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# Impacts of tipping points on optimal climate policy – an analysis based on integrated assessment modelling


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**Abstract**

Global warming of more than 1.5 °C can trigger tipping points (TPs) in the climate system, causing irreversible changes and considerable economic damage. Our research explores the influence of TPs, particularly the melting of the Greenland and West Antarctic ice sheets, on optimal climate policy. Using an adjusted DICE model based on Hänsel et al. (2020), we extend damage and temperature functions to assess TP impacts on temperature, damage trajectories, and the social cost of carbon (SCC). Our findings highlight that incorporating TPs into climate-economy models substantially alters SCC estimates, emphasizing the need for more dynamic and responsive climate policies. Proactive abatement efforts are shown to mitigate the most severe effects of climate change, underscoring the importance of international cooperation. This research advocates for tightening global climate policies to prevent crossing TPs and demonstrates the economic justification for early and eager abatement efforts.

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## Abbreviations

| | |
|---|---|
| BAU | Business as usual |
| DICE | Dynamic Integrated Climate-Economy |
| GIS | Greenland Ice Sheet |
| Gt $CO_2$ | Gigatons of Carbon Dioxide |
| IAM | Integrated Assessment Modelling |
| OPT | Optimal Climate Policy |
| TP(s) | Tipping Point(s) |
| USD | United States Dollar |
| USD/t $CO_2$ | United States Dollar per ton of $CO_2$ |
| WAIS | West Antarctic Ice Sheet |

# 1 Introduction

Exceeding 1.5 °C in global warming may push the earth past several tipping points (TPs), leading to irreversible climate changes and significant economic damages (Armstrong McKay et al., 2022: 1). Triggering these TPs could result in a domino effect, including the collapse of the West Antarctic and Greenland ice sheets, contributing to sea-level rise (SLR) and increased global temperatures due to decreased albedo (Armstrong McKay et al., 2022: 1; Gschnaller, 2020: 4). Recent scientific research suggests that the risk of crossing TPs can no longer be considered low probability (OECD, 2022: 8). Understanding these impacts is crucial for effective climate policy, as ignoring TPs could lead to inadequate policies that exacerbate climate change damages and costs. This highlights the necessity of modelling different scenarios (see 4.1 Selection of Scenarios) to assess policy interventions' impacts on TPs' economic consequences. Since the DICE-2016 (Dynamic Integrated Climate-Economy) model by Nordhaus does not explicitly incorporate TPs, we analyse their additional effects on damages and optimal climate policy (Nordhaus, 2018). Therefore, we come up with the following research question:

> TO WHAT EXTENT DO TIPPING POINTS OF THE CLIMATE SYSTEM, PARTICULARLY THE MELTING OF THE GREENLAND ICE SHEET AND WEST ANTARCTIC ICE SHEET, INFLUENCE THE OPTIMAL CLIMATE POLICY?

We adjust our simplified DICE model based on Hänsel et al. (2020), extending it by modifying damage and temperature functions according to empirical studies. We exemplify their impact on temperature and damage trajectories and the social cost of carbon (SCC) within our selected scenarios.

The structure of this paper is as follows: Chapter 2 elucidates the scientific background and relevant definitions. Chapter 3 presents various modelling approaches, followed by a detailed explanation of our methodology in Chapter 4. Chapter 5 discusses the results of our analysis, and Chapter 6 offers a critical reflection. The paper concludes with policy recommendations in Chapter 7.

# 2 Scientific Background

TPs of the climate system are defined as critical thresholds at which a small additional perturbation causes a qualitative change of the system (Lenton et al., 2008: 1). According to Armstrong McKay et al. (2022: 1), they »occur when change in part of the climate system becomes self-perpetuating beyond a warming threshold as a result of asymmetry in the relevant feedbacks, leading to substantial and widespread earth system impacts«. In addition to the regional impact tipping elements, such as Mountain Glaciers or Boreal Forests, there are global core tipping elements such as the Amazon Rainforest, Boreal Permafrost and Ice Sheets of Antarctic and Greenland. The latter two, in particular the West Antarctic Ice Sheet (WAIS) and the Greenland Ice Sheet (GIS), have the potential to collapse at an estimated global temperature rise of 1.5 °C above pre-industrial level. From this temperature on, the TP is going to start exerting its impact. If the temperature is not reached, they are not triggered. WAIS and GIS have the lowest temperature threshold, while others are triggered by an additional global warming from 1.5 °C up to 7.5 °C (Armstrong McKay et al., 2022: 3). In general, the main cause of melting ice sheets is the increase in higher atmospheric and ocean temperatures. This leads to an average ice mass loss of 142 Gt per year of WAIS and 269 Gt per year of GIS (NASA, 2024). Both TPs affect a reduction of ice-albedo, a rise in sea-level and other tipping elements (so called *domino effect*). A collapse of GIS and WAIS triggers further TPs, particularly the Boreal permafrost which leads to an additional release of methane – with an 28 times greater global warming potential than $CO_2$ – and then to a further global temperature rise of 0.2-0.4 °C (Armstrong McKay et al., 2022: 3; Myhre et al., 2013: 731). All these feedbacks result in economic damages and changes in the climate system.

## 3 Modelling Approaches

Our model framework, based on Hänsel et al. (2020), considers the risk of TPs in the damage function using Weitzman (2012) equation. Catastrophic damages are only relevant with a 6 °C temperature increase, which would not be reached in our model (Hänsel et al., 2020: App.; Weitzman, 2012). This highlights the need for further integration of TPs in IAMs.

Lemoine & Traeger (2016) address TP-related uncertainties in IAMs by modelling stochastic uncertainty with unknown TP thresholds and implementing Bayesian learning mechanisms. This simulates a policymaker adapting to new scientific findings and climate events. They also consider domino effects, showing the probability of triggering one TP after another (Lemoine & Traeger, 2016: 514). Further, they categorize TPs within the DICE model. Global warming could release methane from permafrost and oceans, reduce albedo due to melting ice, and increase climate sensitivity. Another TP group involves increased atmospheric $CO_2$ residence time due to weakened carbon sinks. Lastly, they analyse TPs directly affecting the economic damage function, such as SLR and habitat loss (Lemoine & Traeger, 2016: 515).

Gschnaller (2020) examines albedo loss from GIS melting and the resulting SCC in a modified DICE-GIS model. We model the effects of tipping GIS and WAIS endogenously in DICE, following her approach for albedo feedback.

## 4 Our Approach

### 4.1 Selection of Scenarios

To pursue our research question, we create four different scenarios (Table 1) which, according to our expectations, achieve heterogenous results due to differing model parameters. Initially, we assume the model framework by Hänsel et al. (2020) which serves as a baseline model for optimal climate policy denominated by *OPT*. For the second scenario, we integrate the TP into the aforementioned one and refer to it as *OPT_TP*. For comparison, we create a business-as-usual scenario to account for the case that climate policy is tightened only marginally. Analogously, we use that model again as a baseline before implementing the TP in a second step. We refer to them accordingly as *BAU* and *BAU_TP* in the following.

Table 1: Four different scenarios.

| | Updated DICE Model | Business as usual (BAU) |
|---|---|---|
| Without TPs | OPT | BAU |
| With TPs | OPT_TP | BAU_TP |

Furthermore, we modify the parameter μ that describes the abatement effort. For both *OPT* scenarios, we assume a starting value of 0.03 for μ which adjusts over time. Within both *BAU* scenarios, we assume a fixed μ with the value of 0.05 to simulate lack of abatement effort of climate policy.

### 4.2 Choosing a temperature threshold

The nature of TPs implies a temperature threshold that is hard to be estimated. Based on scientific research, we are aware that melting processes begin before a certain temperature is reached. For the purpose of simplified modelling, in line with the analysis of Armstrong McKay et al. (2022: 3) who found a critical threshold for GIS and WAIS at 1.5 °C to be the best estimate, we define ours accordingly by $T_{crit}$.

### 4.3 Modifying functions

For the integration of the TP into our model, we use two different channels. First, we extend the (1) *Damage Function* by a term that accounts for additional damage through SLR.

$$D_{frac}(i) = \psi * T(i)^2 + \beta * SLR(i) \tag{1}$$

Initially, we define (1a) sea-level rise depending on time $SLR(i)$:

$$SLR(i) = \begin{cases} 0 & if\ T(i) < T_{crit} \\ \alpha[T(i) - T_{crit}] & if\ T(i) \geq T_{crit} \end{cases} \tag{1a}$$

and further set up a *Sigmoid Function* (1b) that operates as a non-linear optimizer to approximate the case that the sea-level rises exponentially from $T_{crit}$ (Figure 1).

$$SLR(i) = \frac{SLR_{max}}{1 + e^{(r1*T(i)+r2)}} \quad \text{with} \quad SLR(i) = \alpha[T(i) - T_{crit}] \tag{1b}$$

$$0 = \frac{SLR_{max}}{1 + e^{(r1*T(i)+r2)}} - \alpha[T(i) - T_{crit}]$$

$$F[1] = \frac{SLR_{max}}{1 + e^{(r1*T_x(i)+r2)}} - \alpha * (T_x(i) - T_{crit})$$

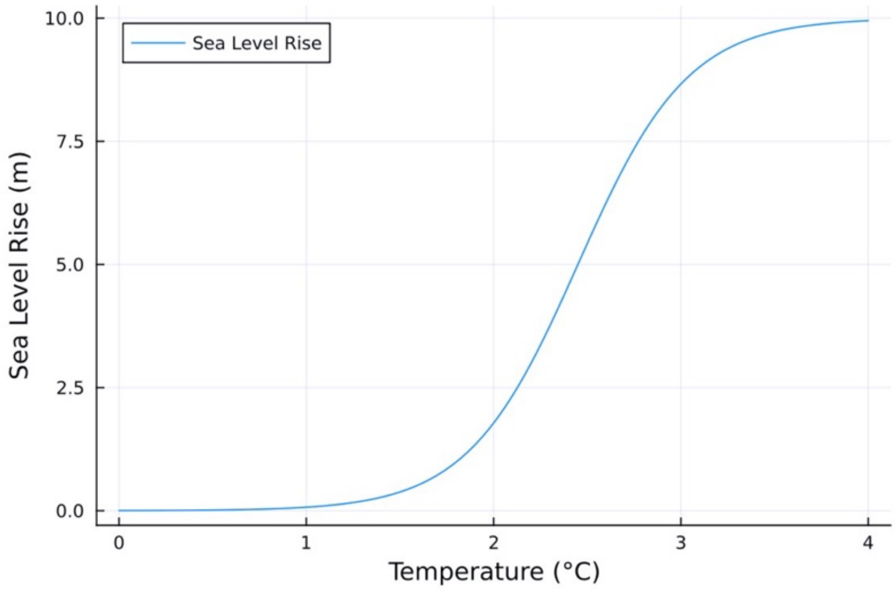


Figure 1: Sea-Level Rise (Sigmoid Function).

The *NLsolver* then tries to minimize the error so that the equation equals approximately zero. The values for $T_x(i)$ shows Table 2.

Table 2: Values for $T_{x(i)}$.

| $T_{x(i)}$ | |
|---|---|
| $x = 1 = T_1$ | $= T_{crit} + 0.1$ |
| $x = 2 = T_2$ | $= T_{crit} + 1.0$ |
| $x = 3 = T_3$ | $= T_{crit} + 1.2$ |
| $x = 4 = T_4$ | $= T_{crit} + 1.4$ |
| $x = 5 = T_5$ | $= T_{crit} + 1.8$ |

Now, we define parameter (1c) α that translates additional temperature above $T_{crit}$ to SLR (see App. 1). According to Lenton & Ciscar (2013: 589), GIS and WAIS may contribute 10 m in total to global average sea level if melted completely. We therefore define 10 m for $SLR_{max}$ accordingly. Further, Nordhaus (2019: 12265) assumes that GIS fully melts in equilibrium at 3.4 °C global temperature. We assume the same for WAIS and therefore derive a maximum temperature $T_{max} = 3.4\,°C$, at which both ice sheets are expected to be fully melted. Thus, we calibrate α such that:

$$\alpha = \frac{SLR_{max}}{T_{max} - T_{crit}} = 5.2632 \tag{1c}$$

In a last step, we define parameter (1d) β that translates additional SLR into economic damage. Jevrejeva et al. (2018:5) depict two scenarios by considering a time horizon up until 2100. According to their analysis, by the end of the 21st century global annual flood costs are projected to be 1.8 % of global GDP under 1.5 °C and 2.0 % of global GDP in a 2.0 °C scenario caused by the corresponding difference in SLR. Therefore, we calculate the change of economic damage for both scenarios and divide it by the anticipated change in SLR.

$$\beta = \frac{D_{2.0\,°C} - D_{1.5\,°C}}{SLR_{2.0\,°C} - SLR_{1.5\,°C}} = 0.0182 \tag{1d}$$

$$\mathrm{D}_{2.0\,°\mathrm{C}} = 2.0\,\% \qquad \mathrm{SLR}_{2.0\,°\mathrm{C}} = 0.63\ \mathrm{m}$$

$$\mathrm{D}_{1.5\,°\mathrm{C}} = 1.8\,\% \qquad \mathrm{SLR}_{1.5\,°\mathrm{C}} = 0.52\ \mathrm{m}$$

This suggests that for each meter of SLR, we can expect annual damages of about 1.82 % of global GDP. This way of calibrating β implies the sensitivity of economic damages caused by a rising sea-level as well as accounting for non-linearity as a rise of one meter in different scenarios do not have the same impact.

The second channel implies a modification of the (2) *Temperature Function* by introducing a parameter ω that is going to operate as a coefficient.

$$T(i+1) = [1 + \omega(i)] * \zeta * \varphi * CE(i) \tag{2}$$

At first, we define an equation (2a) for melted area depending on time $A_{melt}(i)$. Analogously to the first channel, we apply a *Sigmoid Function* (2b) for approximation of exponential increase at the temperature threshold $T_{crit}$ of 1.5 °C. The values for $T_x(i)$ are the same as in the first channel (Table 2).

$$A_{melt}(i) = \begin{cases} 0 & if\ T(i) < T_{crit} \\ \tau[T(i) - T_{crit}\ ] & if\ T(i) \geq T_{crit} \end{cases} \quad (2a)$$

$$A_{melt}(i) = \frac{A_{max}}{1 + e^{(a1*T(i)+a2)}} \quad with\ A_{melt}(i) = \tau[T(i) - T_{crit}\ ]$$

$$0 = \frac{A_{max}}{1 + e^{(a1*T(i)+a2)}} - \tau[T(i) - T_{crit}\ ]$$

$$F[1] = \frac{A_{max}}{1 + e^{(a1*T_x(i)+a2)}} - \tau * (T_x(i) - T_{crit}) \quad (2b)$$

Next, we define parameter τ which translates additional temperature above the temperature threshold $T_{crit}$ to melted area. For calibration, we pursue the approach by Gschnaller (2020: 11f.) and further assume a combined maximum surface area $A_{max}$ for GIS and WAIS. Gschnaller (2020: 11f.) determines for GIS a volume of 2,850,000 km$^3$ and a surface area of 1,781,250 km$^2$ respectively. Based on literature by Holland et al. (2019) and Naughten et al. (2023) we are aware that the ice sheets differ in their physical characteristics and responses to temperature increase. For simplification, we double the size of GIS to account for the implication of WAIS and thereby assume an $A_{max}$ of 3,562,500 km$^2$. The resulting (2c) initial volume $V_0$ of 5,700,000 km$^3$ is scaled such that:

$$V_0 = 100 \quad (2c)$$

$$SF = \frac{5{,}700{,}000}{100} = 57{,}000 \quad (2d)$$

We set up a (2d) scaling factor $SF$ and further define the (2e) initial surface area $A_0$ by dividing the actual surface area by the scaling factor. This provides a value of 62.5. Further, we define (2f) $S_{melt}(i)$ depending on time which states the fraction of the surface area that melts for each 1 °C increase above $T_{crit}$. According to Abdalati and Steffen (1997), an increase in temperature of 1 °C causes GIS to decline about 80,000 km$^2$. Hence, we choose 160,000 km$^2$ for GIS and WAIS.

$$A_0 = \frac{A_{max}}{SF} = 62.5 \quad (2e)$$

$$S_{melt}(i) = 160{,}000\ km^2 \quad (2f)$$

Finally, we calibrate (2g) τ. We divide $S_{melt}(i)$ by the initial surface area $A_0$ which yields 2,560 km$^2$. Thus, we can display the function in the plot below (Figure 2). Figure 2

$$\tau = \frac{S_{melt}(i)}{A_0} = 2{,}560\ km^2 \quad (2g)$$

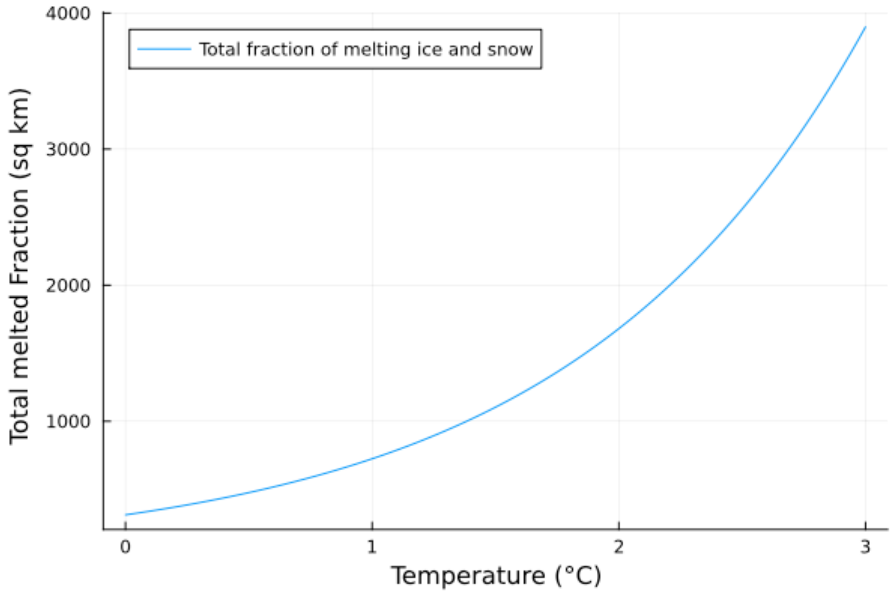


Figure 2: Albedo Effect (Sigmoid Function).

In order to translate the fraction of melted ice and snow into change in albedo that leads to temperature feedback, we calibrate (2h) ω depending on time by dividing $A_{melt}(i)$ depending on time by the combined maximum area of GIS and WAIS $A_{max}$.

$$\omega(i) = \frac{A_{melt}(i)}{A_{max}} \tag{2h}$$

# 5 Results

A selection of the most important results relating to SLR and albedo (chapter 5.1), damage (chapter 5.2), temperature (chapter 5.3) and finally the SCC (chapter 5.4) are given in this chapter. If there is interest in further results for further research, these are listed in the Appendix.

## 5.1 Sea-level rise SLR and the fraction of melted ice and snow ω

First, we show the resulting additional SLR for each period in *OPT_TP* and *BAU_TP*. We reach the highest point in additional SLR in 2060 with 0.38 m and afterwards we see a decline until 2100 with 0.17 m. This finding is consistent with the temperature development, where 2060 is the warmest year. In general, the shape of the SLR function (Figure 3) is similar to the optimal temperature function (Figure 6). Based on this, we conclude that the temperature has a moderating role for SLR. Adding all values from each period leads to a total SLR of 4.74 m in 2100. This total should be seen as unrealistic, because it almost represents half of the total SLR contribution from GIS and WAIS (see chapter 6).

In contrast, in *BAU_TP* we find exponentially increasing SLR. Beginning from 2040 the SLR in *BAU_TP* starts to differ more strongly from *OPT_TP* with respect to time. In *BAU_TP*, 2040 is the year where the temperature threshold of 1.5 °C is initially crossed. The underlying mechanism here is that in *OPT_TP* the SLR is controlled abatement effort μ and in *BAU_TP* the temperature increasingly exceeds the threshold. This results in an exponential increase of SLR and an additional SLR of 3.27 m in 2100. We calculate a total SLR of 19.01 m in 2100 for *BAU_TP*. The result is not only unrealistic, but should be impossible within our model framework, where we define the maximum SLR at 10m.

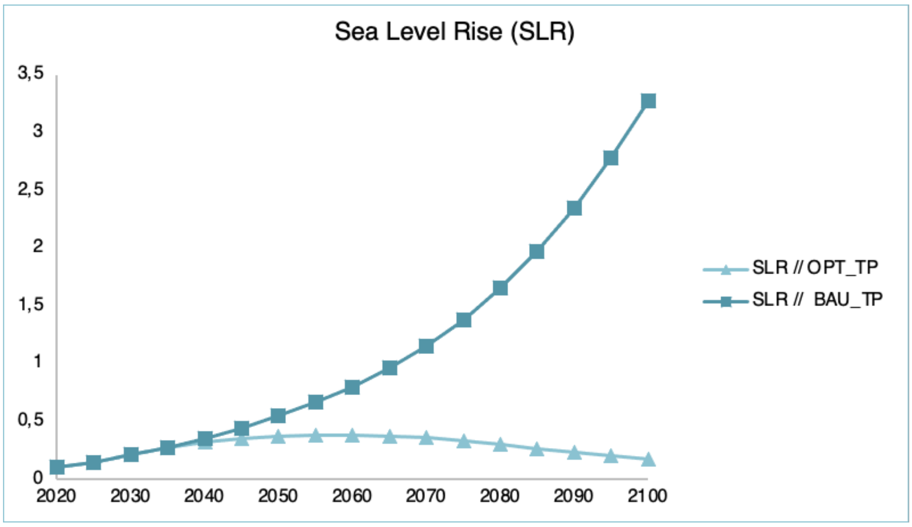


Figure 3: Sea-level rise OPT_TP and BAU_TP.

In this section we focus on the fraction of melted ice and snow ω in percent (Figure 4). We find a similar development of ω for *BAU_TP* and *OPT_TP* compared to SLR with a different measure.

For *OPT_TP* the highest point in ω is reached in 2060 with 0.032 % and afterwards we see a decline until 2100 with 0.026 %. We conclude that ω is also moderated by temperature. In 2100 the total fraction of melted ice and snow is 0.47 % compared to 2020.

In contrast, *BAU_TP* depicts a steadily increasing ω, but the shape looks more linear. From 2040 on, where the threshold is crossed, ω starts to differ more strongly from *OPT_TP* with respect to time. In 2100 we find an ω of 0.059 %. The total melted fraction amounts to 0.64 % in 2100. Comparing the totals for both scenarios, it is striking that the values stay on a very low level, especially compared to SLR, which is unrealistically high. This finding makes the effects of SLR and ω less comparable. If one wants to change the calculation of ω and thus the influence on temperature, one must consider that ω is a sensitive parameter in the temperature function.

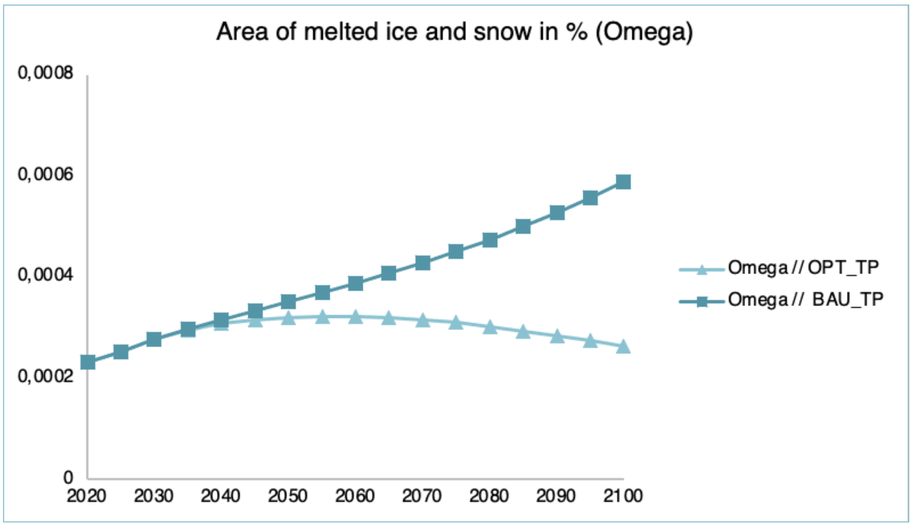


Figure 4: Area of melted ice and snow (omega) in OPT_TP and BAU_TP.

### 5.2 Damages

Beginning with both optimal scenarios, the integration of the TP leads to higher damages in every period compared to baseline. As Figure 5 shows, the damages instantly differ in 2020 and diverge more strongly from 2040 on, where the TP is crossed. This is consistent with our expectations, where SLR should lead to higher damages. After 2070 the damages converge and in 2100 the damages in *OPT* are higher for the first time with 13.72 Trillion USD and 13.48 Trillion USD in *OPT_TP*. This can be explained by the development of temperature. In *OPT_TP* the temperature starts to decline earlier, which results in lower damages with additional SLR. In our baseline *OPT,* temperature remains on a higher level and in 2100 damages resulting from temperature increase are higher even without additional SLR.

In *BAU* scenarios, we find in general an exponential progression of damages with steadily increasing temperatures for both scenarios, but the curve for *BAU_TP* is steeper. The integration of the TP leads to higher damages in every period with increasing divergence over time. In 2100 we detect a damage increase of 15 trillion USD or 58 % compared to the baseline model. This is in line with our expectations, because the additional damage from SLR is not controlled by abatement effort μ in *BAU* scenarios.

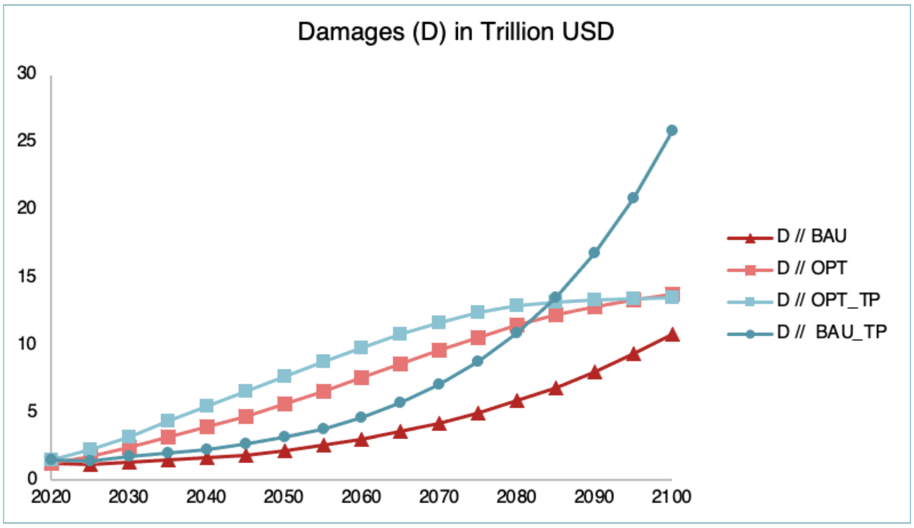


Figure 5: Damage trajectories in all scenarios.

### 5.3 Optimal temperature pathway

In the optimal scenarios, at first both of the graphs depict a similar development (Figure 6). In 2045, where the threshold is crossed in both scenarios, the graphs start to diverge. The baseline peaks in 2070 at 1.66 °C and ends in 2100 with 1.5 °C. Integrating the TP leads to a maximum of 1.54 °C in 2070 and a global warming of 1.31 °C in 2100. We conclude that the crossing of the TP leads to a lower optimal temperature pathway. This can be explained by the lowered production which leads to a decrease in emissions and consequently to lower temperature. The albedo effect makes temperature more sensitive to $CO_2$ which indirectly increases damages. At last, in the tipping scenario, μ rises more rapidly compared to baseline, which results in more abated emissions.

The temperature pathways for both *BAU* scenarios indicate a steady increase until the maximum in 2100. The values for *BAU* and *BAU_TP* stay very close to each other, but in 2070 a diverging trend occurs. After 2070 temperature stays lower in *BAU_TP* and the difference increases over time. This trend ends in the maximum difference in 2100 with 2.31 °C in baseline and 2.26 °C in *BAU_TP*, which is a difference of 0.05 °C. This can be explained by the difference in production (Figure 7). Lower production leads to less emissions and therefore to lower temperature. The effect of increasing μ is much stronger than the temperature reduction due to production loss, when we compare this to the optimal scenario.

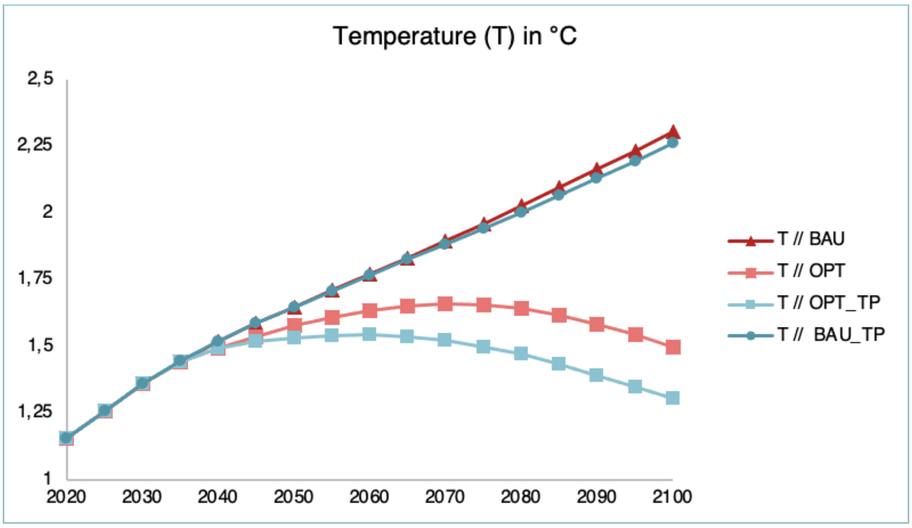


Figure 6: Temperature trajectories in all scenarios.

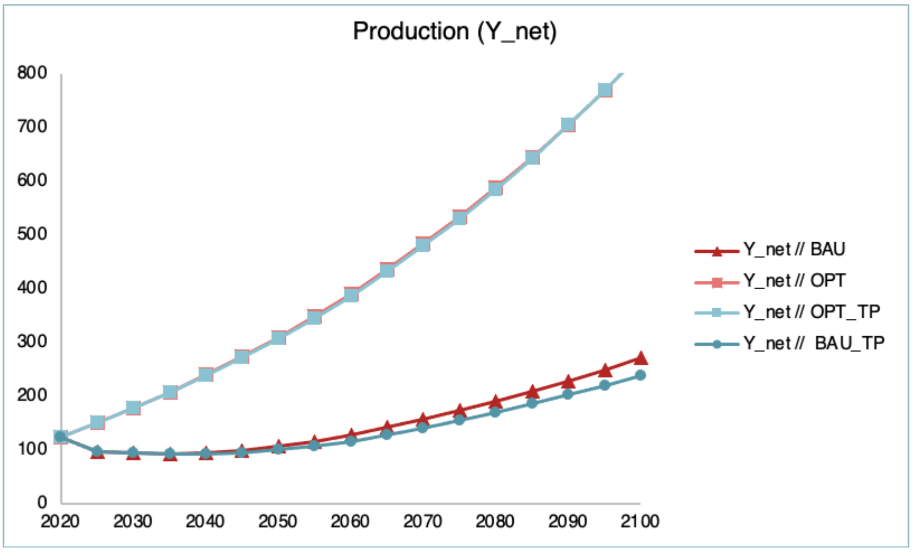


Figure 7: Production trajectories in all scenarios.

## 5.4 Social Cost of Carbon

For the optimal scenarios we instantly find higher SCC in *OPT_TP* for 2020 and a maximum difference in 2035 of 106.28 USD per ton $CO_2$ (USD/t $CO_2$). As Figure 8 shows, the SCC converges after 2035. In 2100 the SCC in baseline of 577.91 USD/t $CO_2$ exceeds the value in *OPT_TP* of 557.57 USD/t $CO_2$. The diverging trend in the beginning can be explained by the faster increasing $\mu$ in *OPT_TP* which leads to higher SCC. Over time, in both scenarios $\mu$ converges to the same value of 1.2 in 2090. This means more abatement effort at the beginning leads to higher SCC and to lower SCC at the end.

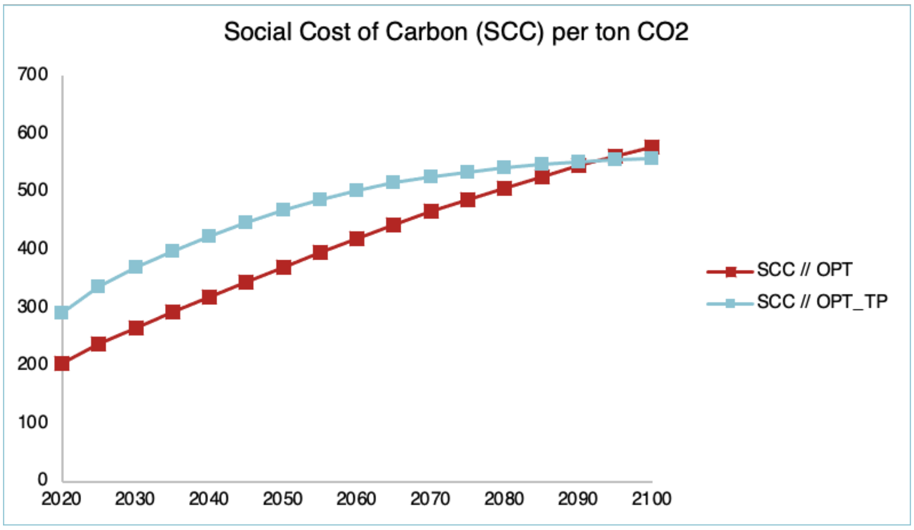


Figure 8: Social Cost of Carbon in optimal scenarios.

In both BAU scenarios, we observe a significant drop in SCC from 2020 to 2025 (Figure 9). Assuming a coding error for 2020, we exclude this value and start our analysis in 2025 to examine the trends. Our SCC values are 100 times larger than the optimal scenarios, so we focus on comparing the underlying mechanisms and trends of the optimal scenarios rather than absolute values.

In *BAU*, there is a slight decline until 2030, followed by a weak exponential increase until 2100, reaching 53695.34 USD/t $CO_2$. *BAU_TP* follows the same trend but more extreme, with consistently higher SCC values. Until 2045, SCC decreases, but after exceeding the threshold, it increases much faster in *BAU_TP* compared to *BAU* due to the exponential impacts of TP, indicating significantly higher economic damages per additional ton of $CO_2$ emitted.

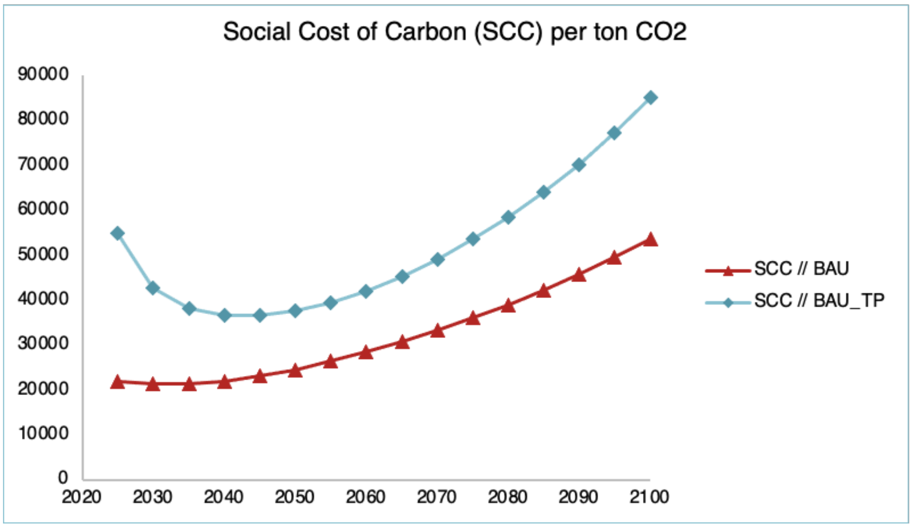


Figure 9: SCC in BAU scenarios (adjusted; values from 2025 until 2100).

## 6 Critical Reflection

We acknowledge that our depiction of reality is constrained by the general limitations of IAMs and the use of a simplified model by Hänsel et al. (2020). While aiming for a realistic analysis, our model does not capture all effects and impacts, yet overarching conclusions can still be drawn from our results. Specifically, the gradual melting process of GIS and WAIS, which takes centuries, limits short-term or mid-term policy implications as our model framework ends in 2100. Current estimates suggest thresholds for most TPs are not reached within this period; for example, the optimal carbon pathway never exceeds 1.66 °C, making irreversible tipping of GIS and WAIS unlikely.

Our model's sea-level rise predictions may be unrealistic compared to Jevrejeva et al. (2018) due to only considering damage from additional SLR per period, not a stock of SLR. Presumably, this happens because we only consider damage from additional SLR per period and not a stock of SLR. Lemoine & Traeger (2016b: 4) point in the direction that this stock could lead to permanent (discounted) damage since e.g. landmass is permanently lost. In contrast, the main drivers of economic damage due to SLR are living areas becoming unhabitable. This can be seen as a one-time cost. It underlines the necessity of well thought-out modifications of functions and an application of appropriately calibrated parameters as they can have a large impact on results and implications. Not all of our defined parameters, reflect the non-linearity of nature's mechanism. In this context, it is crucial which data and literature is used. Sometimes there are differing results even for prominent scientific findings. For this purpose, a sensitivity analysis and multiple test runs should be conducted. Furthermore, we cannot exclude the possibility of coding errors despite careful working methods. Additionally, our model does not account for possible domino effects of TPs, which significantly impact their likelihood of triggering.

## 7 Conclusion and Policy Implication

In conclusion, the emphasis on TPs in the DICE IAM significantly impacts climate policy. Incorporating TPs into climate-economy models can greatly alter the estimated SCC, highlighting the global interconnectedness of our ecosystem. It emphasizes that climate change is a complex issue intersecting with economics, social equity, and international relations. Ignoring non-linear impacts could underestimate the true economic costs of carbon emissions. Policymakers should consider TPs when designing climate policies. Setting temperature targets based on tipping thresholds rather than arbitrary figures like the Paris agreement could lead to a more transparent climate policy framework. This approach would require policymakers to clearly articulate the scientific rationale behind their targets, fostering informed public discourse.

Recognizing TPs necessitates a paradigm shift in climate change mitigation, calling for a dynamic, responsive policy framework. A key implication is that SLR can be controlled by abatement efforts, as demonstrated by comparing *OPT_TP* and *BAU_TP* scenarios. This suggests that proactive policies can mitigate some of the most devastating effects of climate change. The effectiveness of abatement efforts in controlling SLR underscores the importance of international cooperation. Climate change is a global problem requiring global solutions, and international collaboration in climate policy can lead to tangible benefits.

The exponential increase in SCC due to TPs suggests that early and eager abatement efforts are economically justified to avoid crossing such thresholds and potentially reduce the necessity of climate adaptation. This is evident in our optimal scenario, where the SCC remains low, providing a compelling argument for more ambitious carbon reduction targets. Demonstrating the economic benefits of proactive climate policies could shift public opinion and drive greater demand for sustainable practices. The necessity of tightening global climate policy concerning TPs is evident in our comparison of tipping scenarios. More abatement effort could initially increase the SCC but reduce it in the long run. Our research underscores the urgent need to revise and tighten global climate policies, emphasizing proactive abatement efforts and the economic and environmental benefits of preventing TPs. This approach calls for a climate policy that is scientifically informed, economically justified, socially inclusive, and globally coordinated, addressing the multidimensional challenges of climate change and building a sustainable future for all.

## 8 Statement of contribution

The following outlines the contributions made by each author to the various sections of the seminar paper:

- Introduction: All authors contributed equally to this section.
- Scientific Background: This section was primarily written by Dubiel, with partial contributions from Bröckers and Ihme.
- Modelling Approaches: Bröckers was the main contributor to this section, with additional input from Dubiel and Ihme.
- Our Approach: All authors contributed to this section. Ihme was the main contributor, with significant contributions from Bröckers and Dubiel.
- Coding in Julia, Plotting and Visualisation: Dubiel was primarily responsible for this section, with assistance from Bröckers and Ihme.
- Results: Bröckers and Ihme were the main contributors to this section, with partial contributions from Dubiel.
- Critical Reflection and Conclusion: All authors contributed equally to this section.

**Statutory Declaration**

We, Manuel Bröckers, Sophia Dubiel and Paul Ihme, students at the University of Leipzig, hereby declare that the work presented in our paper titled Impacts of TPss on optimal climate policy is entirely our own. We have not used any sources other than those listed in the bibliography and identified as references in the text.

We further declare that:

The work has not been submitted, in whole or in part, for any other degree or qualification at this or any other institution.

Any quotations from published or unpublished works have been acknowledged in the text, and all sources of information have been specifically referenced.

We are aware that any false claims can lead to legal consequences and disciplinary actions by the University of Leipzig.

Leipzig, 8th July 2024

| | | |
|---|---|---|
| Manuel Bröckers | Sophia Dubiel | Paul Ihme |

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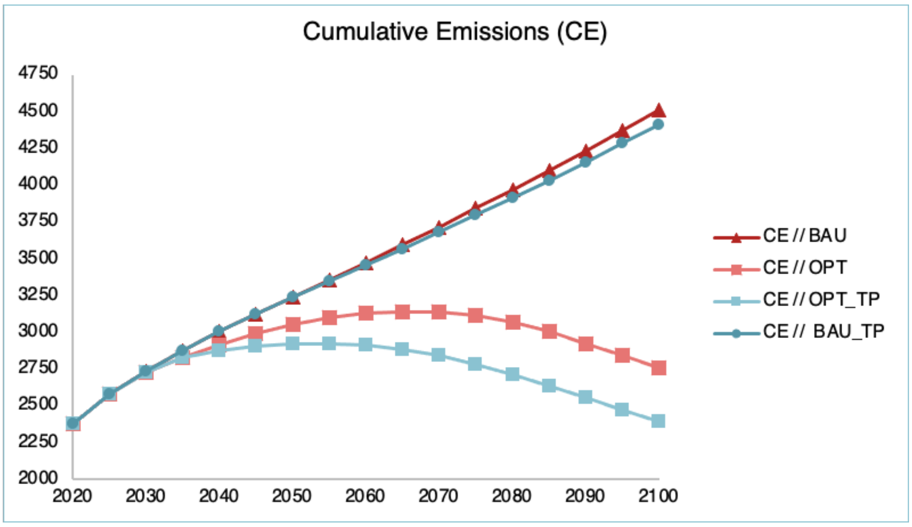
**Appendix**

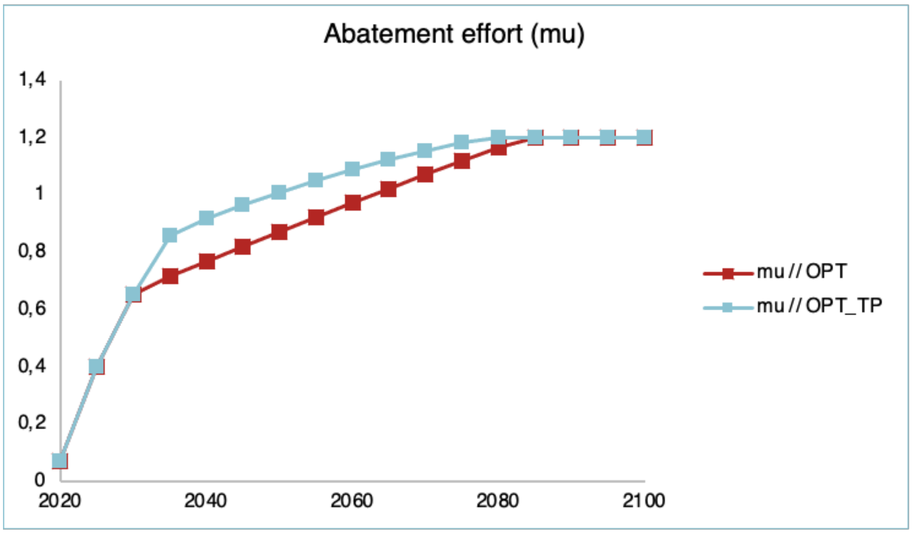
App. 1: Overview of the added parameters.

| Parameter | Description |
|---|---|
| $\alpha$ | sensitivity coefficient: translates additional temperature increase above $T_{crit}$ to SLR per m |
| $\beta$ | sensitivity coefficient: converts SLR into economic damage |
| $\tau$ | translates additional temperature increase above $T_{crit}$ to $A_{melt}(i)$ |
| ω | translates the fraction of melted ice and snow into a change in albedo that leads to temperature feedback |

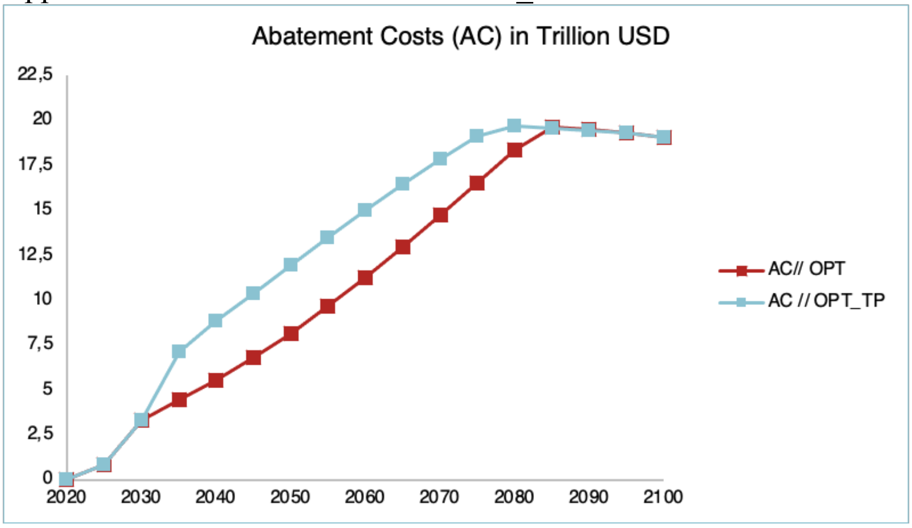
App. 2: Cumulative Emissions in all scenarios.



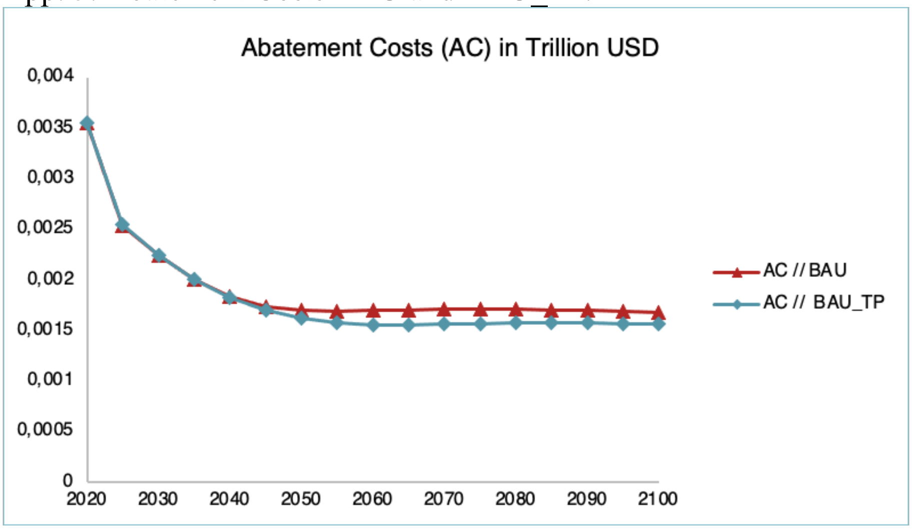

App. 3: Abatement effort OPT and OPT_TP (in BAU constant by 0.05).



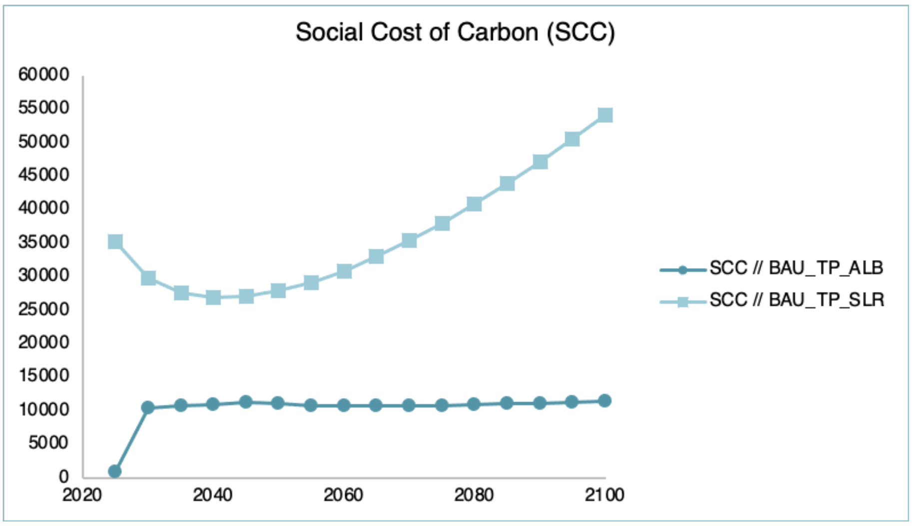
App. 4: Abatement Costs OPT and OPT_TP.



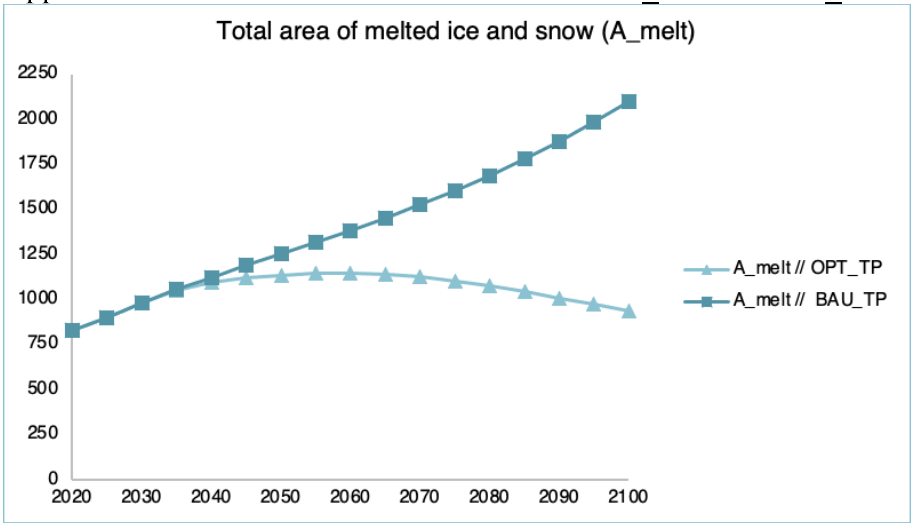

App. 5: Abatement Costs BAU and BAU_TP.



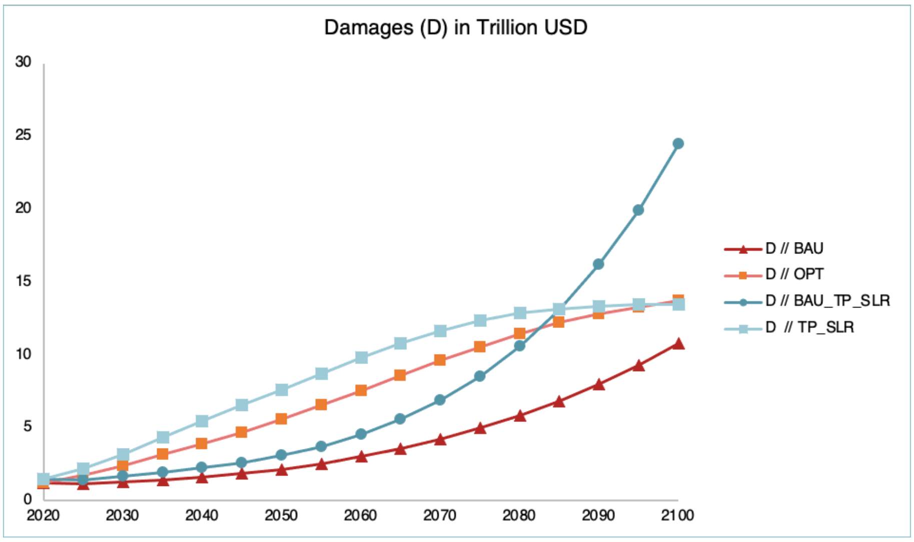

App. 6: Social Cost of Carbon; Albedo Effect and Sea Level Rise BAU_TP.



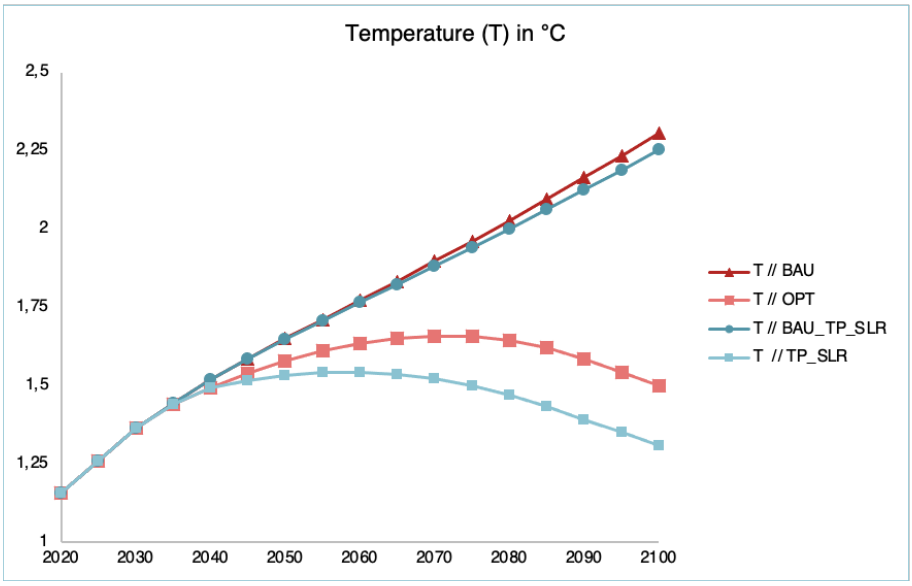
App. 7: Total area of melted ice and snow in OPT_TP and BAU_TP.



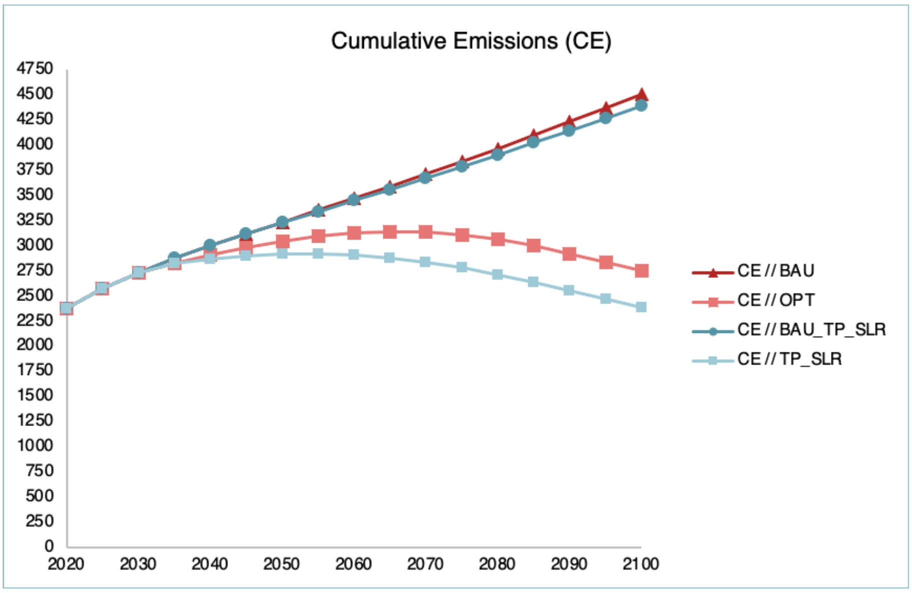

App. 8: Damages; Sea-Level Rise TP in all scenarios.




App. 9: Temperature; Sea-Level Rise TP in all scenarios.



App. 10: Cumulative Emissions; Sea-Level Rise TP in all scenarios.




App. 11: Damages; Albedo TP in all scenarios.