 0.1%, the optimal industrial CO_2 emissions are less than those in the reference case. However, the optimal emissions still increase during this century. The cumulative probability of abrupt change is calculated to be only slightly less than that in the reference case.

On the other hand, in the case of a higher estimate of CS, i.e., CS=4.5 °C, a lower CO_2 emissions level is optimal compared to the above two cases. This is because air temperature becomes liable to rise and so increases the probability of abrupt change, which heighten incentives to reduce CO_2 emissions. In this case, however, the optimal industrial CO_2 emissions up to 2095 are still higher than those in 2005.

Finally, supposing a lower PRTP with a higher EMUC together with a higher CS, the optimal increase rates of industrial CO_2 emissions are much lower than the preceding cases; they even become negative after 2075. The optimal industrial CO_2 emissions in 2055 and 2105 are 1.23 and 1.18 times larger than those in 2005, respectively.



* Probability corresponds to that of abrupt change in the case of a 2.5 °C rise in 2090 relative to 1900.

Figure 3. Conditions for optimal global industrial CO_2 emission levels of 75% and 100% in 2055 relative to 2005.

4.2. Analysis of the Uncertainties of the Probability and Impact of Abrupt Change

The basic analysis shown above was performed on the strong assumption that the probability of an abrupt change in the case of a 2.5 °C rise in 2090 p = 1.2% and the impact of an abrupt change Δ = 30%, which are in reality highly uncertain. We will here assume them as variable parameters: the values of p and Δ are changed within the range of 0-30% and 0-100%, respectively.

Focusing on the optimal industrial CO_2 emissions level in 2055, we now investigate the conditions of the combination of p and Δ for emission levels of 1.5, 1.25, 1.0, 0.75, 0.5, and 0.25 relative to 2005. The results are presented in Figures 2 and 3, in which the horizontal and vertical axes indicate the values of p and Δ, respectively. A smooth L-shaped curve is drawn for each optimal emission level.

While all the curves start at almost the same points close to (p, Δ) = (0%, 100%) regardless of the cases and the optimal emission levels, the curves are gentler for lower optimal emission levels. This means that the optimal emission levels are highly sensitive to changes in Δ. Each curve approaches horizontal as the value of p increases, meaning that the change in p has less effect on the optimal emissions levels for a higher absolute value of p.

The curves are also gentler in the cases of a higher CS value and of a lower PRTP with a higher EMUC. Similar sensitivities to the optimal emission levels are seen between the case of CS=4.5°C and that of PRTP=0.1% (together with EMUC=2.87) as illustrated in Figure 3.

5. Conclusion

In contrast to existing IAM studies, this study did not specify the characteristics of abrupt change events but instead intended to gain insights from a sensitivity analysis taking into account the large uncertainties of the probability and impact of an abrupt change. The findings from Figures 2 and 3 can be summarized as follows:

- If there is the possibility of a very high impact of abrupt change, i.e., Δ >90%, a very stringent target of global industrial CO_2 emissions, even less than 25% in 2055 relative to 2005, is required regardless of the probability of abrupt change in the case of a 2.5 °C rise in 2090, p;
- The emissions target can be greatly relaxed as the impact of an abrupt change, Δ, decreases; if Δ can be assumed less than 20%, the allowable emissions can be moderated to 75% or higher in 2055 relative to 2005 even with a very high probability of an abrupt change in the case of a 2.5 °C rise in 2090, p;
- As the probability of an abrupt change in the case of a 2.5 °C rise in 2090, p, increases, the emissions target becomes more stringent especially in the case in which p < 10%; on the contrary, when we can assume that p > 10%, the required emissions target tends to converge.

These findings imply that devoting our efforts to the development of adaptation measures to reduce the impact of abrupt change to around 20% of total consumption is recommended as well as limiting GHG emissions.

The following issues remain for further extension of this study although they would not influence the essentials of the conclusion described above: while the discontinuous and stochastic modeling technique adopted in this study deals with a single abrupt change event, it can be extended to treat more than one event; the model is expected to be disaggregated to several geographical regions as has been done in the RICE model (Nordhaus and Boyer, 2000), yielding regional policy suggestions.

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