CLIMATE-ECONOMY MODELING CONSIDERING SOLAR RADIATION MANAGEMENT AND ITS TERMINATION RISK

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Abstract: The combination of carbon dioxide (CO_2) emissions mitigation and geoengineering options of solar radiation management (SRM) such as placing sunshades in space and stratospheric aerosol injection is discussed quantitatively using an extended version of the DICE-2007, an integrated assessment model for climate policy analysis. Though SRM measures can contribute considerably to the cost-effectiveness of climate change mitigation, they might cause harmful side effects, such as rapid air temperature increases, if the SRM implementation were to be discontinued for any reason. The author suggests a guideline for the use of SRM: namely, that unexpected SRM termination at any time would not exceed the constraints on the rate of global warming recommended by the German Advisory Council on Global Change. The paper describes a method to incorporate this guideline in the DICE-2007 model, and shows the result of the extended model, which recommends an 80% reduction of global industrial CO_2 emissions below the 2005 level by the end of the 21st century while implementing a complementary SRM option to mitigate climate change.

1 INTRODUCTION

Technological measures to mitigate climatic change include greenhouse gas (GHG) emission reductions and climate geoengineering options. Among these measures, solar radiation management (SRM) technologies such as placing sunshades in space and injecting sulfur aerosol into the stratosphere have been evaluated as having relatively large potential to contribute to the mitigation of climate change (The Royal Society, 2009).

However, while earlier studies dealing with strategies of climate change mitigation have focused on deriving optimal dynamic paths of the GHG emissions, especially carbon dioxide (CO_2), few have additionally considered the timing and scale of implementing SRM options. Though a pioneering study by Wigley (2006) shows plausible trajectories of the combination of CO_2 emissions reduction and SRM by stratospheric aerosol injection in the future, it lacks deep discussion of economics and risk management.

The present study aims at drawing desirable scenarios based on those combined points of view by using an integrated assessment model of climate and economy. For discussing the combination of CO_2 emissions reduction and SRM, the study pays special attention to the so-called "termination problem," i.e., the risk of adverse effects to climatic condition accompanied with a rapid global warming if the use of the SRM option is terminated for any reason after its implementation.

2 INCORPORATING SRM OPTIONS IN A CLIMATE-ECONOMY MODEL

2.1 Modification of the DICE-2007 Integrated Assessment Model

The 2007 version of the DICE model known as an integrated assessment model of climate change, DICE-2007 (Nordhaus, 2008), is modified to deal explicitly with SRM options. The DICE model is available for public use through its developer's Web page and has served as the basis of most other economic models of climate change.

The model is a nonlinear programming model that integrates a neoclassical macroeconomic growth model with the following three models: an emissions model that computes the amount of CO_2 emissions

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caused by economic production and the cost of mitigating the emissions, a climate model that simulates the flow and stock of CO_2 in the air and ocean and their impact on the changes in global mean atmospheric temperature, and a damage model that estimates the damage cost caused by a given rise in air temperature. The objective function is the total discounted sum of a representative individual's instantaneous utility stream. It is a one-region model that covers the entire world and derives the optimal dynamic paths of macro investment and CO_2 reduction rate. The total period of time is divided into 60 time periods, the first of which comprises the ten years centered on 2005.

Since radiative forcing that determines the greenhouse effect is controllable only by atmospheric CO_2 concentration in the DICE model, this study modifies the model to include SRM options as a factor controlling radiative forcing, as applied earlier in Kosugi (2010). The two most important points of the modification are described as follows.

(i) Either placing sunshades in space or injecting aerosols into stratosphere is considered to be applicable. The balance of flow and stock of the sun-shading materials is modeled; the service life of the materials, i.e., the period in which the materials stay in the area effective for SRM, is taken into account

When we define the variables $S(t)$ and $G(t)$ as the mass stock of sun-shading materials accumulated in space or the stratosphere (Mt) and the mass flow of the materials lifted into space or the stratosphere (Mt/yr.), respectively, at time period t, and the parameter δ_S as the depreciation rate of the sun-shading materials accumulated in space or the stratosphere (yr.$^{-1}$), the balance of flow and stock of sunshades in space is modeled as:

$$S(t) = 10G(t) + (1 - \delta_S)^{10} S(t-1), \tag{1}$$

noticing that a time period consists of ten years in the DICE model. Given the short staying period of injected aerosol in the stratosphere of a few years at the longest, the model for it is as follows:

$$S(t) = G(t)/\delta_S \,. \tag{1'}$$

(ii) The decrease in radiative forcing by implementing an option is assumed to be proportional to the up-mass stock of the sun-shading material. Letting $F(t)$ and $F_{EX}(t)$ be total radiative forcing and its exogenous part due to non-CO_2 GHGs (W/m^2 relative to 1900) and $M_{AT}(t)$ the mass of carbon in the atmosphere (GtC), this is modeled as:

$$F(t) = \eta\{\log_2[M_{AT}(t)/M_{AT}(1750)] - S(t)/m\} + F_{EX}(t), \tag{2}$$

where η and m denote the parameters connecting radiative forcing with temperature (°C/W/m^2) and the sunshade mass-effectiveness coefficient, i.e., the mass of the stock of sun-shading materials required to offset the increase in radiative forcing due to a doubling of the atmospheric CO_2 concentration (Mt/2×CO_2), respectively.

By using the calculated radiative forcing, the air temperature is estimated through the following simple climate model as in the original DICE model:

$$T_{AT}(t) = T_{AT}(t-1) + \xi_1\{F(t) - \xi_2 T_{AT}(t-1) - \xi_3[T_{AT}(t-1) - T_{LO}(t-1)]\}, \tag{3}$$

$$T_{LO}(t) = T_{LO}(t-1) + \xi_4[T_{AT}(t-1) - T_{LO}(t-1)], \tag{4}$$

where variables $T_{AT}(t)$ and $T_{LO}(t)$ represent the global mean surface temperature and the temperature of the ocean depths (°C relative to 1900), respectively.

Other modifications include: (iii) the cost of installing the sun-shading materials is subtracted from consumption; (iv) CO_2 emissions induced by installing the sun-shading materials are taken into account; (v) constraints to avoid an air temperature drop are imposed; the global mean air temperature is kept at no less than its 1900 value in the whole period and the rate of temperature decrease doesn't exceed 0.2 °C per decade; and (vi) the CO_2 mitigating trend is assumed to be continued; the rate of CO_2 mitigation is constrained not to decline with an elapse of time.

2.2 Assumptions

Among the variety of parameters in the model, the parameters used in the original DICE model were set to be the same as the reference values applied in the DICE-2007. Table 1 (a) shows a major set of extractions from those parameter settings.

The parameters introduced to incorporate SRM options in the model are set based on a survey of literature data (Hertzfeld, et al., 2005; Lenton and Vaughan, 2009; McClellan et al., 2010; Pearson, et al., 2006) as shown in Table 1 (b).

Table 1: Major parameter settings.

(a) Reference values in DICE-2007 model

Parameter	Value
Climate sensitivity	3 °C
Social time preference	1.5%/yr.
Elasticity of marginal utility, i.e., relative risk aversion	2
Initial growth rate of total factor productivity	0.92%/yr.
Initial autonomous improvement rate of CO_2 intensity	0.73%/yr.
Economic damage relative to world GDP in the case of a 2.5 °C rise*1	1.8%

(b) Assumed values for evaluating SRM options

Parameter	Space	Stratosphere
Cost of lifting sun-shading materials	6000 US$/kg*2	1 US$/kg
CO_2 emissions via lifting sunshades	18.5 kgC/kg	0.5 kgC/kg
Mass of sunshades required to offset CO_2 doubling	5×10^9 kg	8×10^9 kgS
Depreciation rate of sunshade stock	5%/yr.	80%/yr.

*1 Rise in global mean air temperature relative to 1900.

*2 Assumed to decline by 2%/yr. from the initial value of 6000 US$/kg in 2005.

2.3 Initial Results: An Outrageous Influence of SRM on Air Temperature

Figure 1 shows the trajectory of the global mean air temperature calculated by using the modified DICE model described above. The figures hereafter show the results up to 2125 out of the whole time period calculated in the model.

As seen from Figure 1, the optimal path of SRM deployment follows the maximum allowable implementation starting from 2045 or 2015 if the space-sunshade installation or the stratospheric aerosol injection is applicable, respectively. This result implies that depending largely on an SRM option can be a more cost-effective measure for mitigating climatic change than facilitating CO_2 emissions reduction. In this case, as shown in Figure 2 (see "w/o temp. limit" in the figure) the global industrial CO_2 emission is allowed to rise steadily.

However, in the case of such a large dependency on SRM for mitigating climate change, we would be faced with the problem described below should the implementation of SRM be terminated.

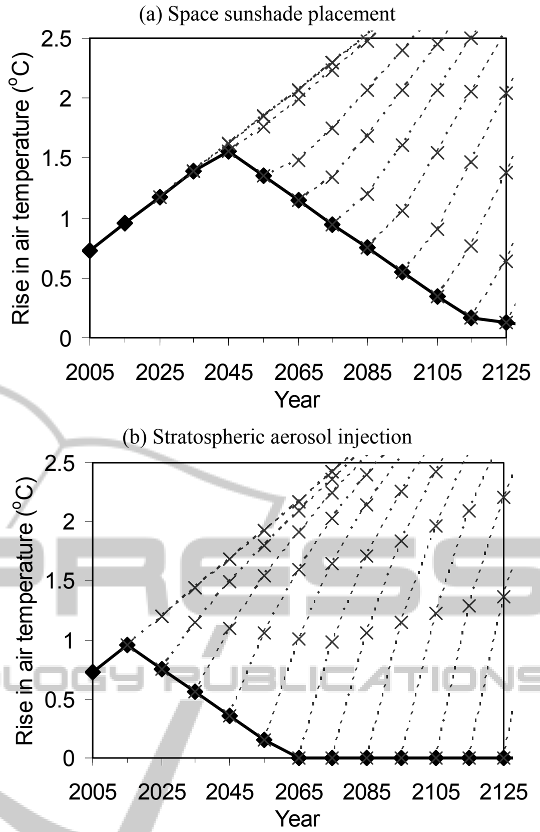

Figure 1: Global mean air temperature without limiting temperature rise after SRM termination, °C relative to 1900. The solid line represents the optimal solution while the broken lines indicate the temperature increases after termination at the respective time periods.

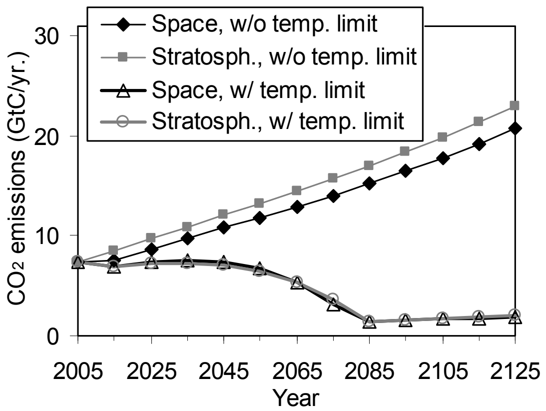

Figure 2: Industrial CO_2 emissions, GtC/yr.

The broken lines in Figure 1 indicate the temperature increases after SRM termination at the respective time periods. More specifically, it shows the calculated global mean air temperature rise hypothesizing that the values of all the variables, e.g.,

CO_2 emissions, are the same as those calculated earlier through the model while no new sun-shading materials are placed into space or the stratosphere after each of the time periods. The abrupt rise in air temperature after the SRM termination is called the "termination problem," which has been described as one of the most serious risks concerning the use of SRM (Brovkin, et al., 2009).

3 EXTENDING THE MODEL TO MANAGE THE RISK OF SRM TERMINATION

3.1 Proposal of a Guideline for the Use of SRM

For the safer use of SRM options, we need to avoid the risk of abrupt warming, which would occur in a situation where SRM implementation is terminated.

The causes of termination could include unsuccessful continuous multilateral political negotiations regarding SRM or the unexpected revelation of a major adverse side effect of the SRM. Although such an occurrence is itself unforeseeable, the extent of the adverse effect brought about by the SRM termination can be estimated, and it is possible to control the use of SRM to keep the damage from unforeseen discontinuation at a certain allowable level.

Given the climate control recommendation by WBGU (2003) to constrain the rise in global average air temperature below 2 °C and the per-decade rate of temperature rise within 0.2 °C, a guideline for SRM use is derived such that the above condition holds even if SRM is terminated at any time.

3.2 Extension of the Model for Managing the Risk of the SRM Termination Problem

The above guideline can be implemented in the model by introducing the following formulae.

Let $\hat{S}(t,t')$ be the group of variables representing the virtual dynamic path of the mass stock of sun-shading materials accumulated in space or the stratosphere (Mt) assuming an SRM termination at time t'. For $t < t'$, clearly

$$\hat{S}(t,t') = S(t), \tag{5}$$

while for $t' \le t < T$, setting the value of $G(t)$ to null in Eqs. (1) and (1'),

$$\hat{S}(t+1,t') = \begin{cases} (1-\delta_S)^{10}\,\hat{S}(t,t') & (\text{Space}) \\ 0 & (\text{Stratosph.}) \end{cases}, \tag{5'}$$

where T denotes the time horizon of the model.

Similarly, when we define variables $\hat{F}(t,t')$, $\hat{T}_{AT}(t,t')$, and $\hat{T}_{LO}(t,t')$ as the anticipated paths of total radiative forcing, global mean surface temperature, and lower ocean temperature in case of SRM termination at t', respectively, as in Eq. (2),

$$\hat{F}(t,t') = \eta\left\{\log_2\left[M_{AT}(t)/M_{AT}(1750)\right] - \hat{S}(t,t')/m\right\} + F_{EX}(t), \tag{6}$$

while $\hat{T}_{AT}(t,t')$ and $\hat{T}_{LO}(t,t')$ are calculated, for $t < t'$, as

$$\hat{T}_{AT}(t,t') = T_{AT}(t) \text{ and} \tag{7}$$

$$\hat{T}_{LO}(t,t') = T_{LO}(t), \tag{8}$$

while for $t' \le t < T$, consistently with Eqs. (3) and (4),

$$\hat{T}_{AT}(t+1,t') = \hat{T}_{AT}(t,t') + \xi_1\left\{\hat{F}(t+1,t') - \xi_2\hat{T}_{AT}(t,t') - \xi_3\left[\hat{T}_{AT}(t,t') - \hat{T}_{LO}(t,t')\right]\right\}, \tag{7'}$$

$$\hat{T}_{LO}(t+1,t') = \hat{T}_{LO}(t,t') + \xi_4\left[\hat{T}_{AT}(t,t') - \hat{T}_{LO}(t,t')\right], \tag{8'}$$

where the units of the variables are the same as those of $F(t)$, $T_{AT}(t)$, and $T_{LO}(t)$, respectively.

With respect to $\hat{T}_{AT}(t,t')$ defined above, the following constraints concerning its absolute level and rate of change are imposed:

$$\hat{T}_{AT}(t,t') \le 2, \tag{9}$$

$$\hat{T}_{AT}(t+1,t') \le \hat{T}_{AT}(t,t') + 0.2. \tag{10}$$

These two constraints should be applied for all t and t'; however, incorporating Eq. (10) for $t < 3$ makes the model infeasible, i.e., the rise in global mean air temperature in the next decade will inevitably be above 0.2 °C. We therefore apply Eq. (10) for $t \ge 3$.

The total numbers of variables and constraints become 13 and 20 times, respectively, as many as those of the model before the extension. The computation time to find the utility maximizing solution is 41 seconds for the extended model when space-sunshades are assumed to be available as an SRM option, which is 27 seconds longer than the pre-extension when the model is solved by GAMS/ CONOPT3 (Brooke et al., 1992; Drud, 1994) with a PC based on the Intel(R) Core(TM) 2 Duo CPU P9300, 2.26GHz with 1.93 GB RAM.

3.3 Results

The global mean air temperature calculated through the extended model is shown as the solid line in Figure 3. Compared with Figure 1, this figure suggests a moderate use of SRM, especially in the case of stratospheric aerosol injection, to lower the air temperature when we adopt the guideline introduced above. As in Figure 1, the broken lines in Figure 3 indicate the trajectory of the temperature after an unexpected SRM termination at the respective time periods; we can confirm that, when the use of SRM is moderated to reflect the guideline of limiting the temperature rise that would occur by SRM termination, abrupt warming by SRM use termination is avoided.

Figure 2 includes the optimal paths of the industrial CO_2 emissions when the constraint on the limit of temperature rise in case of SRM termination is adopted (see "w/ temp. limit") together with those without the limit of temperature rise explained in Section 2.3. The results imply that reducing CO_2 emissions is expected to play a more important role in mitigating climate change when we adopt the guideline of limiting temperature rise. Specifically, the amount of industrial CO_2 emissions should be kept at around the present level in the former half of this century and is expected to be reduced rapidly afterward, reaching only 20% of the 2005 levels by 2085.

Figure 4 shows the calculated atmospheric CO_2 concentration, which steadily increases in this century and reaches 700 ppmv a century hence if the guideline of limiting the temperature rise in case of SRM termination is not adopted. With the limit of temperature rise in such a case, on the other hand, the increase in CO_2 concentration is expected to be mitigated to peak at 490 ppmv by 2075; afterward the concentration decreases to below 450 ppmv after 2125.

To observe the desirable combination of CO_2 emissions reduction and SRM for contributing to mitigating climate change derived under the guideline of limiting temperature rise in case of SRM termination, the decrease in radiative forcing by use of each measure to mitigate climate change, i.e., the difference from the radiative forcing compared to the case where no climate mitigation policy is implemented, is illustrated in Figure 5 assuming that stratospheric aerosol injection is usable as an SRM option.

CO_2 emissions reduction contributes more to lessening radiative forcing than SRM throughout the time periods addressed by the model, and the contribution of emissions reduction becomes much greater as time passes. Though we omit a figure corresponding to the case of using space-based sunshades instead of stratospheric aerosol injection, a similar tendency is observed for this case.

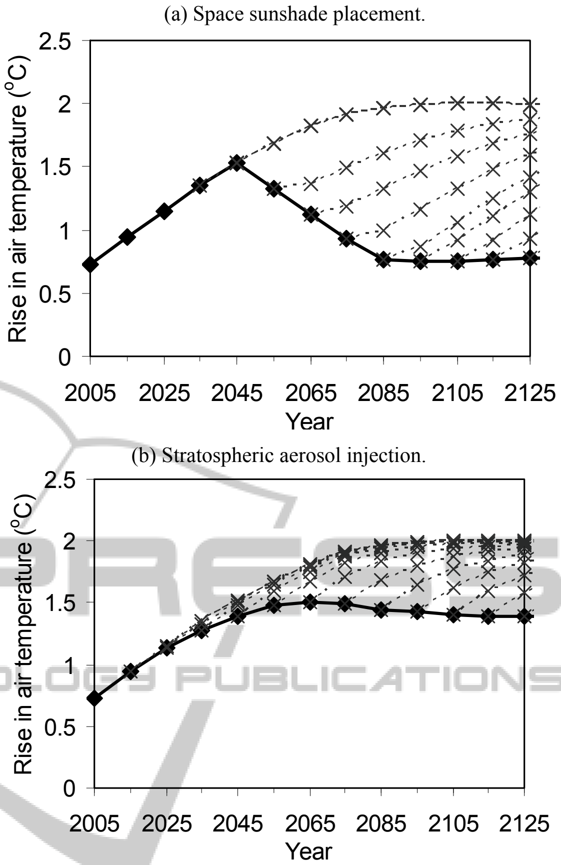

Figure 3: Global mean air temperature with limiting temperature rise after SRM termination, °C relative to 1900. The solid line represents the optimal solution while the broken lines indicate the temperature increases after termination at the respective time periods.

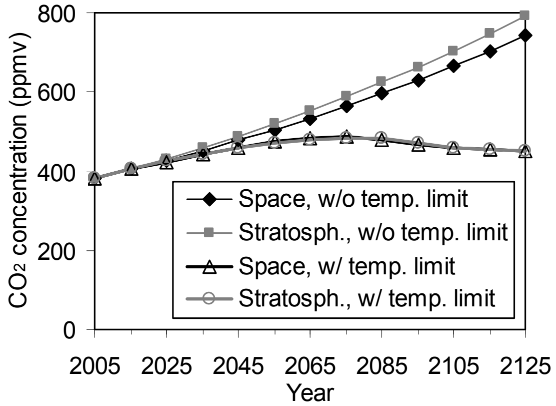

Figure 4: Atmospheric CO_2 concentration, ppmv.

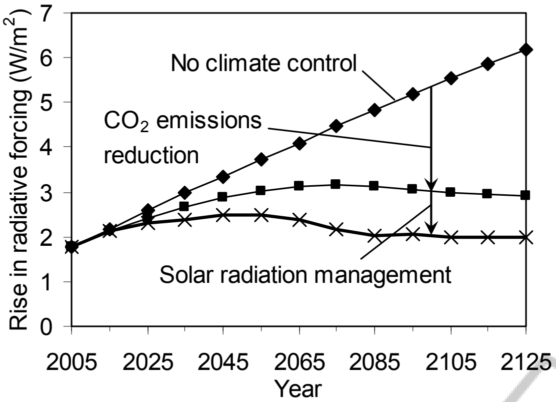

Figure 5: Contribution of CO_2 emissions reduction and SRM to the mitigation of radiative forcing, W/m^2 relative to 1900, in the case of stratospheric aerosol injection.

4 CONCLUDING REMARKS

SRM geoengineering is expected to be a lower-cost option of climate control compared to CO_2 emissions reduction, and may considerably contribute to the cost-effectiveness of global climatic change mitigation. However, this option is accompanied by the risk of rapid global warming if the implementation of SRM is unexpectedly terminated for any reason. As a guideline for the use of SRM to avoid the risk, this study suggests that the adverse effect should be controlled within an acceptable range in case of unexpected SRM termination at any time after its implementation. We incorporated the guideline into the integrated climate-economy model DICE by extending the model and quantitatively showed the contributions of CO_2 emissions reduction and SRM recommended to prevent global warming.

The extension of the model brings increases in the numbers of variables and constraint equations, resulting in a longer computation time to solve the model. The model is still solved within a minute using a PC because it incorporates a very simplified climate module; if we further extend the model to deal with geographic distribution of climate change, the computation time is estimated to increase, which may impose a barrier to practical evaluation.

Finally, it should be emphasized that there are some risks with the use of SRM other than those considered in the present modeling study. The quantitative results obtained from this study should be interpreted as the economic potential of SRM use assuming that such risks are low. If we needed to regard these risks as considerably high, more restrained use of SRM would be recommended.

REFERENCES

Brooke, A., Kendrick, D., Meeraus, A., 1992. GAMS: A User's Guide, release 2.25, *The Scientific Press*, San Francisco.

Brovkin, V., Petoukhov, V., Claussen, M., Bauer, E., Archer, D., Jaeger, C., 2009. Geoengineering climate by stratospheric sulfur injections. *Climatic Change*, 92(3-4), 243-259.

Drud, A. S., 1994. CONOPT: A large-scale GRG code. *ORSA Journal on Computing*, 6(2), 207-216.

German Advisory Council on Global Change (WBGU), 2003. *Climate Protection Strategies for the 21st Century: Kyoto and Beyond*, WBGU, Berlin.

Hertzfeld, H. R., Williamson, R. A., Peter, N., 2005. Launch Vehicles: An Economic Perspective, *George Washington University Space Policy Institute*. Washington, DC.

Kosugi, T., 2010. Role of sunshades in space as a climate control option. *Acta Astronautica*, 67(1-2), 241-253.

Lenton, T., Vaughan, N. E., 2009. The radiative forcing potential of different climate geoengineering options, *Atmospheric Chemistry and Physics*, 9(15), 5539-5561.

McClellan, J., Sisco, J., Suarez, B., Keogh, G., 2010. Geoengineering Cost Analysis: Final Report, UC01-001; AR10-182, *Aurora Flight Sciences Corporation*. Cambridge, MA.

Nordhaus, W. D., 2008. A Question of Balance: Weighing the Options on Global Warming Policies, *Yale University Press*. New Haven, CT.

Pearson, J., Oldson, J., Levin, E., 2006. Earth rings for planetary environment control. *Acta Astronautica*, 58(1), 44-57.

The Royal Society, 2009. Geoengineering the Climate: Science, Governance and Uncertainty, available via http://royalsociety.org/geoengineeringclimate/.

Wigley, T. M. L., 2006. A combined mitigation/ geoengineering approach to climate stabilization. Science, 314, 452–454.