Interactions between Tipping Elements in an Integrated Assessment Model of Climate Change: Modeling and Analysis with a Focus on Melting of the Greenland Ice Sheet and Collapse of the Atlantic Meridional Overturning Circulation

Takashi Otsuki* Yuji Matsuo* Soichi Morimoto*

Abstract

This paper presents a cost-benefit analysis on climate change with a focus on two tipping elements: melting of the Greenland ice sheet (GIS) and collapse of the Atlantic meridional overturning circulation (AMOC). We employ an integrated assessment model based on the DICE-2016R2 framework. Interactions of GIS and AMOC are newly modeled. Simulation results show that interaction between GIS and AMOC largely increases the social cost of carbon and lowers the optimal CO_2 emissions compared to a "no interaction" case. The optimal global CO_2 emissions reach zero by around the year 2090 in some cases, much earlier than the original DICE-2016R2, implying the importance of low-carbon and negative emissions technologies to manage the impacts and risks of tipping elements. The estimated global average temperature rise in 2100 from pre-industrial levels is also lowered from 3.5℃ in the original DICE-2016R2 to 3.2℃ in some cases with interacting tipping elements. Our results indicate that tipping elements and their interactions could be important factors for designing long-term climate strategies.

***Keywords**:* Tipping Element, Greenland Ice Sheet, Atlantic Meridional Overturning Circulation, Integrated Assessment Model

1. Introduction

Rising interest in climate change has spurred international discussions on ambitious greenhouse gas (GHG) reduction targets in recent years. The Paris Agreement adopted a target to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels." In 2018, the IPCC released the Special Report on Global Warming of 1.5°C[1)], pointing that the average temperature has already risen by about 1℃, and that to limit the temperature rise to 1.5℃ or 2℃, global human-generated emissions must be reduced to net zero by around 2050 and 2075, respectively. Meanwhile, it has also been reported that the current Nationally Determined Contributions are insufficient for reaching these goals.[2)]

A decarbonized society is one of the target end-states that humans should pursue. However, temperatures have already risen by almost 1℃ and may rise further to a certain extent, and so another important perspective for climate change policy is to what level humankind should allow temperatures to rise and what kind of GHG emission path is optimal for humans. This type of study is conducted using cost benefit analysis (CBA). CBA considers three factors, namely: the mitigation cost, the adaptation cost and the damages, to determine the GHG emission paths and temperature levels that would minimize the sum of these costs (or maximize the benefits for humans). Note that this is different from cost effectiveness analysis which presents a picture of a cost-optimum society for a given emissions reduction target. CBA is conducted using an Integrated Assessment Model (IAM)[1], and models such as DICE[3)], FUND[4)], and PAGE[5)] have been developed. IAM is used not only for obtaining the optimal path but also for assessing the Social Cost of Carbon (SCC).[6)]

However, there are also many criticisms of CBA and SCC estimates using IAM[7)], particularly the high uncertainty associated with estimating the three costs listed above (especially the estimate for damages). Damages are estimated using physical process modeling, structural economic modeling, and empirical modeling[2] [8)], but it is difficult to cover the impact of climate change comprehensively, convert some impacts into monetary terms, and so forth. To address these issues, there are ongoing attempts to update the models and assessments of these techniques using the latest knowledge[9)10)]. In addition, the possible existence of tipping elements—processes of irreversible and drastic changes in the earth's system—has been identified in

*The Institute of Energy Economics, Japan

[1] Also called cost-benefit-type IAM (CB-IAM) to distinguish from cost effectiveness analysis.

[2] Physical process modeling is a model in which specific impacts and damage caused by climate change are described and evaluated. An example is the "produce model," which evaluates the impact of quantities of temperature, humidity, CO_2 concentration, etc. on the productivity of produce. Structural economic modeling describes the relationship between climate change and behaviors of the economy and the market, and is used to assess economic impact, for example, the impact, damage, and costs caused by climate on labor productivity and demand for air-conditioning. The empirical model describes the relationship between meteorological and climatic changes and the ecological response of humans based on past data. For example, it is used to estimate the relationship between temperature exposure and death rate.

recent years, and incorporating these elements into damage projections has become an important research topic. This study focuses on tipping elements, particularly the melting of the Greenland Ice Sheet (GIS) and the collapse of the Atlantic Meridional Overturning Circulation (AMOC) to quantify their interactions. Many CBAs take tipping elements into account, as noted in Section 2.2, but few have addressed their interactions. Focusing on the interaction between GIS and AMOC, this study aims to refine cost-benefit analyses and acquire knowledge on the damage from the impact of tipping elements.

This paper consists of five chapters. Chapter 2 presents an overview of tipping elements (particularly GIS and AMOC) and summarizes previous studies on them. Chapter 3 describes the DICE-2016R2 model and the modeling of GIS and AMOC adopted in this paper. Chapter 4 presents and discusses the analysis results, followed by Chapter 5 which outlines the conclusions and research themes for the future.

2. Overview of tipping elements and previous cost-benefit analyses

2.1 Overview of tipping elements, the Greenland Ice Sheet and the Atlantic Meridional Overturning Circulation

The earth's climate is considered to have originally maintained an "equilibrium"[11)12)13)]. That is, disturbances up to a certain level (such as rises in atmospheric CO_2 concentration) were counterbalanced by a negative feedback effect, preventing major deviation from the equilibrium. However, it has been pointed out that when these disturbances surpass a certain level, the earth's system reacts with positive feedback, accelerates the deviation and ultimately transitions to a new equilibrium at a higher temperature level. That is, the earth's system may have a saddle point (or a critical point called a tipping point), beyond which conditions transition at an accelerated rate. The mechanisms that induce a tipping point are called tipping elements and include the loss of the Amazon rain forests, collapse of the West Antarctic Ice Sheet, frequent occurrence of the El Nino-Southern Oscillation, melting of GIS and collapse of AMOC. This paper focuses on the latter two since it is relatively clear that there is an interaction between them (melting of GIS may accelerate the collapse of AMOC) compared to other elements.

GIS contains enough freshwater to raise the earth's sea level by 7 meters were it to melt, and its melting could trigger feedback effects associated with a global rise in sea level, weaker Atlantic Meridional Overturning Circulation through an inflow of freshwater into the Atlantic Ocean (described later), and changes in the albedo of the earth's surface. It should be noted here that the melting of GIS exhibits a hysteretic behavior. That is, the relationship between the average global temperature and the volume of the ice sheet is not unique; if the Greenland ice sheet melts extensively, a new ice sheet will not form immediately even if the temperature goes down again. Thus, the melting can be considered almost irreversible.

Deep sea circulation is driven by density gradients in seawater determined by temperature and salt content and hence is called thermohaline circulation. A surface limb of AMOC flowing from south to north is cooled off the coast of Greenland, sinks to the bottom of the sea as it cools, and travels in deeper layers, gradually moving up to the surface again. This surface limb is considered to contribute to the warm climate of the North Atlantic region by transporting heat energy from sub-tropical regions to the northern hemisphere. Further GIS melting could weaken the thermohaline circulation by prompting an inflow of freshwater and lowering the salt concentration (i.e., the density), resulting in extensive effects including a cooler North Atlantic region and warming of the sub-tropical regions, in addition to fiercer cyclones, changes in vegetation, and shifts in river flow rates.

It is suggested that AMOC has a critical point. The strength of AMOC is expressed in units of volumetric rate of transport of seawater per unit time (Sv, 1 Sv = 10^6 m^3/s). A drop in this strength below the critical point, once it occurs, would prompt positive feedback, possibly weakening AMOC sharply and irreversibly. Using CLIMBER-2, an earth system model of the Potsdam Institute for Climate Impact Research, Reference 14) postulated "multiple rates of change in the inflow of freshwater associated with rises in temperature" (unit: Sv/°C; called h in this paper) and analyzed the long-term impact on the strength of AMOC (Figure 4 in the Reference document). The results showed a tendency for AMOC to collapse once h surpasses a certain level. While the value of h depends on the melting of GIS and Arctic sea ice, among others, Reference 14) treated it as an exogenous value and conducted a sensitivity analysis. (In this study, the effects of the melting of GIS were considered endogenously, as described in Chapter 3.) Note that the contribution of melting of GIS on h was estimated to range between 0.002–0.01 Sv/°C, suggesting it has a degree of uncertainty.

2.2 Cost-benefit analysis taking account of tipping elements, and their challenges

There have been many attempts to incorporate tipping elements into CBA. Some studies up to around 2016 modeled the occurrences (on/off) of tipping elements probabilistically and analyzed them using dynamic planning. As specific examples, Reference 15) analyzed thermohaline circulation, Reference 16)

the West Antarctic ice sheet, and Reference 17) GIS and AMOC, to determine the optimal path, also taking other events into account. Furthermore, Reference 18) grouped tipping elements into three types: those with impact on the carbon cycle, those on radiative forcing, and those inflicting direct damage, and analyzed them also using dynamic planning. Meanwhile, in recent years, some studies described the occurrence of tipping elements as a simple process rather than a binary on/off. Examples include studies on AMOC[19)20)], GIS[21)], and methane emissions from permafrost[22)23)24)]. Note that the process description model apparently tends to underestimate the impacts of tipping elements compared to the binary approach; the impact of melting of GIS on SCC was reported to be minor by Nordhaus[21)].

While studies have progressed, as described above, many CBAs covered single tipping elements, and the interactions between them have been ignored as out-of-scope. Among the studies in the previous paragraph, Reference 17) considered many tipping elements and their interactive coefficients. However, it adopted a binary equation, and the processes of interaction were not clearly described.

3. Model formulation

3.1 Overview

In this study, the melting of GIS and collapse of AMOC was incorporated into the DICE-2016R2 model[3)], and their impact on the optimal path was assessed. The source code of the model is open and has been used in many studies[25)]. DICE-2016R2 is written in GAMS but was ported to Pymo[26)] in this study.

3.2 Modeling of the Greenland Ice Sheet (GIS)

GIS was modeled by drawing on Nordhaus[21)]. Specifically, the model consists of an equation for defining the "equilibrium ice sheet volume ratio $V^*(t)$" (equation (1)) and a motion equation representing the "ice sheet volume ratio $V(t)$" (equation (2)). Here, t represents a point in time, and $T(t)$ in equation (1) the average global temperature at time t. The ice sheet volume represents the volume of GIS at time t, and the equilibrium ice sheet volume the volume at which GIS reaches a state of equilibrium at temperature T. These elements expressed as a ratio of the initial ice sheet volume are called the "ice sheet volume ratio $V(t)$" and "equilibrium ice sheet volume ratio $V^*(t)$" and both take a value between 0 and 1 (the starting point of DICE-2016R2 is 2015, therefore $V(2015) = 1$). We assumed that GIS transitions to equilibrium $V^*(t)$ from $V(t)$ at temperature T, and modeled the change in the volume ratio based on the difference between $V(t)$ and $V^*(t)$ (equation (2)).

$$V^*(t) = 1 - \alpha_1 T(t) \tag{1}$$

$$\frac{\Delta V(t)}{\Delta t} = \beta_1 \mathrm{sign}\big(V^*(t) - V(t)\big)\big(V^*(t) - V(t)\big)^2 \tag{2}$$

In formulating the motion equation corresponding to equation (2), Nordhaus[21)] defined the equilibrium temperature based on the ice sheet volume ratio, the reverse of what happens in equation (1), but the approach adopted in this study is mathematically equivalent to that of Nordhaus[21)] (we adjusted the form of the equation for consistency with the equation for AMOC). Parameters were also set based on Nordhaus as $\alpha_1 = 0.294$ and $\beta_1 = 0.000122$. The rise in sea level when the ice sheet melts completely was set at 7 meters, and was assumed to rise in proportion to the volume of GIS that has melted away. The economic damage caused by a rise in sea level of 1 meter was estimated at 1% of global GDP[21)].

3.3 Modeling of the Atlantic Meridional Overturning Circulation

Equations to describe the state of equilibrium and the motion, respectively, were also formulated for AMOC. Hereafter, $X(t)$ represents the strength ratio of AMOC at time t (the strength of AMOC at time t relative to the initial strength), and $X^*(t)$ the equilibrium strength ratio. The values of $X(t)$ and $X^*(t)$ at the initial point (2015 value) are 1. The strength of AMOC was set to 22.6 Sv.

As described in Section 2.1 above, the possible existence of a critical point has been suggested regarding the strength of AMOC. Equations for equilibrium strength ratio $X^*(t)$ were formulated so that negative feedback would be generated when $X(t)$ declines but is still above the critical point X_{th} (the critical point is not passed), while positive feedback would be generated when X_{th} is passed (equations (3-1) and (3-2)).

When $X^*(t) > X_{th}$:

$$X^*(t+1) = X^*(t) - \alpha_2\big(T(t+1) - T(t)\big) + \gamma_{up}\big(1 - X^*(t)\big) \tag{3-1}$$

When $X^*(t) < X_{th}$:

$$X^*(t+1) = X^*(t) - \alpha_2\big(T(t+1) - T(t)\big) - \gamma_{down} X^*(t) \tag{3-2}$$

The section up to the second term on the right-hand side of equations (3-1) and (3-2) indicates that the state of equilibrium is proportional to the average global temperature $T(t)$, and is similar in essence to equation (1). The transitional state before and after passing the critical point is simulated by adding a third term to the equations (the feedback effect intensifies near the critical point). The motion equation for the strength of AMOC $X(t)$ was defined as equation (4) below:

$$\frac{\Delta X(t)}{\Delta t} = \beta_2\big(X^*(t) - X(t)\big) \quad (4)$$

In equation (2) for GIS, the transitional speed was set to be proportional to the square of the difference between the equilibrium ice sheet volume and the ice sheet volume based on Reference 21). On the other hand, in equation (4) above, parameters were set assuming that they are proportional to their values raised to the power of one[3], to ensure consistency with AMOC analysis results for CLIMBER-2[14]. Specifically, parameter α_2 was defined as $\alpha_2 = ah + b$, $a = 1.67$, and $b = 0.0517$, using h as the rate of change in freshwater inflow; other parameters were set as follows: $\beta_2 = 0.043$, $\gamma_{up} = 7.23\times10^{-6}$, and $\gamma_{down} = 2.56\times10^{-6}$. h was set differently depending on the analysis case: in cases in which interactions between GIS and AMOC were not considered (cases a and c in Section 3.5), it was defined as the sum of three constants, as shown in equation (5) below.

$$h = h_{GIS} + h_{SI} + h_0 \quad (5)$$

where, h_{GIS} is the effect of melting of GIS on the rate of change in freshwater inflow, h_{SI} the impact of melting of the Arctic sea ice, and h_0 other impacts. The impacts of Arctic sea ice and other factors (h_{SI} and h_0) were set to $h_{SI} = 0.0125$ Sv/°C, $h_0 = 0.03$ Sv/°C based on the reference case in Reference 20). The assumptions for the impact of the melting of GIS h_{GIS} are described in the section on case settings (Section 3.5). The assumptions for h_{GIS} when considering the interactions between GIS and AMOC (case d) are described in the next section. The economic damage caused by the collapse of AMOC was estimated to be worth 3% of global GDP[20].

3.4 Modeling of interactions

The rise in global temperature based on the optimal solution of DICE-2016R2 (the original model that does not consider tipping elements) shown in **Figure 1a** was fed into the model described in Section 3.2 to obtain the ice sheet volume ratio $V(t)$, as shown in **Figure 1b** (section for 2015–2070). The chart indicates that $T(t)$ tends to be linear while the change in $V(t)$ accelerates. The rate of freshwater inflow into AMOC $H(t)$ (unit: Sv) is considered to be largely proportional to the change in $V(t)$, and if so, the change in the rate of freshwater inflow should also gradually increase as temperature rises. This tendency of gradual change could not be captured if h_{GIS} was set as a constant in Section 3.3, possibly resulting in the inadequate assessment of the impact on AMOC.

With this point in mind, equation (3-1), which defines the state of equilibrium, was expanded as represented by equations (6) to (8) to account for the interaction between GIS and AMOC. The same was done for equation (3-2), though not described here.

$$X^*_1(t) = 1 - \alpha'_2\big(T(t) - T(2015)\big) - a\big(H(t) - H(2015)\big) \quad (6)$$

$$X^*_2(t+1) = X^*_2(t) + \gamma_{up}\big(1 - X^*(t)\big) \quad (7)$$

$$X^*(t) = X^*_1(t) + X^*_2(t) \quad (8)$$

Equation (6) corresponds to the two terms on the right-hand side of equation (3-1) and indicates the change in $X^*(t)$ as temperature rises. The impact of GIS is removed by defining $\alpha'_2 = a(h_0 + h_{SI}) + b$, and instead, the rate of freshwater inflow $H(t)$ calculated based on GIS volume is accounted for with the last term of the equation. $T(2015)$ is the average rise in global temperature at the starting point (2015), estimated at 0.85°C. $H(2015)$ was set to 0.0006 Sv based on an estimate by the IEEJ. The value of $X^*_1(t)$ at the starting point is 1. Furthermore, equation (7) represents the third term on the right-hand side of equation (3.1) which indicates the behavior near the critical point, and the initial value of $X^*_2(t)$ is 0. $X^*(t)$ in equation (8), which adds up the previous two equations, representing the state of equilibrium of $X(t)$.

In the optimal solution for DICE-2016R2, the temperature would rise by 1°C from 2015 to around 2045 (**Figure 1a**)). An estimate of the rate of freshwater inflow $H(t)$ based on the change in GIS volume ratio (**Figure 1b**) shows that the rate of freshwater inflow increases from 0.0006 Sv to 0.0024 Sv during this period, suggesting that the change per 1°C increase would be: 0.0024 − 0.0006 = 0.0018 Sv/°C. This value corresponds to h_{GIS} in the previous section and is hereafter called "h_{GIS} of the GIS model."

3.5 Cases for assessment

In this study, the following four cases were established for modeling the tipping elements, each with five values of h_{GIS} (0.002, 0.004, …, 0.01 Sv/°C) to allow for the uncertainty in the rate of freshwater inflow associated with melting of GIS (described at the end of Section 2.1).

- Case a: DICE-2016R2 with only AMOC considered
- Case b: DICE-2016R2 with only GIS considered
- Case c: DICE-2016R2 with both GIS and AMOC incorporated but their interactions not considered
- Case d: DICE-2016R2 with both GIS and AMOC

[3] Classically, the behavior of AMOC has been assessed using a two-box model[27] simulating two sea areas, the north and the south. Meanwhile, Reference 14) presents a four-box model and argued that the model can simulate the critical point when freshwater inflow increases (i.e., it is possible to simulate the accurate AMOC analysis result from CLIMBER-2). However, an examination of the result by the authors suggested that the response of the four-box model was remarkably faster than CLIMBER-2 (Figures 4 and 5 of Reference 14)). Thus, this study set up equations and parameters by referring not to the four-box model proposed in Reference 14) but the result of CLIMBER-2 used for verification. Figure 4 of Reference 14) indicates multiple responses of AMOC for multiple freshwater inflow change rates h (0.013–0.06). A simulation of AMOC behavior done by feeding those change rates into the equations in this study produces mostly the same result as Figure 4.

incorporated and their interactions considered

As for the details on h_{GIS} settings, for case a in which only AMOC was considered, the five constants above were assigned to h_{GIS} in equation (5), and equations (3-1) and (3-2) were used to obtain the optimal path. For case b in which only GIS was considered, h_{GIS} in the GIS model was set in line with the assumptions above in conducting an analysis (the amount of change in the ice sheet volume ratio $V(t)$ obtained from equations (1) and (2) was mechanically multiplied by the constants so that the change in the rate of freshwater inflow between 2015 and 2045 matched the assumed values). For case c, the assumptions for cases a and b were put together. For case d, only h_{GIS} in the GIS model was adjusted, and the state of equilibrium of AMOC was expressed using equations (6) to (8).

4. Evaluation results and discussions

4.1 Change in the social cost of carbon (SCC)

Figure 2 shows the SCC for each of the cases in 2015. In the chart, the horizontal axis represents the estimated rate of freshwater inflow into AMOC, and "without TEs" noted in the chart legend shows the analysis results for DICE-2016R2 without tipping elements (TE) considered. The SCC for the case "without TEs" for 2015 was determined to be \$30.7/tCO_2 (hereafter, \$ represents the value of U.S. dollars at 2010 price levels). Cases a to d have higher SCC compared to the "without TEs" case due to the modeling of tipping elements. In case a, in which AMOC

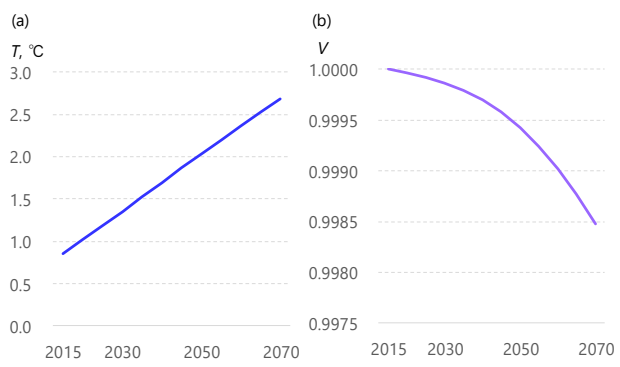

Figure 1 (a) Average global temperature for the optimal path from DICE-2016R2 , and the estimated change in GIS volume ratio based on (b)

(Note) Only 2015–2070 indicated.

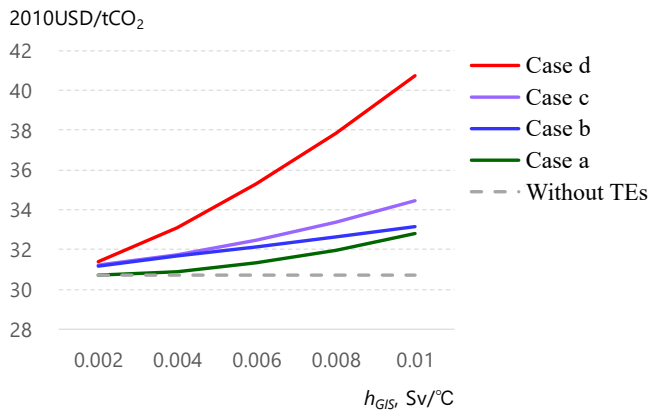

Figure 2 Social cost of carbon (SCC) in 2015

was considered, h_{GIS} had limited impact on SCC when it was low, but the rise in SCC accelerated as h_{GIS} increased as shown by the convex curve, and SCC was estimated at \$32.8/tCO_2 for h_{GIS} = 0.01. This nonlinearity is considered attributable to the critical point of AMOC—that is, the risk of AMOC collapsing is low when h_{GIS} is low but rises sharply once h_{GIS} passes a certain level. Meanwhile, for case b, in which only GIS was considered, SCC rose linearly with the increase in h_{GIS}. The shape of the curve seems to reflect the absence of any clear critical point being considered for GIS. SSC reached \$33.1/tCO_2 at h_{GIS_0} = 0.01 for case b, suggesting that the damage from the impact of the melting of GIS may be greater compared to the collapse of AMOC. This result disagrees with Reference 28), and the difference may arise from the assumptions for h_{GIS}. Reference 28) assumes a low h_{GIS} for GIS but a far higher h_{GIS} for AMOC, and therefore, when the assumptions are adjusted to match, as was done in this study, the impact of melting of GIS would be greater compared to the collapse of AMOC.

In the case where both GIS and AMOC were considered, but without their interactions (case c), the increase in SCC was greater than in the cases in which either GIS or AMOC was modeled, but was smaller than when the increases in cases a and b were simply added together (\$34.4/tCO_2 for h_{GIS} = 0.01 Sv/°C). This can be understood from the nature of the critical point for AMOC. For the case "without TEs," the path which would eventually pass the AMOC critical point became the optimal path, but for the case with AMOC only (case a), the path in which emissions were reduced until collapse would be avoided was selected. Meanwhile, when the optimal path is sought by first taking GIS into account, the optimal path would be one with lower emissions than when GIS is not considered. Therefore, by incorporating AMOC into the case with GIS, it would be possible to prevent AMOC from collapsing with a smaller additional reduction than when AMOC is incorporated into the case "without TEs." This is why the

difference between the case with GIS (case b) and the case with AMOC and GIS (case c) is smaller than the difference between the original optimal solution (the case without TEs) and the case with only AMOC (case a).

In contrast, SCC rose significantly in case d in which the interaction between the two TEs was considered, to \$40.7/tCO_2 under h_{GIS} = 0.01. The difference between case a and case d (the impact of GIS melting and the interaction) was \$7.9/tCO_2, more than triple the impact of GIS melting alone (the \$2.4/tCO_2 difference between case b and the case "without TEs"). This suggests that the interactions between tipping elements may cause consequences that are more serious than when their impacts are considered individually.

4.2 Changes in optimal emission paths

Figure 3 shows the amount of CO_2 emissions for each case in 2050. As with SCC, the impact of GIS (case b) was largely linear to h_{GIS_0} while the impact of AMOC (case a) was nonlinear. However, unlike the trend of SCC, the amount of emissions reduction under h_{GIS} = 0.01 for the GIS-only case (case b) was smaller than that of the AMOC-only case (case a).

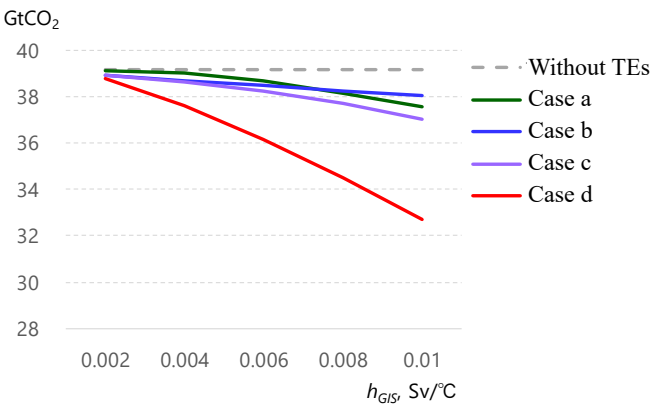

Figure 3 CO_2 emissions for the optimal path in 2050

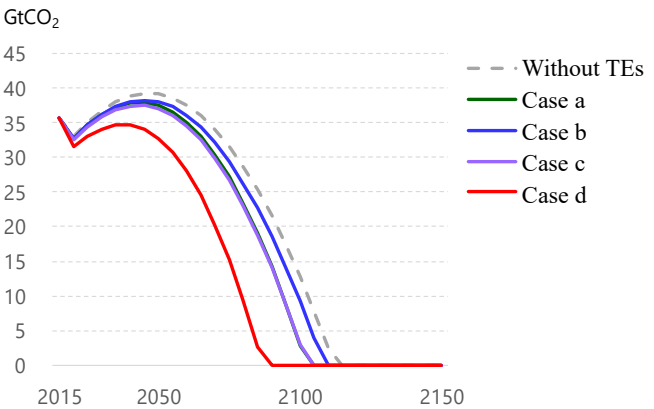

Figure 4 The optimal global CO_2 emission path (h_{GIS} = 0.01)

This was because while the optimal path for case a opted for a relatively large emissions reduction to prevent AMOC from collapsing, for case b, the path which allows a certain level of damage and therefore has a relatively small reduction became the optimal path. Case d showed a remarkable change in the amount of CO_2 emissions as well, suggesting the importance of addressing interactions.

Figure 4 shows the optimal CO_2 emission paths for h_{GIS} = 0.01 up to 2150. Emissions decrease for all cases between 2015 and 2020, but this is due to a feature of the DICE-2016R2 model, in which the optimal path would be to reduce emissions to a certain extent even at the very initial stage, rather than a reduction rate of zero. For the optimal solution for "without TEs," emissions rise gradually from 2020, reaching 39.1 GtCO_2 in 2050 (up 9.5% from 2015). In contrast, the emission paths for cases a to c are lower as the risk of GIS melting and AMOC collapsing are reduced.

As shown in **Figure 3**, in 2050, a slight gap remains between the optimal emission volumes of cases a and c, but the gap thereafter becomes narrower toward 2100 (but will not close up completely). This would be because the combined effects of two tipping elements will not be a simple sum of the two (without modeling their interactions), and will diminish as reduction makes progress.

For case d, for which interaction was modeled explicitly, emissions decreased dramatically. The reduction would not be so striking in the relatively near future as in 2030 through 2050 (with a reduction of just 8.5% from 2015 in 2050), but the effects would be remarkably prominent in the second half of this century. The amount of optimal emissions would reach zero in the 2090s, about 10 to 20 years earlier than cases a to c or the case without TEs. This is presumably because it would become rational to introduce larger amounts of decarbonizing technologies to mitigate the damage from interactions between tipping elements.

4.3 Change in rise in temperature

Figure 5 shows the rise in the average global temperature for each case when h_{GIS} = 0.01. For the optimum solution for the case "without TEs," the temperature will rise by 3.5℃ by 2100 and by 4.1℃ by 2165, hitting the peak, and thereafter gradually decrease. By comparison, the rise in temperature was estimated to be somewhat more moderate for cases a to c, rising by 3.4℃ by 2100 and even more moderate for case d, rising by 3.2℃.

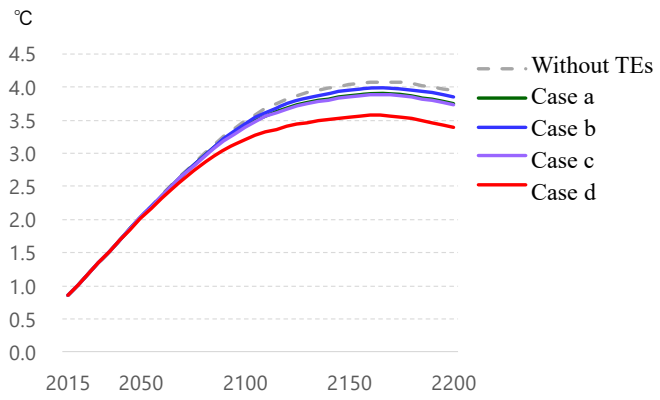

Figure 5 Rise in temperature up until 2200 (h_{GIS} = 0.01)

5. Conclusion

In this study, a cost-benefit analysis was conducted by incorporating the behavior of GIS and AMOC into DICE-2016R2. The result showed that the impact of interaction becomes prominent when h_{GIS} is relatively high, significantly affecting SCC and the amount of optimal CO_2 emissions. Interactions between tipping elements will be essential factors in considering climate policies in the future. When interactions were taken into account (h_{GIS} = 0.01), zero emissions became the optimal solution in 2100. In terms of mitigating the damage of tipping elements and managing their risks, developing technologies for achieving zero or negative carbon emissions and implementing them in society will become crucial.

However, even under the optimal emission path for case d (h_{GIS} = 0.01) analyzed in this study, the temperature will rise by some 3.2℃ in 2100. The DICE model is known to produce optimal temperature rises greater than 2℃ or 1.5℃ envisioned by the Paris Agreement. However, there are analysis results[17] indicating that it would be optimal to keep the rise in temperature within 2℃ by changing the damage function and discount rate. These subjects need to be discussed in greater depth in order to assess the scientific rationality of climate change targets.

Topics requiring further research include the modeling and analysis of tipping elements other than GIS and AMOC. As mentioned above, the results of this analysis are dependent on numerous conditions including the discount rate, availability of technologies that contribute to "negative emissions," and a decrease in reduction costs toward the future. How the results of this analysis would change based on these conditions must also be examined.

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Contact:report@tky.ieej.or.jp