Multiple tipping points in the climate system

Implications for climate policy

Ida Nordin
Abstract

Tipping points in the climate system have the possibility to cause large damages to civilization. Through modeling them in the integrated assessment model DICE as multiple tipping points with distinct characteristics and thresholds, implications for policy are found. When the first tipping point has a threshold level of 2°C, it would be optimal to avoid this first threshold and introduce high mitigation targets with full mitigation in 2060. This is applicable when impacts amount to some percentages of gross world product. Carbon prices would need to be $224 in 2050 when facing tipping points, compared to $53 when not facing tipping points.

Key words

Tipping point, integrated assessment model, carbon price, mitigation, threshold, climate change
Acknowledgments

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“It all starts somewhere
It all starts with one
Everything comes from something
It all starts with one

It all starts somewhere
It all starts with one
Nothing comes from nothing
It all starts with one

First everything is dry
Before the dew and the drops align
Then the rain starts falling down
Then comes the flood, the flood
The flood, the flood
The flood, the flood”

- Ane Brun, One
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### Wordlist and Acronyms

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<th>Term</th>
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<tr>
<td>Climate sensitivity</td>
<td>A measure of how much temperatures will increase if greenhouse gas concentrations are doubled relative 1900 levels</td>
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<tr>
<td>CO₂-equivalents</td>
<td>The forcing capacity of greenhouse gases are recalculated into CO₂-equivalents to make them comparable</td>
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<tr>
<td>Greenhouse gas</td>
<td>Greenhouse gases are gases in the atmosphere contributing to global warming, e.g. carbon dioxide and methane.</td>
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<tr>
<td>DICE</td>
<td>Dynamic Integrated Climate-Economy model</td>
</tr>
<tr>
<td>GWP</td>
<td>Refers to Gross Word Product, gross output totally in the world net only of damages from climate change and mitigation costs</td>
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<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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1 Introduction

The latest report from the IPCC (IPCC, 2014), gives a discouraging picture about the outcomes of climate change. Under both unregulated (i.e. business as usual) and committed climate policy (i.e. policy so far committed to by the international community) scenarios, droughts, sea level rise, conflicts, food shortage, weather extremes, to mention some impacts, are predicted to increase. The most common target suggested in the climate change debate is to keep temperature increases below 2°C over pre-industrial temperatures. On the other hand, integrated assessment models for climate change, with the DICE, (developed by William Nordhaus 1993) being one of the more widely used, proposes only modest declines in emissions. The optimal temperature path for the 2013 version of DICE is peaking at around 3.4 °C, well above the 2°C the IPCC suggests, leading to the question: are the problems less important than IPCC believes, or is DICE wrong? The modeling of so called "tipping points" in DICE could be one source of disagreement.

Tipping points, describing abrupt and irreversible changes to the climate system, could have large impacts on the world. Their complex, uncertain nature and their relatively recent appearance in climate change debate provides some explanation to the little attention paid to them in economic analysis, despite their severe nature and extensive scientific literature.

Crossing a threshold value for one of these tipping points could cause an amplification of climate change, (e.g. the release of the greenhouse gas methane from permafrost), or alter subsystems of the climate system, (e.g. meltdown of Greenland ice sheet and rapid rise of the sea level). This change to a qualitatively new state is irreversible, at least in a policy relevant time horizon. A change is considered abrupt if it exceeds the system’s capacity to adapt. The threshold could be crossing a temperature level, or some other variable, e.g. length of the dry season, that in its turn can be linked to the temperature; therefore we can loosely speak of threshold temperatures for all tipping points. The National Research Council (2013) proposes that not only should
abrupt climate change include changes to the climate system, but also abrupt changes in *impacts* on society and ecosystems, that are triggered by a climate change, even if the system change itself is not abrupt.

The uncertainties about threshold levels and the nature and magnitudes of their impact are large since the climate changes we are approaching have not been recorded in millions of years, and not at this pace, but abrupt changes are known to have occurred (National Research Council 2013). Ackerman et al (2009) describe it as impossible to ever know the probability distribution for the damages of climate change. Weitzman (2011) believes that the probability distributions for catastrophic outcomes have fat tails rather than thin, implying that large levels of damage are a relatively realistic outcome of modest temperature changes.

Despite these uncertainties there are some estimations for the location of threshold temperatures and for impacts that offers a direction, even if there are disagreements. The state of knowledge is very insecure and will continue to change. The National Research Council (2013) have summarized research about abrupt impacts from climate change, Lenton et al (2007) identified and estimated thresholds for 9 tipping points and Kriegler et al (2009) made an expert elicitation of threshold levels for 5 of these tipping elements. The most important tipping elements identified are: the Atlantic meridional overturning circulation; sea level rise due to melting of the West Antarctic ice sheet and Greenland and other ice sheets; changes in ocean chemistry; changes in atmospheric circulation (e.g. El Nino/Southern oscillation); increased weather and climate extremes; methane gas release from oceans and permafrost; sea ice changes; abrupt changes in ecosystems (e.g. dieback of the Amazon forest) and; species extinctions. These are not isolated systems but the tipping of one can affect others. Three of these tipping points will be described in more detail in section 2.

Some of the tipping points are predicted to have moderate to high probability of occurring in this century, e.g. disappearance of Arctic sea ice that may already have passed its threshold (National Research Council, 2013) - that is before a likely tem-
perature increases of 2°C above pre-industrial levels (IPCC, 2014). Almost all tipping events have high probability of occurrence over the coming centuries, more or less abruptly. The uncertainty about threshold levels can be illustrated by the fact that the experts in Kriegler et al (2009) often assigned the probability of a threshold a large interval, e.g. the Greenland ice sheet that is assigned between about 15% and 90% chance to tip at thresholds between 2.7°C and 4.7°C above pre-industrial temperatures (Kriegler et al, 2009).

This thesis looks at how the presence of multiple tipping points affects optimal mitigation. Using a particular method to model tipping points in the DICE model with changes in climate dynamics and in the damage function, the effects are investigated. The implications for climate policy are illustrated.

The main finding is that when facing multiple tipping points with the first having a threshold at 2°C above pre-industrial levels, and damages amounting to some percentages of gross world product, it would be optimal to impose a policy with full mitigation already in 2060.

Instead of optimizing with a climate policy indicating a carbon price of $53 per ton of carbon in 2050 as a scenario that is not taking tipping points into account, the carbon price should be $225. The significantly higher price is motivated by a need to avoid large and fast damages that could occur in a short time if emissions were not cut. For a low discount rate where the far future becomes important also the continuation of high damages for coming centuries makes immediate action even more motivated. Despite the relatively low probability of a tipping point occurring at low temperatures, a precautionary principle to avoid severe damages motivates viewing the tipping events as a fact.

Tipping points are modeled in various ways in previous literature. Ackerman et al (2010) investigate them by looking at the impact of uncertainties about two key
parameters in the DICE model; climate sensitivity and the damage function. A combination of high values for both of these leads to catastrophic outcomes in their model, illustrating tipping points. As the probability distribution for the damage function is unknown they argue that these outcomes could well be probable.

Lemoine and Treager (2012) look at how tipping points modeled through permanent changes in climate dynamics affect optimal policies. In the model an endogenously changing hazard rate for passing the threshold is used. Ambiguity about less confident uncertainties, such as tipping points, is also introduced in the model.

Bickel (2013) looks at how valuable climate-engineering\(^1\) could be in the presence of tipping points, modeled through introduction of an irreversible indicator variable to the damage function in DICE. This is causing a persistent percentage loss in gross world product, GWP. The value of intervention of temperature changes through geo-engineering is estimated for a range of threshold values.

Lontzek et al (2012) models tipping points as a stochastic process calibrated with expert’s opinions. When occurring it will give a persistent damage of some percentages of GWP.

Lenton and Ciscar (2013) identifies some aspects that should be considered to model tipping points more accurately. Outdated information should be updated as it is renewed. As there are different tipping points with different probabilities and thresholds a model should include multiple tipping points. These should also be allowed to occur over different time scales. Other improvements would be to look at regional radiation and damage, and damage functions should be revised since e.g. the DICE damage function have little empirical foundation for higher temperatures.

\(^1\) Climate-engineering refers to large scale operations to prevent global warming. An example is release of aerosols in the atmosphere to block solar radiation from reaching earth’s surface (Bickel, 2013).
Nordhaus and Sztorc (2013) models catastrophic events, such as tipping points, in the DICE model through adding the expected value of a tipping point – occurring with low probability but high impacts – to the damage function.
2 Method

Three tipping points are modeled individually and implemented in the DICE model. Different scenarios are simulated in the model to analyze implications for policy.

2.1 The DICE model

The DICE2013 model used for the analysis here is a widely used integrated assessment model that has an open source code that is easy to modify. Nordhaus (1993) developed the model to investigate the optimal path for climate change policy. It models the economy, the climate system and the links between them. The objective is discounted utility, that in DICE2013 (Nordhaus and Sztorc, 2013) is optimized over 300 years, where the level of mitigation is the control variable.\(^2\)

The production function is Cobb-Douglas and is increasing with an exogenously determined growth rate. It has the special feature that production leads to greenhouse gas emissions. Due to technological progress this fraction is assumed to decrease over time at an exogenous rate. Mitigation is determined endogenously in the model and reduces emissions by a fraction of the total. The cost of mitigation is reduced exogenously over time as technology develops. Costs of mitigation and damage from climate change is included in the production function where GWP refers to output less these costs and damages:

\(^2\) Several theoretical and normative assumptions come with the DICE model of which there are disagreements in the economic literature. The analysis has an anthropocentric perspective where human utility is the objective, opposed to a biocentric or ecocentric perspective (Kronlid 2005). The utility is derived from increased consumption only and will be optimized in a discounted utilitarian framework, where future values are assumed to be less important. For a discussion about the discount rate, see for example Weitzman (1998) Nordhaus (2013), Dasgupta (2008), Karp (2005). The model also assumes substitutability between environmental and consumption goods, for a discussion about this see for example Weitzman (2011) and Ackerman and Stanton (2011).
World output \( = Y(t) = A(t)L(t)^{1-r}K(t)^r \)

\( GWP(t) = Y(t)(1 - D(t) - C(t)_{Mitigation}) \)

The largest source of emission is industry, but a small part also comes from natural sources.

\( E(t) = E(t)_{Industrial} + E(t)_{Natural} \)

\( E(t)_{Industrial} = \sigma Y(t)(1 - M(t)) , \ M(t) = Mitigation \)

The model of the climate system is calibrated against large climate models. Through the climate system emissions causes increases in global mean temperature, \( T(t) \).

The damage function is calculated as the fraction of output lost when the climate changes and depends on temperature. It can be simplified to:

\( D(t)_{Nordhaus} = a_2 T(t)^2 , \ a_2 = 0.00267 \)

This function with the coefficient \( a_2 \) is calibrated against studies of what damages climate change can have on the economy. These damages are consistent with scientifically predicted damages up to 2-2.5°C above pre-industrial levels, but have little scientific underpinning after this, for which it has been criticized (Ackerman and Stanton, 2011). The coefficient \( a_2 \) has in the later versions of the model been increased with 25% to take non estimable values and low probability catastrophic events into account.

\[ \text{Global mean temperature is a measure of the level of climate change} \]
2.2 Tipping points

To make a more realistic picture of climate change where many tipping points could cross their threshold, three instead of one tipping point are modeled. Often one, (or an aggregation of tipping points in general), are modeled which make it simpler, but it would be more reasonable to believe that tipping points will occur at different thresholds. Three tipping points better captures interesting dynamics between them, having their own characteristics and thresholds. The melting of Greenland and other ice sheets (GIS), the dieback of the Amazon forest and methane release are chosen as tipping points as their thresholds could be assumed to be at different temperature levels, according to the literature. The other identified tipping points are not modeled for simplicity and because there is a very low probability that all of them will turn out to have the low threshold temperatures suggested here. The three tipping points should be seen as representatives of the omitted tipping points. If for example the Amazon tipping event would not occur at 2°C, the omitted Arctic summer ice tipping event could possibly do instead. Of course, neither or both could tip as well. Their impacts will not be equal, but they can be compared to some extent as they have the tipping point characteristics. It should also be noted that even if there seems to be a larger possibility that the Amazon threshold is located before GIS, it could well turn out that GIS will pass its threshold first.

The GIS and Amazon are modeled as modifications to the damage function, whereas methane release is added to the emission function. Thresholds have to be arbitrary to a large extent due to the large uncertainty about them, but estimated probabilities from National Research Council (2013), Kriegler et al (2009) and Lenton et al (2007) points in the direction given below. The given thresholds are not the most probable, as these are low probability events, but rather an approximation of what they could be with a not too small likelihood. The impacts, that also are uncertain, are modeled with a higher and a lower value.
2.2.1  *Abrupt changes in ecosystems, the Amazon Forest*

An abrupt change in ecosystems alters the living conditions for species and can cause extinctions. Ecosystem services can be decreased and food and water supplies be threatened. The transformation of the Amazon forest due to climate change and deforestation is one important example and will serve as a representative for ecosystem tipping points. Ecosystem services such as the absorption of CO$_2$ will be severely affected if this tipping point is passed.

The Amazon is given the models lowest threshold of 2°C. National Research Council (2013) indicates ecosystems have a moderate chance of tipping this century, before 2°C increase in global temperatures, thus this appears most probable to have a low threshold. Kriegler et al (2009) provide the dieback of the Amazon a chance of 0-50% tip at low temperature increases.

The level of impact of this tipping point is guided by the cost of biodiversity loss already seen of at least $68 billion a year, 0.1% of today's GWP (Ackerman and Stanton, 2011) and also estimations of the cost of passing the threshold for the tipping point for Atlantic meridional overturning circulation that is estimated to 0-3% of GWP by Tol and Keller (Bickel 2013). Even though referring to another tipping point, it provides a direction of possible magnitudes of impact from a tipping element when there is a lack of information about impacts from an Amazon dieback.

The tipping point is modeled by an addition to the damage function in DICE. At the threshold level it increases abruptly to continue with damages persistently increased with 2% or 4%, otherwise following the same pattern as the original function. This reflects a onetime irrecoverable loss of ecosystem services if the forest collapses.

The damage function for Amazon is given below and is illustrated and compared to DICE in Figure 1:
\[ D(t) = \begin{cases} D(t)_{\text{Nordhaus}} ; & T(t) < 2 \\ D(t)_{\text{Nordhaus}} + D(t)_{\text{Amazon}} ; & T(t) \geq 2 \end{cases} \]

\[ D(t)_{\text{Amazon}} = \frac{TP_{\text{Amazon,}i}}{1 + e^{1-100(T(t)-2)}} , \quad TP_{\text{Amazon,}i} = 0.02, 0.04 \]

### 2.2.2 Ice sheet melting, GIS

The West Antarctic ice sheet (WAIS) and the Greenland and other ice sheets (GIS) can start to melt at an accelerating pace and collapse after passing a threshold. It would be an abrupt change of the climate system even if it could be a process of 1000 years. The melting from warmer temperatures itself can be fast enough to cause abrupt impacts even if it would not collapse. The melting causes sea level rise, where GIS could raise sea levels of up to 60 meters and WAIS could give a sea level rise of 3-5 meters, where WAIS have more risk of a rapid collapse (National Research Council, 2013).

This tipping point will be named GIS but refers to both GIS and WAIS. It is assumed to have its threshold at 3°C as it is given around 15-90% probability to tip at 2.7-4.7°C temperature increase by Kriegler et al (2009), but not assumed to tip this century by National Research Council (2013).

The tipping point is modeled as a modification to the damage function. At the threshold the damage function take a quite abrupt jump to a higher level of damage. This illustrates that the first sea level rise will have impact on coastal settlement, ecosystems and infrastructure that is built for a known sea level, with around 40% of the world’s population living within 100 km from the coast (National Research Council, 2013), that will be exposed to changed conditions. These lost values are assumed to be persistent as the sea level will not sink. To illustrate the continuing flooding to higher sea levels the damage function is made steeper than the original.
The value of coastal infrastructure is some trillions of dollars (National Research Council, 2013), some percentages of today’s GWP. All this infrastructure will not be damaged, but there are additional damages to buildings, agriculture, freshwater, ecosystems, increased vulnerability to storm and migration that will add impact. As these numbers are guiding only and not possible to find they are made similar to the Amazon’s, but somewhat higher. The first abrupt change will be assumed to give a loss of 2% and 4% of GWP.

The shape of the damage function is given below and illustrated in comparison to DICE damages in Figure 1:

\[
D(t) = \begin{cases} 
D(t)_{\text{Nordhaus}} & ; \quad T(t) < 3 \\
D(t)_{\text{Nordhaus}} + D(t)_{\text{GIS}} & ; \quad T(t) \geq 3 
\end{cases}
\]

\[
D(t)_{\text{GIS}} = TP_{\text{GIS},i} \frac{0.1(T(t) - 3) + 0.02(T(t) - 3)^3 + 1}{1 + e^{1-20(T(t)-3)}} ; \quad TP_{\text{GIS},i} = 0.02, 0.04
\]

![Figure 1. Damage from tipping points - high impact](image)
2.2.3 Methane release

Frozen methane lies in Arctic permafrost soils and Arctic ocean sediments. If these greenhouse gases were released into the atmosphere they could amplify human made climate change. Compared to earlier studies, the risk is considered lower now that this will give rise to an abrupt change. Knowledge in these fields is however still limited and there are still implications that this could be a tipping point.

The methane tipping point is modeled with the threshold 4°C as this tipping point has a low probability of occurring (National Research Council, 2013). It also represents other tipping points that could have a late threshold.

With a global warming potential of 25 over 100 years\(^4\) emission of methane equaling at least 1 663 Gt (Gigatonnes) CO\(_2\) equivalents can be emitted and this will be assumed to happen in 50 years, with 33.4 Gt CO\(_2\) equivalents per year (compared to 33 Gt CO\(_2\)-equivalents industrial emissions per year by 2010). For a higher level of impact, the double amount will be supposed to be released (National Research Council, 2013).

A variable for methane release is added to the emissions equation. It follows a continuous function that will emit on average approximately 33.4 Gt CO\(_2\)-equivalents every year for approximately 50 years\(^5\).

\[
E(t) = \begin{cases} 
E(t)_{\text{Industrial}} + E(t)_{\text{Natural}} ; & T(t) < 4 \\
E(t)_{\text{Industrial}} + E(t)_{\text{Natural}} + E(t)_{\text{Methane}} ; & T(t) \geq 3
\end{cases}
\]

---

\(^4\) The Global warming potential takes the additional effect of a stronger greenhouse gas into account (Forster et al 2007). Here the measure is chosen over 100 years as a long time perspective is used, but also taking into account direct effects better. A 50 GtC methane weight released (National Research Council, 2013) was recalculated to 1.33 times higher methane molecular mass, and by the global warming potential transformed into Gt CO\(_2\) equivalents.

\(^5\) For the business as usual case, a more accurate emission of 66.7 Gt CO\(_2\) equivalents per year for 50 years was used for high levels of impact, but this was not possible in the optimizing case.
The methane release as a function of temperature can be seen in Figure 2

\[ E(t)_{\text{Methane}} = MR_i e^{\frac{(T(t)-4.7)^2}{2 \times 0.4^2}} ; \quad MR_i = 55,110 \]

The full model consists of the DICE damage function with an addition of the Amazon and GIS tipping point, and the emissions function including methane release. It will be given by the following equations:

\[
D(t) = \begin{cases} 
D(t)_{\text{Nordhaus}} ; & T(t) < 2 \\
D(t)_{\text{Nordhaus}} + D(t)_{\text{Amazon}} ; & 2 \leq T(t) < 3 \\
D(t)_{\text{Nordhaus}} + D(t)_{\text{Amazon}} + D(t)_{\text{GIS}} ; & T(t) \geq 3 
\end{cases}
\]

\[
E(t) = \begin{cases} 
E(t)_{\text{Industrial}} + E(t)_{\text{Natural}} ; & T(t) < 4 \\
E(t)_{\text{Industrial}} + E(t)_{\text{Natural}} + E(t)_{\text{Methane}} ; & T(t) \geq 4 
\end{cases}
\]
2.3 Irreversibility

One characteristic of tipping points is irreversibility. Therefore the temperature function will be prevented from decreasing and the damage function that is dependent on temperature will not be able to decrease as in the original model. This is also consistent with some recent research that finds that temperature changes due to climate change will plateau at a level rather than decrease even if the greenhouse gas concentration in the atmosphere is reduced (Ackerman and Stanton, 2011). The effects on mitigation for no tipping points is shown in Figure 3. The mitigation rate will only be slightly higher for irreversible temperatures than for reversible temperatures. The reason for this should be that the persistent damages, caused by persistent temperatures, in the irreversible model will occur far in the future and will be discounted to a very low value. Therefore there will be small incentives to avoid them.

The other difference is that with reversible temperatures there will be a time period with more than 100% mitigation, where greenhouse gases are removed from the atmosphere. In the irreversible case this will not happen since it will not make any difference if greenhouse gas concentrations are decreased. Temperatures will reach their full level at 3.29°C in 2135 with irreversibility, instead of 3.34 °C in year 2135.

![Figure 3](image-url)
2.4 Model difficulties

Some problems arose when the model was altered to include tipping points since the structure puts some limitations to what can be done. The dieback of the Amazon forest would probably take about 50 years in reality, and not at once. In the model it had to be modeled more abruptly to make sure all damages were realized, otherwise it had been possible to stop them halfway, since damages here are a function of temperature. The same is true for GIS.

Methane releases are modeled as a function of temperature and calibrated against temperatures that are covered over 50 years in the business as usual scenario without tipping points. One problem encountered was that the model optimizes at a temperature level where some amount methane gas is released. As the temperatures stays on the same level, so do methane emissions, and in the long run more methane will be released than was intended. Another problem that can arise is that it becomes optimal to quickly pass these temperatures, thus a smaller amount of methane would be released. However, as methane is given such a high threshold, this should not affect outcomes that much.

The tipping points’ functions are not modeled exactly to match the original function before passing the thresholds; therefore some differences must occur even before thresholds are approaching. This should however affect details rather than general results.
3 Results

In this section the outcomes from the model simulations for optimal mitigation, temperature increases above pre-industrial levels and carbon price paths for different scenarios will be provided. The main scenario where thresholds are assumed to be at 2°C, 3°C and 4°C (referred to as “2-3-4”) is compared to the original DICE (called DICE) to see the effect of introducing tipping points. It is also compared to the individual tipping points (Amazon, GIS and Methane) and an aggregation of all three tipping points with the same threshold 3°C instead of three different (“3”), to see the effects of specifically modeling multiple tipping points. The differences for high and low impacts are discussed and what level of impact is the limit for when the first threshold is passed (“2-3-4 pass”). Damages in the business as usual case are provided to see what damages are likely in these scenarios if mitigation action is not taken. The differences in outcomes for various discount rates are also investigated. In all these scenarios it is assumed that the temperature increase is irreversible, also for DICE.

3.1 Main scenario

In Figure 4 optimal temperatures for the scenarios “2-3-4”, DICE, “3”, Amazon, GIS and Methane for low levels of damage are illustrated, in Figure 5 optimal mitigation paths for the same are illustrated and in Table 1 optimal carbon prices are provided. Optimal temperatures can be expected to be lower under threat of tipping points than without them for the DICE scenario. While the DICE scenarios’ optimal temperature is 3.3°C, optimal temperatures for the “2-3-4” scenario should be just below the first or the second threshold, avoiding the damage occurring when passing the threshold, but trying to go as close to DICE’s optimal temperatures as possible, that was preferable before introducing tipping points. If damages are low enough at an early threshold the tipping point could possibly be passed, allowing for higher total damages than DICE. This would be possible as damages to a large part occur in the future, whereas mitigation costs to the most part occur closer in time and the result is
that discounting decreases damages more than mitigation costs. The second threshold could also be passed if damages were low enough, but this does not seem as likely as the DICE scenarios’ optimal temperature are only 0.3°C above the threshold 3°C. Results should not be altered too much by in the Methane scenario as its threshold is above 3.3°C. Under the “3” scenario, optimal temperatures should not be as low as if one of the thresholds were assumed to be at 2°C, but there should be stronger incentives to stay under 3°C as three and not one tipping event is assumed to be realized there. The individual tipping points should not give as strong incentives to stay under the thresholds, as they lack the effect of other tipping points.

Mitigation rates should accordingly increase faster with tipping points than in the DICE scenario, and reach full mitigation earlier. Carbon prices should rise faster to make this mitigation policy possible.

3.1.1 Temperature increases and Mitigation level

For the temperature increases with low damages in Figure 4, temperature increases in the main scenario “2-3-4” will be optimized by keeping temperatures just under 2°C, reaching its maximum in 2100, compared to DICE scenario optimizing at 3.3°C. Also under the GeS and “3” scenarios, threshold temperatures are not passed, staying at 2.9°C and 2.8°C respectively, and the Methane scenario suggest temperature increase about 3.3°C. The temperature under the Amazon scenario on the other hand will pass the threshold at 2°C and reach 3.1°C. Since temperatures cannot decrease in the model, they will all plateau after reaching their highest values.
The optimal mitigation policies shown in Figure 5, refers to how large fraction of emissions should be abated, and reflects the optimal temperatures. Facing tipping points mitigation rates have to be radically higher than under DICE scenario to manage to stay at the new optimal temperatures.

The mitigation rate in 2050 under the “2-3-4” scenario is already 88% of emissions, whereas it is only 36% for the DICE scenario. For the same year mitigation under the scenario “3” would be 49%, for the Amazon scenario 58%, for the GIS scenario 46% and for the Methane scenario 40%. Under the DICE scenario mitigation will not be full, but peak at 98% in 2125, while under the “2-3-4” scenario it will already reach 100% mitigation in 2060. The “3” scenario will suggest full mitigation in 2100, GIS scenario in 2100, Methane scenario will peak at 98% in 2125 and the Amazon scenario will peak at 99% in 2125 after a small dip in mitigation in 2060.\footnote{After year 2150, 120% mitigation is possible through backstop technologies that reduce greenhouse gas concentration in the atmosphere. This will not be used in most cases, since temperatures cannot decrease in this model. The natural decay of greenhouse gas concentration and the lower rate of emissions due to technological progress will instead hold down concentrations. Therefore, mitigation can be decreased below 100% but still keep non-increasing temperatures. For “3”, the
Figure 5. Mitigation rate. Low impact tipping points

For “2-3-4”, facing tipping points, the additional damage from the last small temperature increase to 2°C, going to a state with some percentages higher damage, will be too high to make it optimal to cross the threshold. Mitigation costs are higher in earlier time periods since technological progress is assumed to lead to decreased cost over time, and a rapid change will therefore be costlier than a slow change in mitigation. Despite this, cost would in this case have had to be even higher to make the threshold temperature be passed and the mitigation path slower.

Under the Amazon scenario on the other hand mitigation costs are too large and the threshold is passed. As the Amazon scenario pass the threshold it takes the tipping point-damages into account, but also avoids costs of mitigating fast by allowing further temperature increases. Therefore some damages from the original damage function are accepted and the optimal temperature becomes 3.1°C in the Amazon scenario. The reason for mitigation reduction for a few years after passing the threshold is that it will be optimal to delay passing the tipping point for a few years. After pass-
ing the threshold the damage has already occurred and mitigation can be reduced since only relatively small changes in damage will occur.

The GIS scenario optimizes at just below 2.9°C, somewhat lower than its threshold, since the GIS function is allowed to start increasing slowly a little bit before its threshold. This fact affects “2-3-4” scenario outcomes. In the “2-3-4” scenario it is not possible to optimize at 3.1°C as under the Amazon scenario and do not have the same possibility to optimize by passing the threshold. Nevertheless, with somewhat smaller damages, the first threshold could be expected to be passed.

The reason that temperature increases under the Methane scenario will just about reach 3.3°C, is that it will be affected by small emissions of methane at these temperature, that is both increasing temperatures, and making it optimal to mitigate more industrial emissions to avoid higher levels of methane emissions. The “3” scenario optimizes at 2.8°C, below the temperature under the GIS scenario, as it will be affected by a methane release that is initiated before 3°C.

The results for higher levels of impacts are omitted here, but give optimal temperatures of around 0.1°C below the results for low impacts and slightly higher mitigation rates.

Multiple tipping points with assumed thresholds at 2°C, 3°C and 4°C, gives optimal temperatures that are lower than without tipping points. The mitigation rates needs to more than double in 2050 to reach these targets, whereas under the “3” scenario mitigation rates are in between.

### 3.1.3 Carbon prices

Table 1 provides optimal carbon prices for different scenarios. The carbon price is the price that should be assigned to greenhouse gas emissions to implement a mitigation policy, e.g. a carbon tax. In a well-functioning market this should be the same as the optimal social cost of carbon. The social cost of carbon equals the change
in discounted value of the utility of consumption that arises from an additional unit of emissions, the marginal cost of emissions (Nordhaus, 2011). These figures are important since they are used to implement mitigation policies.

<table>
<thead>
<tr>
<th></th>
<th>DICE</th>
<th>“2-3-4”</th>
<th>Amazon</th>
<th>GIS</th>
<th>Methane</th>
<th>“2-3-4 pass” low</th>
<th>“2-3-4 pass” high</th>
</tr>
</thead>
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<tr>
<td>2050</td>
<td>53</td>
<td>225</td>
<td>105</td>
<td>70</td>
<td>53</td>
<td>74</td>
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<tr>
<td>2100</td>
<td>153</td>
<td>210</td>
<td>150</td>
<td>218</td>
<td>154</td>
<td>218</td>
<td>218</td>
</tr>
<tr>
<td>Peak</td>
<td>188</td>
<td>271</td>
<td>188</td>
<td>218</td>
<td>188</td>
<td>221</td>
<td>218</td>
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<tr>
<td>Peak year</td>
<td>2120</td>
<td>2055</td>
<td>2125</td>
<td>2100</td>
<td>2120</td>
<td>2095</td>
<td>2100</td>
</tr>
<tr>
<td>First peak/bottom</td>
<td></td>
<td>105/68</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First peak/bottom year</td>
<td></td>
<td>2050/2060</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Carbon prices, dollars per ton CO₂ equivalents and years. Low impact tipping points except for “2-3-4 pass” high. Carbon prices for 2050, 2100 are given. Peak refers to the highest price and peak year the year this occurs. First peak/bottom refers to a first peak of carbon prices that then goes down before continuing its path to the peak price.

The table shows values that makes the optimal mitigation paths possible, for low levels of impact for the previous model runs and “2-3-4 pass” low and “2-3-4 pass” high⁷. Optimal carbon prices in dollars per ton CO₂ equivalents for 2050 and 2100 are provided to compare implications for policies, and also the year that the carbon prices will have their peaks in prices. After the peak, carbon prices will decrease since technological change will make mitigation cheaper, and thus mitigation can be sustained at lower prices. Under the Amazon scenario there will first be one peak in carbon prices, followed by decreasing prices (labeled first peak/bottom), after which prices rises again as a threshold is passed.

Under the DICE scenario carbon price is optimally $53 per ton CO₂ equivalents in 2050 and rise to $153 in 2100, to peak at $184 in 2120. The “2-3-4” scenario with

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⁷ The first threshold has an impact low enough to pass the threshold, more explained in section 3.3.
stricter mitigation policy requires a carbon price of $225 already in 2050, peaking with $271 in 2055, falling to $210 in 2100 and then fall further. For the Amazon scenario the carbon price is $105 in 2050, after which it falls to $68 in 2055. When the tipping point is passed carbon prices will rise again to peak at $188 in 2125. The “3” scenario will have carbon prices between the DICE and “2-3-4” scenarios, $76 in 2050 and $218 in 2100. These changes in carbon prices will make the mitigation policy described above possible.

3.2 Previous studies

Ackerman et al (2009) find that if climate sensitivity is very high and the damage function steep, a full rate of mitigation could have to be realized as soon as 2020. If the climate sensitivity parameter is 5 – compared to the most probable value 3 – and the damage function is steep, full mitigation would be needed at about 2050, closer to mitigation for “2-3-4” scenario. Thus the results here do not include the worst outcomes that Ackerman et al find.

Lemoine and Treager (2012) finds different results depending on the type change to the climate system the tipping point is causing. For their highest impact of tipping points optimal temperatures are found to be 2.8°C or 3.0°C, following different temperature and mitigation paths. The reason that they are lower than for the results here should be that they are using a hazard rate for thresholds while this model assumes the tipping points are known and also they do not use irreversible temperatures. The carbon prices are consequently lower.

Lontzek et al (2012) finds that with their stochastic modeled tipping point the mitigation paths will be much flatter, than what is also found in this thesis, with higher mitigation at an early stage.

Bickel (2013) finds values for intervening passing a threshold with climate – engineering. For a damage of 5% of GWP from a tipping point and otherwise following optimal DICE strategy, the value of intervening going above 2°C, would be $26 trillion
if the threshold actually was at 2°C, and about $11 trillion if the threshold was at 3°C. The results are for assumed zero damages from deploying the technique. This can be compared to today's GWP of about $60 trillion. This can measure the damages avoided, but as the technique is assumed to be relatively cheap so that the cost for mitigation is low.

### 3.3 First threshold is passed

If the first tipping point has low enough impact, it can be optimal to pass it. The following results will give a hint of what magnitudes of damages are needed to start taking tipping points into account. In Figure 6 and 7 optimal temperatures and mitigation rates for scenarios with multiple tipping points, where the first tipping point is passed, are illustrated. This is compared to the “2-3-4” and “3” scenarios, the later since it gives a comparison to one aggregated tipping point. The Amazon tipping point will have impacts just low enough to pass its threshold in this scenario (called “2-3-4 pass”), lower than in the previous “low” scenario. In Figure 6 and 7 the remaining tipping points will have low damage whereas results for high damages will be provided in the text.

*Figure 6. Temperature increase - First threshold passed. Low impact tipping points*
Under a scenario with low levels of damage for the two later tipping points, the level of impact for the Amazon tipping point that will make it optimal to pass the first threshold, “2-3-4 pass”, is a loss of 1.4% of GWP, or below. Optimal temperature increase reaches 2.9°C, still staying below the second threshold. Both the second threshold at 3°C and the fact that damages are at a higher level after passing the first threshold makes the damages of increasing temperatures further outweigh mitigation costs. Compared to the “3” scenario, the “2-3-4-pass” scenario will have a higher optimal temperature, but slightly lower mitigation, as under the “3” scenario methane is also mitigated, and both are reaching full mitigation about 2100. The “2-3-4 pass” scenario will not as the Amazon scenario decrease mitigation after passing the threshold. The low damage compared to the other tipping points makes the damage relatively unimportant, once it has happened.

For high impacts, damages from the Amazon tipping point can be no more than 0.8% of GWP if the threshold is to be passed under the “2-3-4 pass” scenario. Optimal temperatures will be about the same as for the “3” scenario, 2.8°C. For a feeling of what magnitudes of change that is, this would be around $510 billion in today’s GWP, compared to the $68 billion already estimated to come from biodiversity loss (Ackerman and Stanton, 2011).
3.6 Business as usual damages

Business as usual damages serves as an illustration of potential damages when only small mitigation action is taken, illustrated in Figure 8. Damages as fraction of GWP are shown for DICE, Amazon, GIS, Methane and “2-3-4” scenarios. All are modeled with high impacts, the highest impact climate change damages could reach in this model, although not an upper bound in reality. What can be seen is that damages for the “2-3-4” scenario would stay at 27% of GWP, at 6.9°C. This modeling does however not give tipping points the possibility total destruction of the economy, as for example in Ackerman et al (2009), where adverse outcomes could cause future losses in GWP to be extremely high. What also can be seen is that the release of methane does only give a small increase in damages. This could be explained by the low damages possible in the original damage function, even with a temperature increase, and that in this function methane release, though high, will not be more than about a of tenth of total emissions per year. As output but not mitigation has increased in the business as usual scenario, industrial emissions will be high; in a scenario with full mitigation methane will have more impact.

Figure 8. Business as usual damages. High impact tipping points
3.7 Discounting

The results are sensitive to parameter values in the model. The rate for pure time preference – the part of the discount rate describing how much the future is valued compared to the present – in the DICE model is set to 1.5%, out of normative assumptions. As this can ethically be judged right or wrong, it can be instructive to see how a lower rate of 0.1% – describing an assumption that all generations are given almost the same value – and a higher rate of 3% – describing an assumption of little care about future generations – affect optimal mitigation. In Figure 9 optimal mitigation for DICE and “2-3-4”, low impacts, with pure time preference rates of 0.1%, 1.5% and 3%, are illustrated.

Mitigation rates increases much faster for DICE with a low rate, reaching 74% in 2050 approaching the levels of the main scenario for “2-3-4”, whereas it will be lower with a high rate, only 26% in 2050. This reflects a bigger concern for high damages in the far future in the former case and conversely more concern for high mitigation costs in the near future in the later case. For “2-3-4” mitigation rates will only be changed somewhat when using a low rate of pure time preference, with higher mitiga-
tion rates at once, to increase more slowly. With a higher rate on the other hand the threshold will be passed, and optimal mitigation will be 58% in 2050 and full in 2105, almost comparable to the main scenario for DICE, reaching an optimal temperature of 2.9°C. For a low discount rate, damages from the first threshold would have to be diminishingly small to make it optimal to pass it. This illustrates the importance of these assumptions, but also for what range of discount rates tipping points could be considered important.
4 Discussion

The major result found is that when assuming multiple tipping points in the climate system, with thresholds at 2°C, 3°C, and 4°C and irreversible temperature changes, climate policy should aim at staying below the lowest threshold 2°C and reach full mitigation already in 2060. To achieve this carbon prices should be $225 in 2050 compared to $53 for a no-tipping-point scenario, where the optimal temperature increase is 3.3°C. This holds for damage levels of some percent of Gross World Product (net of mitigation costs and climate change damages, GWP) for crossing the threshold and realizing the tipping event. An inclusion of tipping points thus gives large changes of the result in the DICE model, illustrating that this is an important matter to bring into climate debate. The desirable goal becomes closer to the IPCC’s goal of 2°C, even if it is not for exactly the same reasons, as the IPCC builds its recommendations to a larger part on non-tipping point reasons.

Depending on the magnitude of damage of the first of the three thresholds the threshold could be passed and not avoided. For high and low levels of damage of the other tipping points respectively these levels are 0.8% and 1.4% of GWP. Even if the damage from a tipping point is low enough to make it optimal to pass the threshold, optimal temperatures will be lower than if no tipping point exist taking the added damages into account, implying stricter policy. When considering an ethical approach with a lower rate of pure time preference a smaller level of impact make it optimal to stay under a threshold. A higher rate on the other hand makes it easy to pass an early threshold, displaying that ethical assumptions will have an impact on optimal policy.

When looking at tipping points modeled together at one threshold 3°C and not individually, this threshold would be avoided instead. Full mitigation should under such assumptions not be required until 2100, with a carbon price of $76 in 2050. This means for the same type and impact of tipping points the location of their thresholds are important for climate policy. As these thresholds are uncertain, even if having some probability interval, this question of how to deal with this needs to be addressed.
A hazard rate (as in e.g. Lemoine and Treager, 2012) where the probability of passing a threshold affects the expected value of the impact is one approach to find optimal outcomes and gives lower optimal mitigation rates than found in this thesis. It takes into account that tipping points are no certain event to happen, but would not help to avoid the tipping point if, for example the Amazon actually has its threshold at 2°C. A precautionary principle was used instead for this thesis (see e.g. Weitzman, 2009). According to this, to avoid realizing uncertain severe damages it would be preferable to assume the thresholds exist even with quite low probabilities. That is, acting as if they will come, to not have the surprise of them happening is more important than the possibility that no damage will be imposed (i.e. no tipping point).

The approach used here is of course only precautionary to some extent, as thresholds could be at lower levels than 2°C, and actually all and not only one tipping point have some probability of tipping at low temperatures. If the damages are just high enough to avoid a threshold – as the 0.8% and 1.4% of GWP above – there is less incentive to be precautionary, but if damages high enough to destroy the economy is possible, as in Ackerman et al (2009), the incentive to avoid the same threshold temperature grows. With a variation of the discount rate the limit for when it is optimal to pass the thresholds are altered again, creating less or more incentives to avoid tipping points if the rate is increased or decreased. There is always need to choose between the risk and the costs. A better understanding of the magnitude of the impact from different tipping points and their thresholds could guide in understanding to which degree they are a threat, even if this could only give a better guess.

Tipping point specific characteristics did not show much difference, as the Greenland ice sheet and Amazon in much were equally modeled with a large abrupt damage, and Methane release had a threshold above DICE’s optimal temperature. A revised order could have illustrated some changes. Modeling feedback systems between tipping points could be instructive since these subsystems are not isolated, but the tipping of one will affect others, taking it closer to, or possibly in some cases further away from their threshold. Other improvements would be to look at what plausi-
ble ways there are to discount irreversible changes from tipping points and substitut-
ability between environmental impacts and consumption. Modeling tipping points 
through the climate system as Lemoine and Treager (2012) and adding adaptation as 
a policy tool in addition to mitigation when this is more applicable, would give a more 
through and accurate change in the model. A difficulty is that the model needs to be 
more complex and difficult to be able to implement desirable changes.
5 References


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Cracken, P.R. Mastrandrea and L.S. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, USA, pp 1-32.


