TRANSITION PATHWAYS AND RISK ANALYSIS FOR CLIMATE CHANGE MITIGATION AND ADAPTATION STRATEGIES

D4.1: Economic implications of climate change

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TRANSrisk

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Preface

Both the models concerning the future climate evolution and its impacts, as well as the models assessing the costs and benefits associated with different mitigation pathways face a high degree of uncertainty. There is an urgent need to not only understand the costs and benefits associated with climate change but also the risks, uncertainties and co-effects related to different mitigation pathways as well as public acceptance (or lack of) of low-carbon (technology) options. The main aims and objectives of TRANSrisk therefore are to create a novel assessment framework for analysing costs and benefits of transition pathways that will integrate well-established approaches to modelling the costs of resilient, low-carbon pathways with a wider interdisciplinary approach including risk assessments. In addition TRANSrisk aims to design a decision support tool that should help policy makers to better understand uncertainties and risks and enable them to include risk assessments into more robust policy design.

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Executive Summary

Climate change is expected to generate significant impacts on human and natural systems now and in the future if actions to correct the current trends are not taken soon. According to the Intergovernmental Panel on Climate Change (IPCC) the warming of the climate system is "unequivocal" and human influence on the climate system is "clear". In the future, continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts such as sea level rise, water scarcity and more extreme events. Impacts are unevenly distributed and are generally greater for disadvantaged people and communities. Additionally, there is the risk that if temperatures increase beyond certain limits non-linear responses of the climate system may lead to more abrupt and more drastic changes. According to the IPCC, the precise level of climate change needed to cross critical thresholds or tipping points remains uncertain, but a temperature increase of between 1ºC and 4ºC entails a high risk of crossing some tipping points.

The first part of this report shows the quantitative impacts that are expected from climate change in a business-as-usual scenario. The Paris Agreement in 2015 and the Intended Nationally Determined Contributions (the so-called INDCs) approved by many countries indicate that some climate measures will be adopted, but it is also accepted that they will not be sufficient to avoid dangerous climate change. Our results indicate that the economic losses that can be expected from climate change are very likely to be much higher than the cost of mitigation, even without considering some of the well-known co-benefits of mitigation, such those related to air pollution and health. However, the report stresses that the quantification of this damage depends crucially on three key factors in which there are high levels of uncertainty. These three key sources of uncertainty are climate sensitivity, the damage function and discount rates. We show, for example, that the choice of the damage function can change the damage from climate change by 2100 from below 10% of global GDP for a 4 ºC scenario to more than 30% if the risk of crossing some tipping points is factored into the analysis. We also show that the main sources of uncertainty are highly unlikely to decrease in the near future.

Given these unavoidable sources of uncertainties some authors (Pindyck 2013, and Stern 2013, 2016) have suggested that research efforts would be better focused on climate change economics with a view to understanding and integrating the implications of some processes that have not yet been incorporated into models, such as the thawing of permafrost or sea ice melting in the Arctic, and that these processes should also be incorporated in a low carbon emission scenario. The relevant research question now is how some of these processes that have not yet been considered can affect mitigation efforts and the possibility of remaining below the 2ºC limit as stated in the Paris Agreement. This is covered in the second and third parts of this report.

The second part of the report analyses the implications of an important risk for climate change control: thawing permafrost. Large amounts of carbon are stored in permafrost in the Arctic and sub-Arctic regions and as permafrost thaws due to climate warming, carbon dioxide and methane are released. Recent studies indicate that the pool of carbon susceptible to future thawing is greater than was previously thought and that more carbon could be released by 2100, even under low emission pathways. In this report we show how factoring in the emissions projected by experts influences the holding of climate change to levels likely to keep the temperature increase below 2°C (radiative forcing of 2.6 Wm-2). According to our simulations, fossil fuel and industrial CO_2 emissions need to peak 5 - 10 years earlier and the carbon budget needs to be reduced by 6 - 17% to offset this additional source of warming. The required increase in carbon prices implies a 6 - 21% higher mitigation cost for society than a situation where emissions from permafrost are not considered.

In the third part we consider another important feedback mechanism: sea ice melting in the Arctic, which is in fact one of the most striking manifestations of global warming. As sea ice melts, more open water is exposed to absorb solar radiation, generating a sea-ice albedo feedback effect. Recent studies indicate ice-free summer conditions may occur faster than expected also in a low carbon scenario, although there is much uncertainty as to when this may happen. Therefore, we study a hypothetical rapid sea-ice loss event that ends in one full month free of ice in September by 2050, as described in Hudson (2011), and different transitions for sea ice afterwards in an RCP2.6 scenario. Again, according to our simulations, if stabilisation/ recovery of sea ice is expected after 2050, fossil fuel and industrial CO_2 emissions need to peak 5-10 years earlier and the carbon budget needs to be reduced by 15 - 22% to offset this additional source of warming. However, if no-recovery behaviour or tipping point behaviour is expected the possibilities of staying below 2°C are quite low as CO_2 emissions would need to have peaked already. Although the results of this part of the study are based on “stylised” scenarios they show how more and more sea-ice melting translates directly into stringent mitigation efforts and climate policies.

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1 EC Summary Requirements

1.1 Changes with respect to the DoA

There is a small change in the title of the deliverable with respect to the DOA given that after the Paris Agreement it is quite difficult to talk about climate inaction. In the DOA we mention that one process will be analysed (permafrost thawing or sea-ice melting) but in the end we have covered both processes. All the rest remains as in the DOA.

1.2 Dissemination and uptake

This document is confidential and cannot be made public until some parts are published or until the end of the project. TRANSrisk Partners may not modify, send or share this document without the permission of the authors.

1.3 Short Summary of results (<250 words)

This report shows from a global perspective the damage from climate change are much higher than the cost of mitigation even without considering the potential co-benefits. However, we show that the uncertainties associated with these damage estimations are very large and, unfortunately, are highly unlikely to decrease in the near future. Finally, the report shows the effects of two major risks for climate change control: permafrost thawing and summer sea ice melting in the Arctic. We show the relevant economic and mitigation implications of these two processes due to the extra warming effect that they will generate. If these two processes, which have not been considered to date in economic models, are factored into the analysis more stringent mitigation efforts and more acute climate policies will be needed to keep the rise in global temperatures below 2 ºC.

1.4 Evidence of accomplishment

This deliverable.

2 INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), if greenhouse gas emissions continue their current trends they will cause long-lasting changes and damage in our economy and societies (IPCC 2013b).

In this context, a significant debate has emerged about the difficulties and uncertainties (Pindyck 2013, Stern 2013, Stern 2016) associated with the quantification of this damage by Integrated Assessment Models (IAMs), i.e. models that integrate the economic and climate system. For example, Lenton and Ciscar 2012 suggest that there is a “huge gulf between natural scientists’ understanding of climate tipping points and threshold and economists’ representations of them in integrated assessment models (IAMs)”. These authors mention different processes such as abrupt loss of Arctic summer sea ice, irreversible meltdown of the Greenland ice sheet, disintegration of the West Antarctic ice sheet, reorganisation of Atlantic thermohaline circulation and permafrost thawing, among others. Some of these processes (see also Lenton et al. 2008) may have a significant probability of occurring this century for climate conditions involving medium warming (between 2 - 4 °C) and even low warming (<2 °C). It has therefore been suggested that a priority area for research should be to incorporate these feedbacks and tipping points into economic analysis and models in order to understand better how they affect decision making.

This report seeks to contribute to this important, emerging research area. We use the Dynamic Integrated Climate-Economy model (DICE version 2013R), an integrated assessment model (IAM) well-known in climate-change economics (Nordhaus 1992; Butler et al. 2014; Moore and Diaz 2015). We keep the main aspects of the original DICE model unaltered (see Appendix 1 for more information about the model), so our results can easily be compared to previous findings. However, we also explore other damage functions used by other authors/models to complement our analysis, such as those proposed by Stern (2006) and Weitzman (2012).

The report is divided into three parts. The first part explores the main impacts that are expected to emerge in the future from climate change in a reference scenario or no-climate-policy scenario. In it we seek to understand how large the economic impacts could be and what the main uncertainties and barriers for a robust estimation of these damages are. The second and third parts factor into the analysis two risks that have hitherto not been incorporated into the economic analysis: the role of permafrost thawing and the implications of an abrupt loss of Arctic summer sea ice. These parts aim to explore what the economic and mitigation implications of two different but connected events are if we want to keep our planet below the 2 ºC maximum limit.

3 THE ECONOMIC IMPLICATIONS OF INACTION

3.1 Introduction

This part of the report gives an overview of the expected impacts from climate change in a situation where there is no global climate policy ("inaction"). First, we set out the climate change impacts, risk and mitigation cost that can be expected from climate change (subsection 3.2) and then we show the quantification of damage from climate change and the key uncertainties associated with it (subsection 3.3). Finally, we provide the conclusions of the first part of the report (subsection 3.4) and point out different paths for further research.

3.2 Climate change damage and mitigation costs

According to (IPCC 2014b), the warming of the climate system is "unequivocal" and human influence on the climate system is "clear". The atmospheric concentrations of carbon dioxide, methane and nitrous oxide currently observed are unprecedented in at least the last 800,000 years. Recent climate changes have had widespread impacts on human and natural systems. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished and sea level has risen. Also, the IPCC shows (with a high confidence level) that negative impacts of climate change on crop yields have been more common than positive impacts.

In the future, continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive, irreversible impacts for people and ecosystems. Climate change will amplify existing risks and create new risks for natural and human systems. Examples include water scarcity, challenges to urban settlements and infrastructure from sea level rise and adverse impacts from extreme heat, floods and droughts in areas where increased occurrence of these extreme events is forecast.

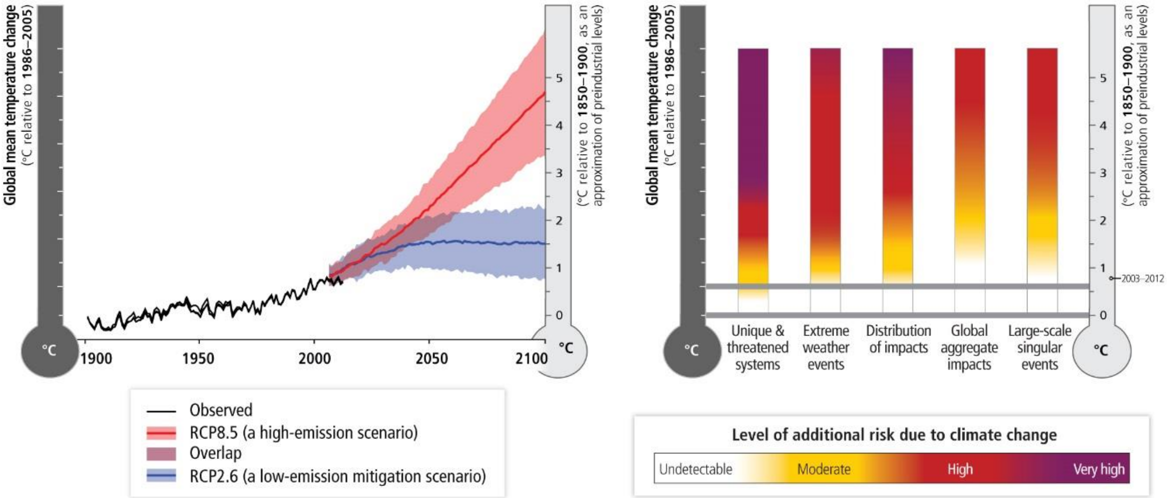
Impacts and risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. According to IPCC (2013a) the five main "reasons for concern" in relation to climate change and its future impacts are the following:

1. **Unique and threatened systems**: physical, biological and human systems that are restricted to relatively narrow geographical ranges are threatened by future changes in climate as they may not have time to adapt. This is the case of, for example, polar human and natural systems, coral reefs and unique alpine ecosystems and species.
2. **Extreme weather events**: risks associated with coastal and river flooding, heat waves, cyclones, droughts and other extreme events will increase with increasing global temperatures.
3. **Distribution impacts**: impacts will not be equally distributed across regions, nations or time. Unfortunately, the most vulnerable areas and people are often the most exposed and developing countries which have contributed little to climate change will suffer most from its impact. Moreover, this unequal distribution is not only found at the international level: the most vulnerable groups and sectors of developed countries are also at risk.
4. **Global aggregate impacts**: these include risks that are aggregated globally into a single metric, such as monetary damage, lives and species or ecosystems lost. Moderate risks to the global economy and biodiversity have been estimated for a temperature increase of 1-2ºC. Risks are high if temperature increases beyond 3ºC.
5. **Large-scale singular events or abrupt, drastic changes:** this could happen in some physical, ecological, or social systems in response to smooth variations in driving forces. The precise level of climate change needed to cross critical thresholds or tipping points remains uncertain, but a temperature increase of between 1ºC and 4ºC implies a high risk of crossing tipping points, according to the IPCC. An example of such a large scale singular event is the deglaciation of the Greenland ice-sheet, which could cause sea-level to rise by up to 7m.

Figure 1 summarises these major effects and risks associated with climate change, according to the (IPCC 2014a). The Figure shows a global perspective on climate-related risks, where the risks associated with these five reasons for concern are shown on the right for increasing levels of climate change.

Greater warming increases the risks. Some risks from climate change are considerable at 1˚C or 2˚C above preindustrial levels. Global climate change risks are high to very high with a global mean temperature increase of 4˚C or more in all 5 reasons for concern, and include severe and widespread impacts on unique and threatened systems, substantial species extinction and large risks to global and regional food security. The precise levels of climate change that will suffice to trigger tipping points (thresholds for abrupt and irreversible change) remain uncertain, but the risk associated with crossing multiple tipping points in the earth system or in interlinked human and natural systems increases with rising temperatures.

Figure 1. A global perspective on climate-related risks



Source: IPCC (2014, WG2, Technical Summary, Figure TS.5)

The overall risks of climate change impacts can be reduced by limiting the rate and magnitude of climate change. Risks are reduced substantially under the scenario assessed with the lowest temperature projections (RCP2.6 – low emissions) compared to the highest temperature projections (RCP8.5 – high emissions), particularly in the second half of the 21st century.

Adaptation can reduce the risks of climate change impacts, but there are limits to its effectiveness, especially with greater magnitudes and rates of climate change. In the context of sustainable development, taking a longer-term perspective increases the likelihood that more immediate adaptation actions will also enhance future options and preparedness. But adaptation cannot generally overcome all climate change effects, and thus mitigation is an essential part of avoiding this damage.

There are multiple mitigation pathways that are likely to limit warming to below 2°C (RCP2.6) and avoid the worst consequences of climate change. These pathways require substantial emission reductions over the next few decades and near zero emissions of CO_2 and other long-lived greenhouse gases by the end of the century or even before. Implementing such reductions poses substantial technological, economic, social and institutional challenges, which increase with delays in additional mitigation and if key technologies are not available. Limiting warming to a lesser or greater extent involves similar challenges but on different timescales. Table 1 shows the mitigation that will be needed and the associated likelihood of staying below certain temperature change levels.

Table 1. Mitigation scenarios and associated likelihood of temperature change

Scenario	Change in CO_2-eq. emissions		Likelihood of staying below a specific temperature level over the 21st cen-			
	2050	2100	1.5 °C	2 °C	3 °C	4 °C
RCP2.6	-55%	-100%	Unlikely	Likely	Likely	Likely
RCP4.5	-15%	- 80%	Unlikely	Unlikely	Likely	Likely
RCP6	+30%	+40%	Unlikely	Unlikely	Unlikely	Likely
RCP8.5	+80%	+125%	Unlikely	Unlikely	Unlikely	Unlikely

Source: Own work based on IPCC (2013, Table SPM.1, *Likely 66-100%*). All the details are in the original table.

In relation to the choice of technologies, the IPCC has stressed in its reports that there is no “magic bullet” or technology that can deliver all the mitigation that is needed, but rather a portfolio of technologies and measures that will depend greatly on each country and sector. The choice of these technologies will be determined, for example, by their cost (which may be different for each country) and by their public acceptability, which may also differ due to different negative or positive side-effects as perceived by society and stakeholders (this issue will be developed further in other work packages of the TRANSrisk project).

Estimates of the aggregate economic costs of mitigation vary widely depending on methodologies and assumptions, but increase with the stringency of mitigation. Mitigation scenarios that are likely to limit warming to below 2°C through the 21st century relative to pre-industrial levels entail losses in global consumption of 1-4% in 2030, 2-6% in 2050 and 3-11% in 2100 relative to consumption in baseline scenarios. It is important to mention that these losses do not include the benefits of reduced climate change (see next sub-section 2.3.2 in this report) or the co-benefits of mitigation (see other report of TRANSrisk project). Also the economic growth that is projected over the century (with GDP increasing from 3 to 9 times compared to the current levels) implies that these costs are indeed very low. IPCC estimate that these numbers correspond to an annualised reduction in growth in consumption of 0.04-

0.14% and, therefore, instead of, for example, 2% growth over the century one would have 1.86-1.96% growth. In the next section the cost of mitigation is compared to the cost of inaction.

3.3 The damage from climate change: key uncertainties

Aggregated economic impacts from climate change are difficult to estimate. According to IPPC (2014b, chapter 10), the studies completed so far vary greatly in their coverage of sectors and depend on a large number of assumptions. The impacts or damage from climate change are intended to include (but are not limited to) changes in net agricultural productivity, human health, property damage from increased flood risk and the value of ecosystem services due to climate change. Many estimates do not account for catastrophic changes, tipping points and many other factors. Additionally, there are large differences between and within countries.

Three key uncertainties are considered (Butler et al. 2014; Ackerman, Stanton, and Bueno 2010) to be the main factors in estimating future damage from climate change: 1) Equilibrium Climate Sensitivity (ECS), which refers to the equilibrium change in global mean temperature that would result from a doubling of CO_2 concentrations from preindustrial levels; 2) the damage function, which seeks to capture the link between the increase in global mean temperature and the expected loss in terms of GDP or consumption; and 3) the discount rate, which captures the rate used to bring future values into the present when considering the time value of money.

We explain these uncertainties in more detail in the following subsections, as they will be used in other part of this report (and will also be explored in more detail in other WPs of the TRANSrisk project).

3.3.1 Equilibrium Climate Sensitivity

Equilibrium Climate Sensitivity (ECS) is one of the key parameters used in climate and Integrated Assessment modelling. ECS[1] is defined as the equilibrium change in global

[1] In reality, these are two 'standard' measures of climate sensitivity that are used in climate change science: Equilibrium Climate Sensitivity (ECS) and Transient Climate Response (TCR). The TCR corresponds to the global temperature increase that has occurred at the point in time that atmospheric CO_2 concentrations reach double pre-industrial levels. However, if atmospheric CO_2 were held at double pre-industrial concentrations, the planet would still continue to warm. This is because the world's

annual mean surface air temperature due to an increment in radiative forcing that would result from sustained doubling of atmospheric CO_2 over its preindustrial value. This measure is typically characterised as a distribution due to underlying uncertainty in the behaviour of some aspects of the climate system. This parameter is relevant to real world atmospheric changes. With continued high emissions, we are likely to exceed a doubling of CO_2 (around 550 ppm) during this century compared to pre-industrial levels.

Studies based on observations, energy balance models, temperature reconstructions and global climate models (GCMs) have conclude that the probability density distribution of ECS peaks at around 3°C, with a long tail of small but finite probabilities of very large temperature increases. According to the IPCC's Fifth Assessment Report (IPCC 2013, WG1, Technical summary, p. 81), estimates of the ECS indicate that it is *likely*[2] to be in the range between 1.5°C to 4.5°C (with high confidence), *extremely unlikely* to be less than 1°C (high confidence) and *very unlikely* to be greater than 6°C (medium confidence).

Figure 2 shows the probability distribution of ECS using Roe and Baker's function[3] (Roe and Baker 2007) and calibrated to the recent IPCC AR5 estimations. It can be seen that there is a high probability (80%) that ECS will be in the range of 1.5 °C and 4.5°C. There is a low probability (8.2%) of ECS being below 2°C. However, there is also a probability (18.4%) of ECS of being greater than 4.5°C and a low probability (8.6 %) of it being greater than 6°C. These extreme temperature outcomes of the distribution function are sometimes referred to as "fat tails". Some authors (Weitzman 2009; Weitzman 2012) have proposed that decisions on climate policy should actually be based on trying to avoid extreme outcomes of low probability rather than on a cost-benefit analysis (CBA) based on the most likely outcomes. Therefore, any increase in

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oceans take longer to heat up in response to the enhanced greenhouse effect. The Equilibrium Climate Sensitivity (ECS) is the amount of warming that results when the entire climate system reaches 'equilibrium' or the stable temperature response to a doubling of CO_2. TCR and ECS are closely related measures of climate sensitivity, but TCR is always lower than ECS. When looking forward 100 or more years it is standard practice to use the ECS.

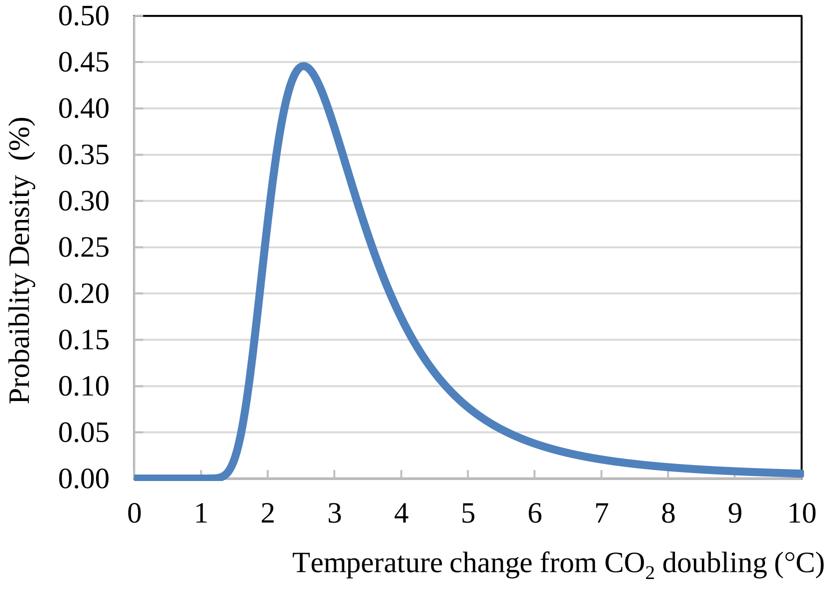
[2] IPCC 2013 Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0-10%, Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate.

[3] According to Roe and Baker (2007), and despite the enormous complexity of the climate system, the probability distribution of the ECS can be characterised by a normal distribution of the feedback parameter h(f) that ranges from 0 to 1. The uncertainties in measurements and in model parameterisations can be represented as uncertainties in the parameter f, where the average value is $\overline{f}$ and its standard deviation is σ_f. Equation 1 in Roe and Baker (2007), shows how uncertainties in feedbacks lead to uncertainty in the climate sensitivity response. The results in Figures 1 and 2 are obtained with the values ($\overline{f} = 0.61$ and $\sigma_f = 0.24$), which fit well with IPCC AR5 indications.

mitigation effort to avoid an extreme outcome can be defended as an insurance against catastrophic climate change risks.

Finally, it is important to mention that the uncertainty in characterising ECS has not changed substantially in recent decades. According to (Roe and Baker 2007), this is an “inevitable and general consequence of the nature of the climate system”. Moreover, they say: “foreseeable improvements in the understanding of physical processes, and in the estimation of their effects from observations, will not yield large reductions in the envelope of climate sensitivity. The relative insensitivity of the probability distributions to feedback factors is a likely reason why uncertainty in climate sensitivity estimates has not diminished substantially in the past three decades". Therefore, it can be concluded that ECS uncertainty is not expected to decrease much in the future.

Figure 2. Probability density distribution for ECS parameter



Source: Own work

3.3.2 Damage functions

One of the major sources of uncertainty in estimating economic damage from climate change is the way in which the damage from global warming is represented, i.e. the characterisation of the “damage function”. Damage functions are recognised as being one of the weakest links in the economics of climate change (Pindyck 2013), because it is very difficult to obtain empirical data given that we have never experienced a human-induced climate change. In most cases data are therefore based on expert opinion. Also, the results obtained from integrated assessment models (IAM) -oriented towards cost-benefit analysis (CBA) - can be very sensitive to the functional form of the damage function, particularly when high temperatures are considered.

In this subsection, we explore the uncertainty about the damage function by examining the most widely used functions: DICE (Nordhaus and Sztorc 2013) and the PAGE model (Hope 2006). These two models (together with the FUND[4] model) were used by the US Environmental Protection Agency (EPA 2010) to provide values for the damage that should be associated with CO_2. Additionally, in order to capture the possibility of an abrupt or catastrophic climate change, we include another damage function proposed by (Weitzman 2012), which describes a function with large impacts beyond a 4-6°C temperature increase. Weitzman motivates this function based on an expert panel study involving 52 experts according to which at this temperature change three out of five important tipping points (see Lenton et al. 2008) for major climate change events are expected to emerge. It is important to mention that these damage functions include the impacts after adaptation has occurred, so adaptation is already included[5].

Equation 1 captures the damage function used in the DICE model (Ω^N, Nordhaus and Sztorc 2013). Equation 2 captures the damage function used by the PAGE model (Ω^S) in the Stern Review report (Stern 2006). Finally, Equation 3 captures the function used by Weitzman[6] (Ω^W, Weitzman 2012). All these equations provide estimations of the losses measured as a fraction of future GDP, Ω (%), and for different globally averaged temperature changes ($\mathrm{T_{AT}}$), with different degrees of convexity. In the case of PAGE, the damage exponent (b_2) is treated as a random variable characterised by a discrete triangular probability distribution with a minimum of 1 (which results in a linear function) and a maximum of 3 (stronger convexity) and probabilistic analyses are then conducted of the values of these parameters. For the sake of simplicity here we use just the a two-point distribution ($b_2 = 1 \; or \; 3$ with equal probability p = 0.5)

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[4] We do not use the damage function from the FUND model because it is based on bottom-up estimations (Tol 2009), and, therefore, as far as we know, no functions are available in isolation. However, the DICE function is said to be calibrated as a starting point for the FUND damage function (Nordhaus and Sztorc 2013), with the monetized damage then being increased (by 25%) in order to account for non-monetised impacts such as the economic value of losses from biodiversity, extreme events and other uncertainties. This inclusion avoids the net positive effect of climate change for global temperatures below 2°C obtained by the FUND model, which also seems consistent with the last report of IPCC (IPCC 2014a) for the observed damage from climate change.

[5] Some authors (see, for example, Bruin, Dellink, and Tol 2009) have included the possibility of reducing damage through adaptation in IAM models so that they can therefore capture the trade-off between adaptation and mitigation.

[6] A comparison between DICE and Weitzman damage functions can be found in (Botzen and van den Bergh 2012).

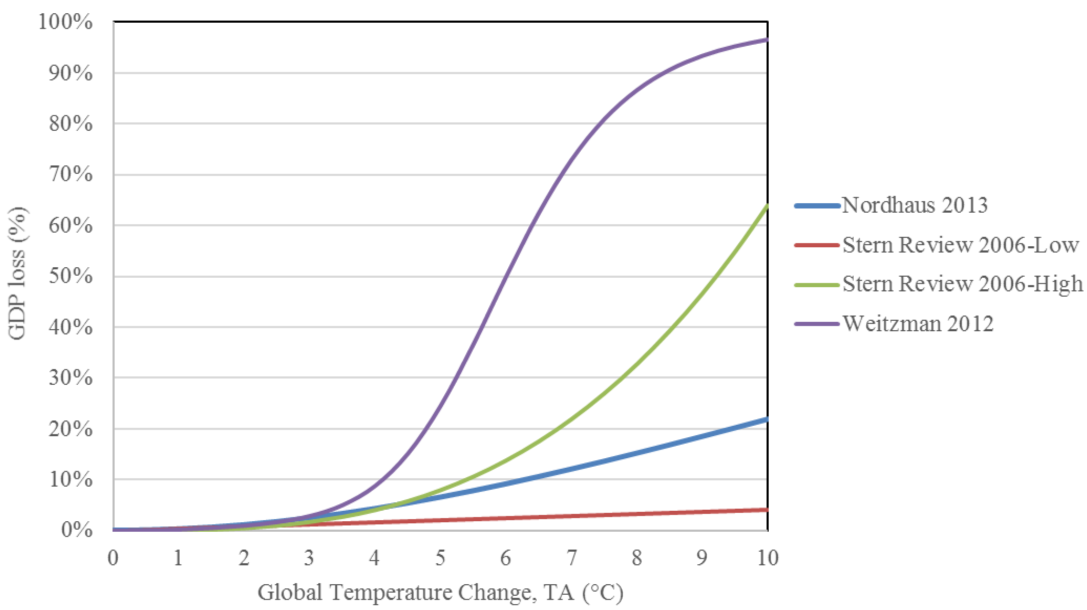
$$\Omega^N(t) = 1 - 1/[1 + a_1 T_{AT}(t) + a_2[T_{AT}(t)]^2] = \ 1 -/[1 + 0.0028[T_{AT}(t)]^2] \quad \text{(Eq. 1)}$$

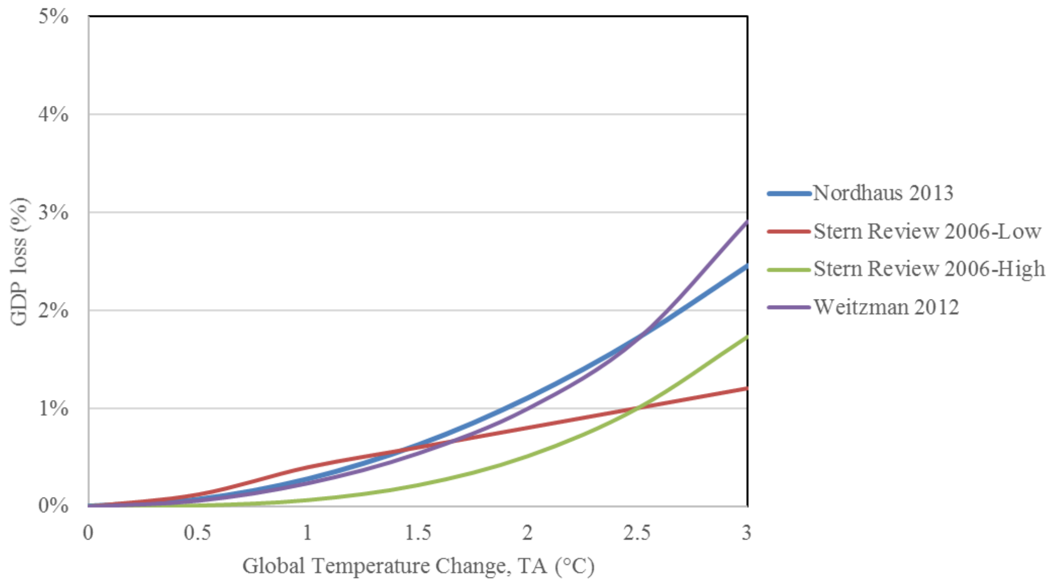
$$\Omega^S(t) = [T_{AT}(t)]^{b_2}/b_1] \ /100 = \ [T_{AT}(t)]^{b_2}/2.5]/100 \quad \text{(Eq. 2)}$$

$$\Omega^W(t) = 1 - 1[1 + [T_{AT}(t)/c_1]^{c_2} + [T_{AT}(t)/c_3]^{c_4}] = \ 1 - 1[1 + [T_{AT}(t)/20.46]^2 + [T_{AT}(t)/6.081]^{6.754}] \quad \text{(Eq. 3)}$$

Fig. 3 illustrates the different outcomes of these damage functions. Although hardly visible, the GDP fraction loss in Weitzman damage is slightly lower than Nordhaus damage for temperature increases from 0.5 up to 2°C. The damage function of Nordhaus lies between the two Stern functions. Finally, for the Weizmann damage function the impacts increase rapidly beyond the 4 °C temperature change and are around 50% of GDP at 6 °C. Most modellers advise that at higher temperatures the damage functions go beyond their useful limits. Nordhaus, for example, suggests that we have insufficient evidence to extrapolate reliably beyond 3°C ((Nordhaus 2013). However, it is also true that there is a significant risk of temperatures rising well above 3°C in the course of this century in the absence of climate policy, so temperatures of 3°C also need to be explored. In any case, we show in the figure 3 also a zoom into the 0-3°C.

Figure 3. Damage from climate change with different damage functions (% GDP)





Source: own work

Table 2 distributes the global damage by 2100 by regions for global estimates of each damage function (Nordhaus, Stern and Weitzman). The global damage is regionally weighted following the RICE-2010 regional model (Nordhaus 2014). The damages increase with the steepness of the damage function used and are expected to be higher (in terms of GDP%) than the average in regions including European Union, China, India and Africa. However, according to this disaggregation the damage experienced in some other regions such as Japan, Russia and Latin America will be lower than the average. It is important in any case to realise that the uncertainty related to aggregated damage is high and that the regional distribution of this damage is still poorly understood. Therefore, the damage shown in Figure 1 and Table 1 should also be considered just as an indication of the potential damage.

Table 2. Regional distribution of climate change damages in 2100 (%GDP)

	Nordhaus	Stern_Low	Stern_High	Weitzman
US	4.3%	1.6%	4.1%	8.9%
EU	5.2%	1.9%	4.9%	10.7%
Japan	1.0%	0.4%	0.9%	1.9%
Russia	0.4%	0.2%	0.4%	0.8%
Eurasia	0.4%	0.1%	0.3%	0.7%
China	6.7%	2.5%	6.4%	13.9%
India	4.9%	1.8%	4.7%	10.2%
Middle East	4.2%	1.6%	4.0%	8.7%
Africa	4.7%	1.7%	4.5%	9.6%

Latin America	2.9%	1.1%	2.8%	6.0%
ROW	5.1%	1.9%	4.9%	10.5%
Global	**4.3%**	**1.6%**	**4.1%**	**8.9%**

Source: Own work

It can be concluded that uncertainty in relation to damage functions can be huge and it its implications are critical. Our knowledge about the characterisation of damage functions is also very unlikely to improve in the future. On this basis, (Pindyck 2013) argues that given the huge uncertainty concerning damage functions Integrated Assessments (IAMs) tell us "very little" or even worse can "create a perception of knowledge and precision, but that perception is illusory and misleading". However, there are two things that are important to mention in this respect: first, that critique can only be applied to those IAMs which include damage functions and which are oriented towards a cost-benefit analysis (such as DICE, FUND or PAGE). There are many types of IAM that do not follow a cost-benefit approach and the "integration" of disciplines (in this case, the climate and economic systems) should be seen as a positive effort for a better understanding of the complex problem of climate change. Second, even in those IAMs that include damage functions (such as DICE, FUND or PAGE) the information that they provide could be useful if uncertainty is captured and the limitations of the results are explained properly. To that end, a sensitivity analysis on the exponent parameter of the damage function is unavoidable and a careful explanation of the result is necessary. Also more bottom-up analysis of the current damage of climate change is an also required. Moreover, the role of uncertainty in the damage function is less relevant in IAMs when they are used in low-carbon scenarios, as the damage increases with global temperature changes.

However, if these range of damage is compared with the cost of mitigation (see in Section 2.2, that show for a 2ºC stabilization a GDP or consumption loss of between 3-11% by 2100 relative to consumption in baseline scenarios), the values indicate that the damage is expected to be much higher, especially if non-linear behaviour and tipping points are considered.

3.3.3 Discount rates

Another major source of uncertainty is the rate at which the future benefits and cost are discounted from the present. The effect of this choice is relevant for projects with very long time-frames such as climate change (but also for other issues such the construction of long-lived infrastructures and for nuclear waste disposal). Whether the benefits of climate policy outweigh the costs depends crucially on the discount rate selected as the damage from climate change typically occurs in a more distant future than the cost of action.

According to Arrow et al. (2013) there are two rationales for discounting, one is consumption-based and the other is investment-based. The discount rate of consumption reflects the rate at which society is willing to trade consumption today for consumption in the future. The investment approach says that as long as the rate of return on investment is positive an incentive will be required in the form of interest payment for consumption today to be postponed. Under the investment approach the discount rate is the rate of return on capital and is determined by the market. However, the discount rate from the investment approach and the consumption approach may differ because the former is based on actual behaviour in the markets (positive approach) and the latter can also be based on ethical grounds (normative approach).

In the simplest deterministic economic standard Ramsey framework (Ramsey 1928), which provides the equilibrium rate of return in an optimal growth model with constant growth in population and consumption per capita without risk or taxes, the real interest rate (r) equals the pure rate of time preference (δ) plus the rate of growth of per capita consumption (g) times the consumption elasticity of the utility function (η). In the long-term equilibrium the following equation should hold:

$$r = \delta + \eta g \qquad \text{(Eq. 4)}$$

Financial data reflecting investors' decisions and macroeconomic data reflecting consumers' behaviour suggest that δ is in the range of 2 to 5%. However, some authors argue on ethical grounds that future generations should be treated equally, implying that the discount rate should be zero (Stern 2008). Finally, the elasticity of marginal utility, which measures risk aversion to inequality across generations, also has a normative component. If a positive approach is followed (similar to Nordhaus 2014) with $\delta = 1.5\%$ and $\eta = 2$) the real interest rate will be around 5%, which is closer to the real data, but that will also mean higher social discount rates. Alternatively, a normative approach could be taken (similar to Stern 2008, with δ=0.1% and η= 1) so the social discount rate will be low but so will the real interest rates.

A central point of the appropriate (long-term) social discount rate, therefore, is whether a normative approach (involving ethics and justice towards future generations) or a descriptive approach (involving observed returns on financial assets and real behaviour in the markets), or indeed a mix of both, should be used. (Drupp et al. 2015) find that although most experts think that both dimensions are relevant and should be considered, governmental institutions are recommended to place greater weight on normative issues. Drupp et al. (2015) record the values of key parameters associated with discounting based on a survey of 197 experts. Table 3 shows the values obtained for these parameters, among them the pure rate of time preference (δ) and the elasticity of marginal utility (η). The table shows that the experts disagree over the appropriate value for δ, with recommendations ranging from 0% to 8%, although most of them recommend intervals below 0.5. In the case of the elasticity of marginal utility (η) the most recommend value is 1. Finally, there is considerable disagreement between experts over the appropriate long-term social discount rate, with recommendations ranging from 0% to 10%. However, 92% of the experts surveyed are comfortable with an interval of 1% to 3%.

Table 3. Descriptive statistics on survey results on discounting

	Mean	StdDev	Median	Mode	Min	Max	N
Real growth rate per capita	1.7	0.91	1.6	2	-2	5	181
Pure rate of social time preference	1.1	1.47	0.5	0	0	8	180
Elasticity of marginal utility	1.35	0.85	1	1	0	5	173
Real risk-free interest rate	2.38	1.32	2	2	0	6	176
Normative weight	61.53	28.56	70	50	0	100	182
Positive weight	38.47	28.56	30	50	0	100	182
Social discount rate (SDR)	2.25	1.63	2	2	0	10	181
SDR lower bound	1.15	1.38	1	0	-3	8	182
SDR upper bound	4.14	2.8	3.5	3	0	20	183

Source: (Drupp, M.A., Freeman, M.C., Groom, B. and F. Nesje 2015)

Finally, the main issue concerning discounting is in reality whether discount rates based on "ethical" or on "market-based" values should be used when addressing long-term problems such as climate change. Most experts consider that both approaches should be considered, but that a normative approach is better for this type of long-term intergenerational problem. However, irrespective of the approach one still needs to choose a value. No consensus on the appropriate social discount rate can be expected in the near future, so a reduction in the uncertainty of this parameter is also unlikely.

3.4 Conclusion

Our analysis shows that the damage from climate change is greater than the cost of mitigation, even without considering some important co-benefits of mitigation (which will be explored in the TRANSrisk project). Additionally, the damage is much greater if the risks of crossing certain significant thresholds or tipping points are considered (using, for example, a Weitzman-type damage function). It is also important to notice that the damage is unevenly distributed among regions, although the regional effects of climate change are still poorly understood.

We also analyse the main uncertainties related to the quantitative estimations of the damage from climate change and conclude that the three main sources of uncertainty (the equilibrium climate sensitivity parameter, the damage function and the discount rate) are unlikely to decrease in the near future.

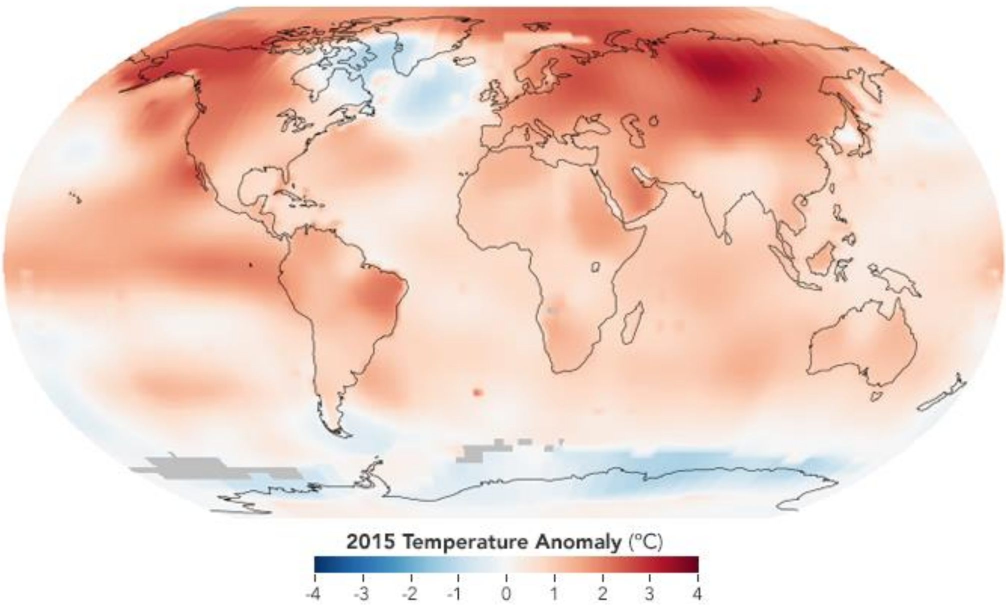
Finally, two future lines of research emerge from the analysis of this part of the report. First, it is important to start incorporating natural processes (or tipping-points) that have not yet been incorporated into economic models, especially in low-carbon scenarios that are likely to keep global warming below the 2 ºC limit (this will be done in the next two parts of this document). Second, given that uncertainty cannot be reduced much, it is important to consider the existing uncertainties and their interactions more consistently (to be explored in WP5). This is especially relevant as future climate damage figures, even if uncertain, will need to be used by governments (see EPA 2010 on the social cost of carbon) in evaluating public investment projects.

4 IMPLICATIONS OF PERMAFROST CARBON FEEDBACK FOR CLIMATE CHANGE CONTROL

4.1 Introduction

Permafrost (permanently frozen ground) is a major component of the Arctic region occupying 24% of the Northern Hemisphere's land surface (Zhang et al. 2008). It occupies about 60% of Russia, 50% of Canada, 23% of China and 90% of Alaska. Observed warming in the Arctic area during the last 30 years was as high as 3°C in parts of Northern Alaska and as high as 2°C in parts of the Russian European North between two to three times the global average (IPCC 2013), exposing more permafrost area to thawing (Figure 4).

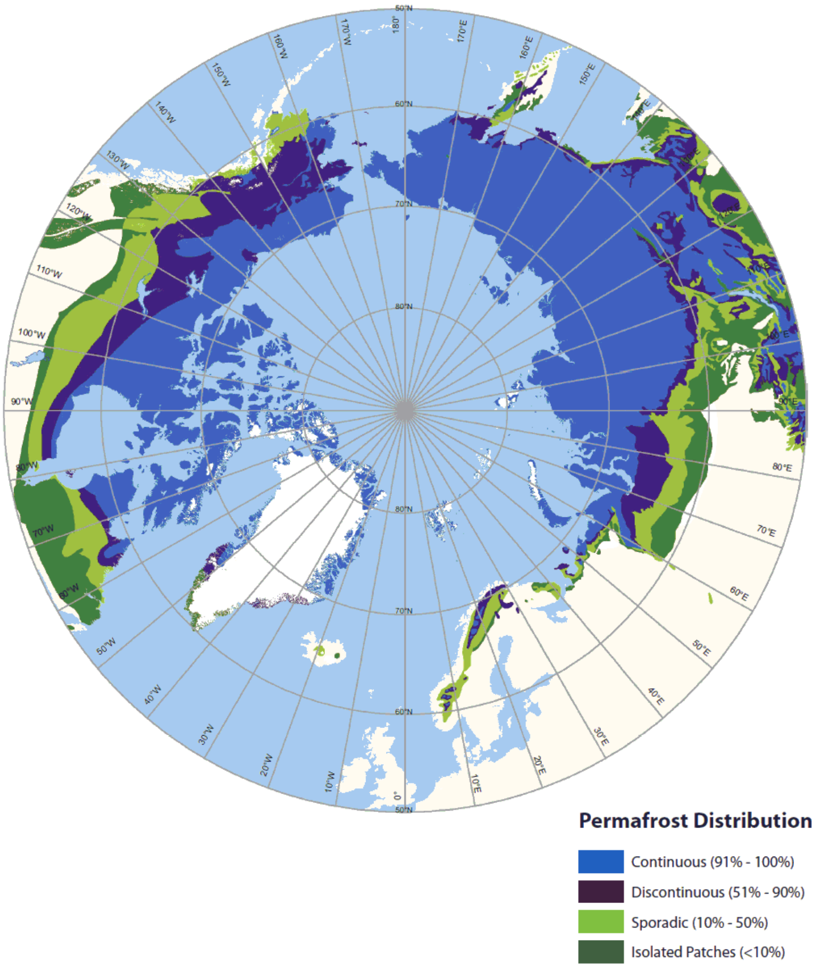
Figure 4. Temperature change in 2015 (compared to 1951-1980 average)



Source: NASA's Goddard Institute for Space Studies, 2015.

The permafrost in the northern circumpolar region is commonly divided into four broad zones depending on the intensity and extent of the permafrost: continuous, discontinuous, sporadic and isolated. Figure 5 shows the distribution of the various permafrost zones in the Arctic and sub-Arctic regions. The continuous zone makes up nearly 50% of the permafrost area and is mostly located in the northern latitudes and in the coldest climates. In the continuous zone permafrost is found essentially everywhere and the active layer (the layer susceptible to thawing and re-freezing) is generally less than 1 meter deep, as mean annual temperatures in this area (>75 ºN) are around -15 ºC. The discontinuous zone is located further south. In the discontinuous zone the depth of permafrost is lower and the active layer is more pronounced. Finally, the zones of sporadic and isolated permafrost, located between 65-75ºN, contain a limited and dispersed amount of fragmented permafrost but the active layer can be several metres thick as temperatures can reach 0 ºC. The thickness of the permafrost can range from a few tens of centimetres in the sub-Arctic regions to hundreds of metres (even as much as 1,400 m) in the north Arctic.

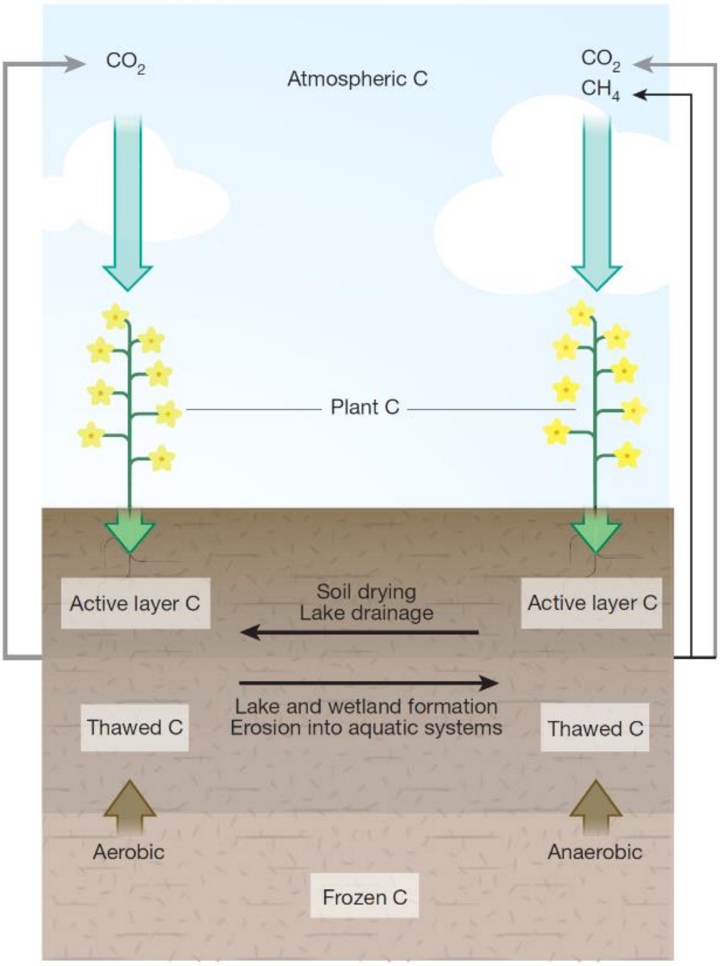
Figure 5. Distribution of permafrost zones in the Arctic and Sub-Arctic regions



Source: Soil Atlas of Northern Circumpolar Regions

A reduction in permafrost thickness and surface area is being observed (Brown and Romanovsky 2008). As previously frozen soils thaw, substantial quantities of organic carbon become available for decomposition by soil microbes. Figure 6 shows this mechanism following Schuur et al. (2015). In aerobic soils, CO_2 is released by microbial decomposition of soil organic carbon, whereas both CO_2 and CH_4 are released from anaerobic soils and sediments. Microbial breakdown of soil organic carbon can happen in the surface active layer, which thaws each summer and refreezes in the winter, and in the subsurface as newly thawed carbon becomes available for decomposition after it has emerged from the perennially frozen pool. The decomposability of soil organic carbon varies across the landscape and water conditions. Plants growing on previously frozen soils can uptake carbon emissions, which in part can offset the losses from soils. Figure 6 shows collapsed permafrost along the Alaskan coast exposing the three layers "frozen" "thaw" and "active" layer visible. Finally, thawing also opens up older stores of "geologic" methane trapped by glaciers and soil.

Figure 6. Illustration of permafrost carbon feedback effect



Source: Schuur et al. 2015

Figure 7. Picture of permafrost collapsed in the Alaskan coast

Source: Soil Atlas of Northern Circumpolar Regions

Permafrost contains twice as much carbon as is currently stored in the atmosphere (Zimov et al. 2006) and the release of a small fraction - in the form of carbon dioxide (CO_2) and methane (CH_4) - may lead to a positive feedback and increase the rate of future climate change (Burke et al. 2012). The first studies estimated a permafrost carbon pool of almost 1700 gigatons (Gt) (see for an overview Zimov et al. 2006). New lines of evidence (Schuur et al. 2015), based on recent observations, show that substantial amounts of carbon are also accumulated in deeper areas and that these are susceptible to future thaw (active layer). Recent evidence also suggests that the most likely process is a gradual and prolonged release of greenhouse gases (Schuur et al. 2015), but also indicating that a significant amount of carbon would be released in low emission pathways before 2100.

The extra warming caused by the permafrost carbon feedback (PCF) has been investigated (see MacDougall et al. 2012, Schneider von Deimling et al. 2012, Burke et al. 2012 and Schaefer et al. 2014). However, this feedback is not currently incorporated in economic assessment models (Stern 2016). The additional economic damage caused by permafrost carbon release was analysed (Hope and Schaefer 2015). In comparison to Hope and Schaefer's study which focused on economic damages, this part of the report examines the implications of permafrost thawing within a climate change control setting. More specifically, we estimate the additional efforts required to maintain a radiative forcing of 2.6 Watts per m^2 (Wm^{-2}) in 2100 when adding the extra emissions from permafrost thawing.

4.2 Scenarios

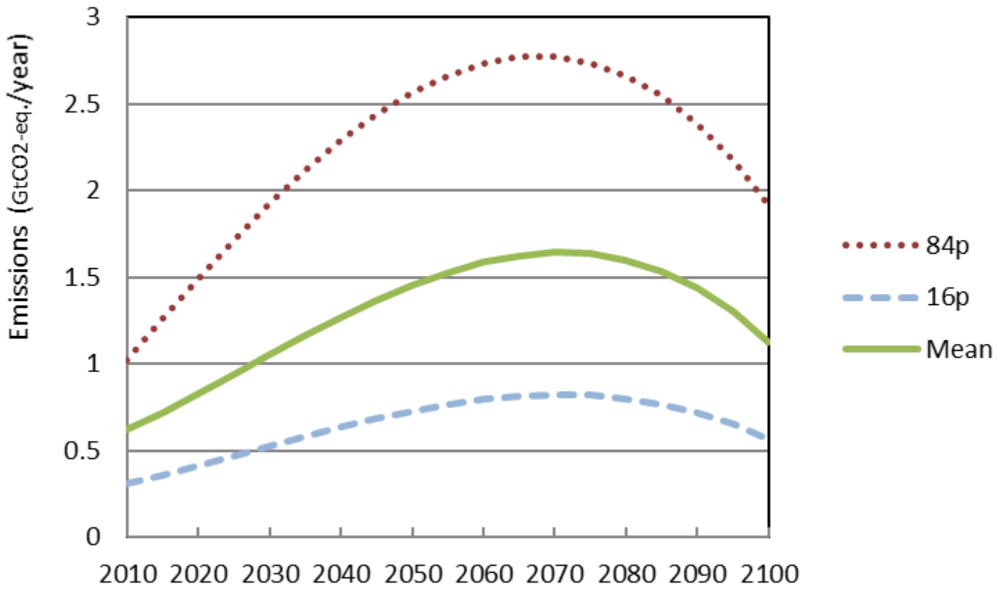
We set a radiative forcing target of 2.6 Wm^{-2} for the year 2100 (allowing for "overshooting" during the century) following the RCP approach used by IPCC (see IPCC 2013). We consider two scenarios: The first scenario does not consider the permafrost carbon feedback (*Scenario RCP2.6*) while the second one does (*Scenario RCP2.6_PCF*). *Scenario RCP2.6* introduces the constraint that the total radiative forcing should be equal to 2.6 Wm^{-2} in 2100, which according to IPCC (2013) corresponds to *likely*[7] remaining below a 2°C temperature increase. To be consistent with RCP scenarios from literature, we consider that the exogenous radiative forcing from non-CO_2 factors increases from 0.25 to 0.4 Wm^{-2} and that land-use emissions are reduced progressively to zero by 2100 (IIASA RCP database 2015, Van Vuuren et al. 2011). *Scenario RCP2.6_PCF* corresponds exactly to *Scenario RCP2.6* but includes emissions from permafrost. This scenario therefore requires that the emissions of fossil fuel and industrial CO_2 need to be reduced more to achieve the same climate target.

We use the study from Schneider von Deimling et al. 2015 which includes the most recent available projections of CO_2 and CH_4 fluxes[8] from thawing permafrost under the RCP2.6 scenario (Figure 8). In their estimation the emissions from permafrost peak during the second half of the century and then decline. The emissions continue beyond 2100; however as they are monotonously declining it is feasible to set a control target in 2100. The only source of uncertainty we include relates to the 68% confidence interval on the permafrost emission estimates by these authors. Although many other sources of uncertainty are present, the goal of our study is not to conduct a probabilistic analysis but to estimate how the expected permafrost carbon feedback impacts climate change with all other factors being equal.

[7] Note that according to some authors (Rockström et al. 2009) a 2.6 Wm^{-2} forcing could trigger "slow feedback" mechanisms or tipping points (Lenton et al. 2008) which may move the climate system beyond 2 °C.

[8] Methane was converted to CO_2-eq. using a Global Warming Potential factor of 34 (for 100-year time horizon), following the recommendation of IPPC (2013).

Figure 8. Emissions from permafrost for a RCP2.6 scenario ($GtCO_2$-eq/year)



Source: Own work based on Schneider von Deimling et al. 2015

4.3 Method

We use the Dynamic Integrated Climate-Economy model (DICE version 2013R, Nordhaus and Sztorc 2013), a well-known integrated assessment model (IAM) of climate-change economics (Nordhaus 1992, 2014, Butler et al. 2014, Moore and Diaz 2015). In this approach, society invests in capital goods, thereby reducing consumption today, in order to increase consumption in the future. Investing in emissions reduces consumption today but prevents future damage from climate change. In our study an optimal path for fossil fuel and industrial CO_2 emission reduction is sought that maximizes the net present value of cumulative economic welfare from 2010 to 2100 subject to a constraint[9] on radiative forcing (2.6 Wm^{-2} in 2100). In this approach economic welfare corresponds to net welfare, i.e. the damages[10] from climate change and the mitigation costs have already been deducted. More detailed technical

[9] In this study we set an exogenous constraint of 2.6 W/m^2; Notice that if the DICE model would be run without constraints the optimal value obtained will be beyond this level of radiative forcing (see Nordhaus and Sztorc 2013)

[10] The damages from climate change involve large uncertainties, especially for high emissions and large temperature changes (Pindyck 2013). However, here the choice of the damage function is less relevant as we analyse a low carbon emission scenario.

information on DICE can be found in Nordhaus and Sztorc (2013) and in the Appendix 1 at the end of this report.

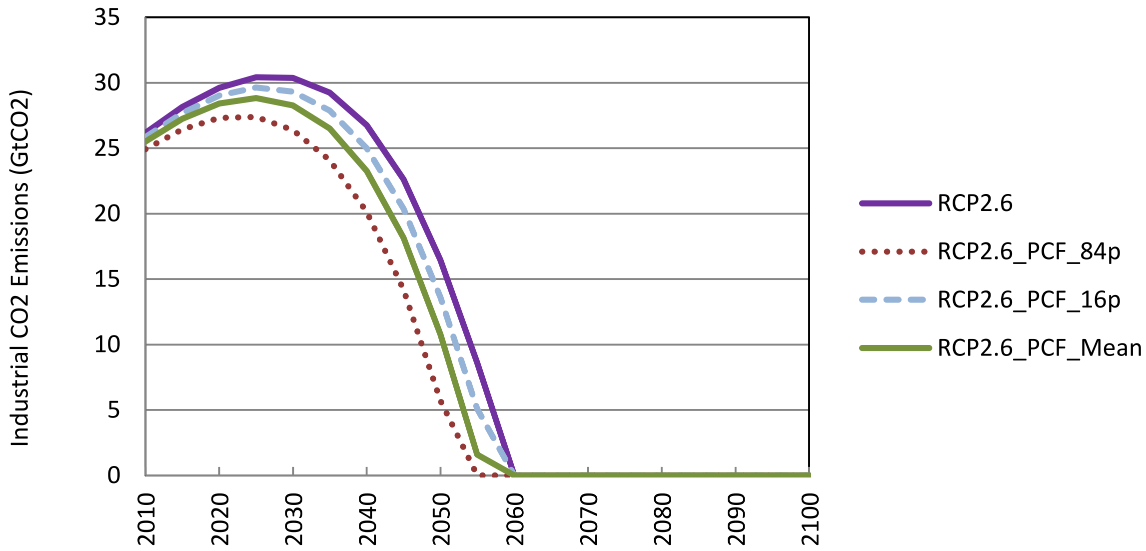
4.4 Results

Figure 9 depicts the resulting CO_2 emission pathways to reach the 2.6 Wm^{-2} climate change control target. The results indicate that in the presence of a permafrost carbon feedback the fossil fuel and industrial CO_2 emissions need to peak between 5 to 10 years earlier. The carbon budget needs to be reduced from 1,570 $GtCO_2$ to 1,420 [1,310-1,500] $GtCO_2$, equivalent to a 10 [5.7-16.5] % reduction (Figure 10). The CO_2 concentration in the atmosphere would be slightly lower during the entire century (Figure 11). The required reductions of fossil fuel and industrial CO_2 emissions of 149.1 [74.6-259.0] $GtCO_2$ are higher than the cumulative emissions generated along the century from permafrost (122.0 [61.0-211.0] $GtCO_2$-eq). This is because the overshooting potential is reduced (see Figure 12) due to the presence of continued emissions from permafrost in the second half of the century.

In summary, the presence of a permafrost carbon feedback requires that the reduction of fossil fuel and industrial CO_2 emissions needs to be greater and occur earlier. This implies that the price (tax) of carbon must be higher, both now and in the future (Figure 13). In the absence of the permafrost carbon feedback, the global price of CO_2 (assuming full participation) would need to rise from 36 US$/$tCO_2$ in 2015 to 180 US$/$tCO_2$ in 2050. In the presence of a permafrost carbon feedback the respective increase would need to be from 41[38-46] US$/$tCO_2$ in 2015 to 210 [200-240] US$/$tCO_2$ in 2050 (Figure 13).

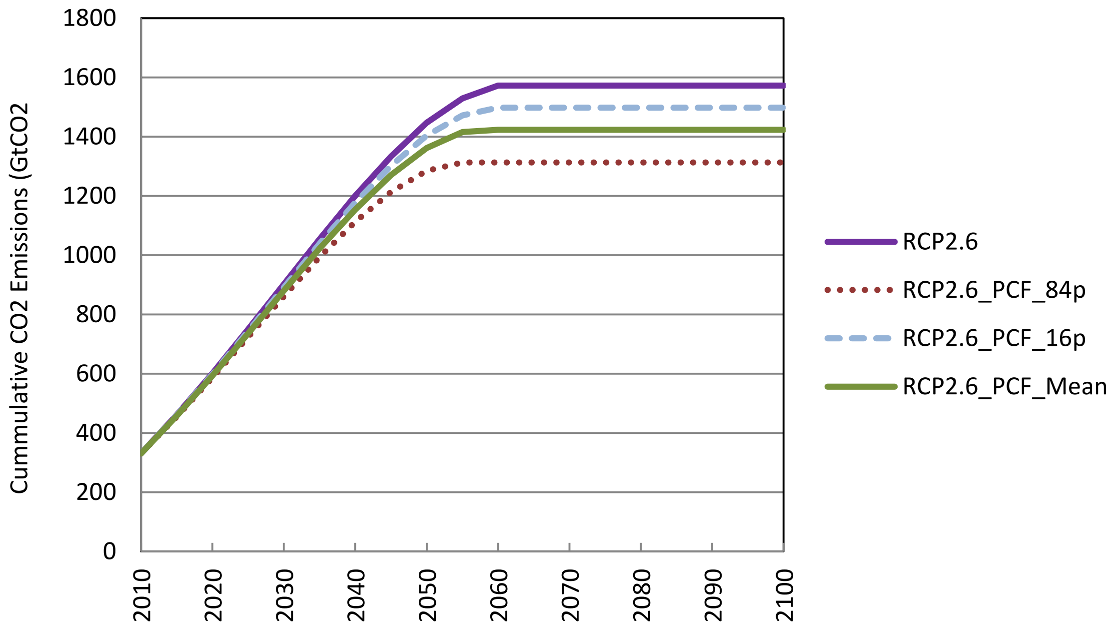
The higher carbon price implies higher costs to society. The presence of a permafrost carbon feedback would increase the mitigation cost from US$8.1 to US$9.0 [8.5-9.8] trillion, equivalent to a 6-21% increase (Figure 14). Devoting more resources to mitigation implies a reduction of consumption and investment, implying a loss in welfare. Our results show that the net present value of total welfare from 2010 to 2100 is reduced due to permafrost carbon feedback by US$ 4.2 [2-7.8] trillion.

Figure 9. Implication of PCF for fossil fuel and industrial CO_2 emissions ($GtCO_2$)



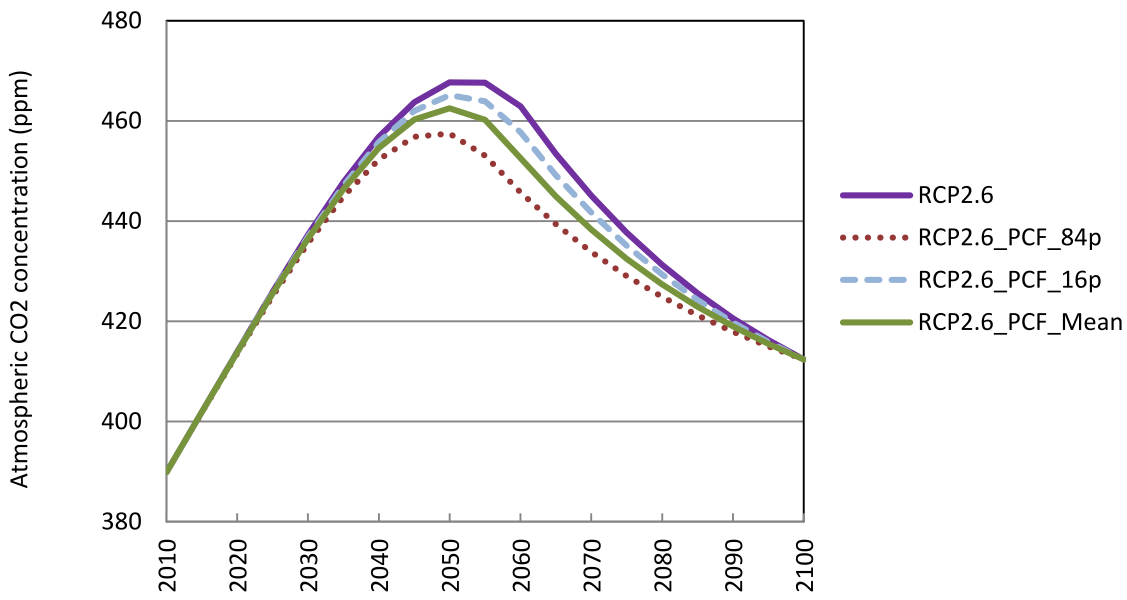
Source: Own work

Figure 10. Implication of PCF for cumulative fossil fuel and industrial CO_2 emissions ($GtCO_2$)



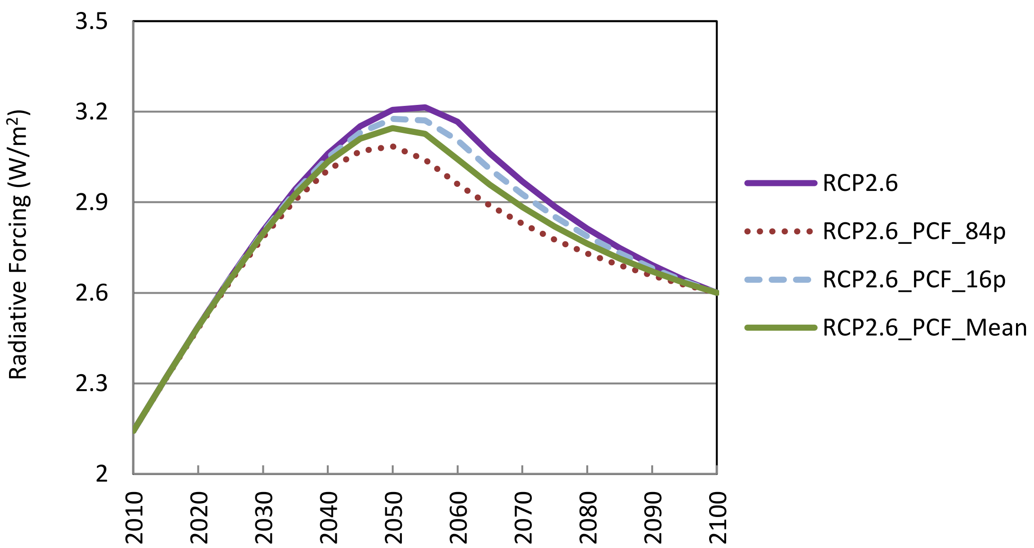
Source: Own work

Figure 11. Implication of PCF for CO_2 concentration in the atmosphere 2010-2100 (ppm)



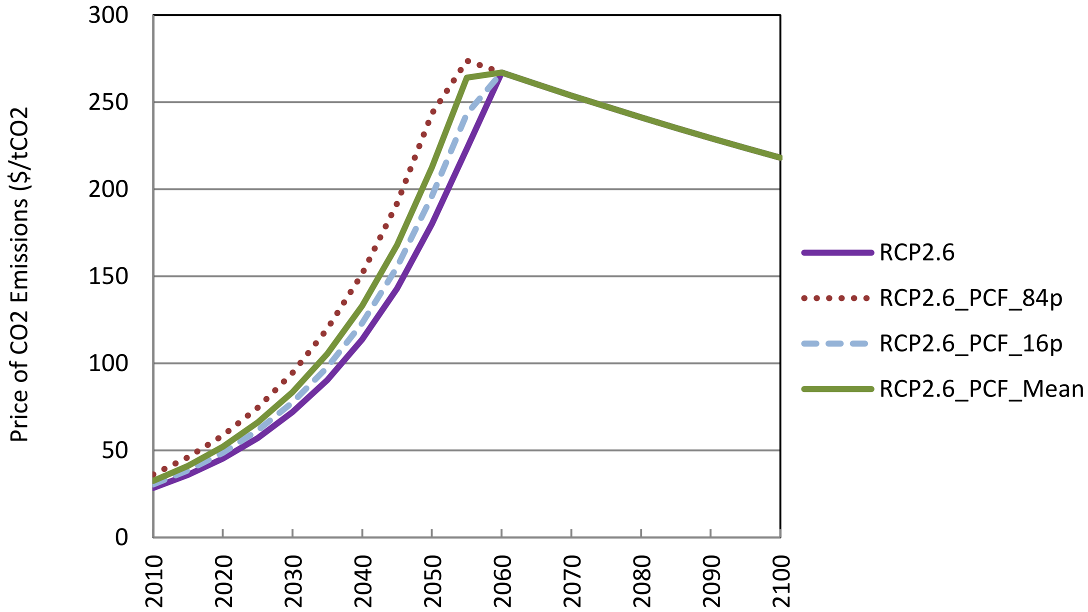
Source: Own work

Figure 12. Implication of PCF for radiative forcing 2010-2100 (w/m²)



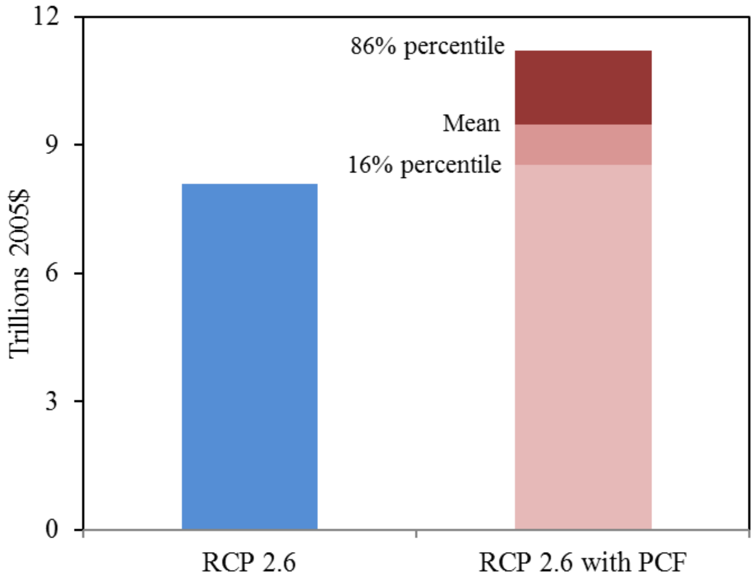
Source: Own work

Figure 13. Implication of PCF for carbon prices ($\$/tCO_2$)



Source: Own work

Figure 14. Implication of PCF for mitigation costs (Trillion 2005$)



Source: Own work

4.5 Sensitivity analysis for the mitigation cost

The mitigation costs obtained in our study are in the low range of the literature (see Clarke et al. 2014). There are two important factors explaining this result: the first being the discount rate[11] and the second the cost of the backstop technology[12]. To address this, we have studied (Table 4) the sensitivity of the mitigation cost towards changes in i) the pure rate of social time preference (ρ), which refers to the willingness of consumer to delay consumption, and ii) the cost of backstop technology (*pback*), which refers to the cost of a carbon-free technology that may not produce or reduce CO2 in the future

Table 4. Sensitivity analysis for the mitigation costs (Trillion USD 2005)

Cost of backstop technology (2005 US$/$tCO_2$)	Scenarios	Pure rate of social time preference (ρ, %)			
		0.1	1.5	3	0.1 *(Recalibrated)*
100	RCP2.6	8.3	2.4	0.8	2.5
	RCP2.6_PCF	8.8 [8.5-9.2]	2.7 [2.5-2.9]	0.9 [0.9-1.0]	2.7 [2.6-3.0]
	% change	*3-12%*	*5-20%*	*8-30%*	*5-21%*
344	RCP2.6	27.6	8.1	2.6	8.3
	RCP2.6_PCF	29.6 [28.6-31.5]	9.0 [8.5-9.8]	3.1 [2.9-3.5]	9.2 [8.7-10.0]
	% change	*4-13%*	*6-21%*	*8-32%*	*5-21%*
1000	RCP2.6	78.2	22.9	7.5	23.5
	RCP2.6_PCF	84.0 [81.0-88.6]	25.6 [24.2-27.8]	8.7 [8.1-9.9]	26.8 [24.8-28.4]
	% change	*4-13%*	*6-21%*	*8-32%*	*5-19%*

Source: Own work

[11] The discount rate is made up of two components: The pure rate of social time preference ρ and the rate of inequality aversion α. Following Nordhaus 2014, the decrease in social time preference to 0.1% is compensated for by increasing the risk aversion parameter from α = 1.45 to α = 2.1. Although there is an on going discussion if the social discount rates should be consistent with market discount rates (see Stern 2008 and Nordhaus 2014), this is an issue beyond the scope of this study.

[12] In DICE, this backstop technology is available at 344 US$/$tCO_2$ (2005 US$, at 100% removal) in 2010 declining at 0.5% per year. This effect can be observed in Figure 13 where the carbon price cannot increase beyond that limit.

The results for the default values of the DICE model (pure rate of social time preference of 1.5% and a backstop technology at $344 per ton of CO_2) have been described in the previous section. As expected, the mitigation costs increase for lower discount rates and for higher prices of backstop technology. In the case of a pure rate of social time preference of 0.1%, similar to the one used in Stern (2008) and a backstop technology price of 1000 US$/t$CO_2$, the present value of mitigation cost would be US$78.2 trillion for the RCP2.6 scenario and would rise to US$84.0 [81.0-88.6] trillion when including the permafrost carbon feedback. Conversely, with a pure rate of social time preference of 3% and with a backstop technology at 100 US$/t$CO_2$, the present value of mitigation cost would be US$0.8 trillion in the RCP2.6 scenario and US$0.9 [0.9-1.0] trillion when including the permafrost carbon feedback.

Following Nordhaus (2014), we include an additional scenario (*ρ=0.1% Recalibrated*), which refers to a situation where the decrease in pure rate of social time preference is compensated for by increasing the risk aversion parameter in order to maintain the market discount rate. As expected, the cost of mitigation is significantly lowered through recalibration and the results are very close to those obtained with ρ=1.5%.

The sensitivity analysis shows that the discount rate and the price of backstop technology significantly impact the mitigation costs. However, more importantly for our study, the relative additional mitigation costs are far less affected (see Table 4).

4.6 Conclusions

Much of the current evidence on permafrost thawing has appeared subsequently to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC 2014c) and has therefore not yet been included in the integrated assessment models (Schaefer et al. 2014). Our study shows significant consequences for climate change control. Thus the task of keeping warming below 2°C becomes more challenging when considering the additional emissions from thawing permafrost. It is important to realise that permafrost thawing may not be the only feedback due to rapid Arctic change (Duarte et al. 2012) currently excluded from integrated assessment models. Other examples are the possibility of an abrupt melting of hydrates beneath the East Siberian Sea (Shakhova et al. 2010 and Whiteman et al. 2013) or a possible underestimation of the albedo feedback effect due to sea ice melting (Pistone et al. 2014).

5 IMPLICATION OF SEA ICE ALBEDO FEEDBACK AND TIPPING POINTS IN THE ARCTIC

5.1 Introduction

The rapid decline of Arctic sea ice extent in the past few decades is one of the most visible indicators of global climate change. A better understanding of this process has been identified as a “grand challenge” for climate science (Kattsov et al. 2010) as it will have profound climatic (Liu et al. 2012), ecologic (Post et al. 2013), economic (Gautier et al. 2009; Smith and Stephenson 2013) and societal (Laidler et al. 2008) implications in the Artic region and globally (Duarte et al. 2012; Lenton et al. 2008; Lenton 2012). One of the more important effects of sea ice melting is the sea-ice albedo feedback which amplifies Arctic temperature change[13].

Since satellite data records began in 1978, the Arctic sea ice extent[14] has shown a significant decrease in all months. This decrease is most pronounced in September, corresponding to the end of the melt season. In September 2012, when the record minimum was recorded, the sea ice extent was 3.31 million km^2, equivalent to a 50% reduction compared to the sea ice cover during the early 1980s. On average, the sea ice extent declined at a rate of 6.5% per decade for the period of 1979-2001 but at 13.4% per decade for the period 1979-2015 (ARC 2015). The trend in sea ice extension can be observed in Figure 15. Figure 16 shows the minimum sea ice extension in September 2012 compared to the average sea ice minimum for the period 1980-2010 (yellow line).

The retreat in the extent of sea ice is part of an ongoing more abrupt decline in ice age, thickness and volume. The oldest ice (>4 years old) in March (when sea ice extent normally reaches its maximum) has declined from 20% of the ice pack in 1985 to only 3% in 2015(ARC 2015). First-year ice now dominates the ice cover, comprising around 70% of the March ice pack, compared to half that in the 1980s (ARC 2015). Figure 17 shows a time series of sea ice age in March from 1985 to 2015 and also a map of sea ice age in March 1985 (lower left) and March 2015 (lower right).

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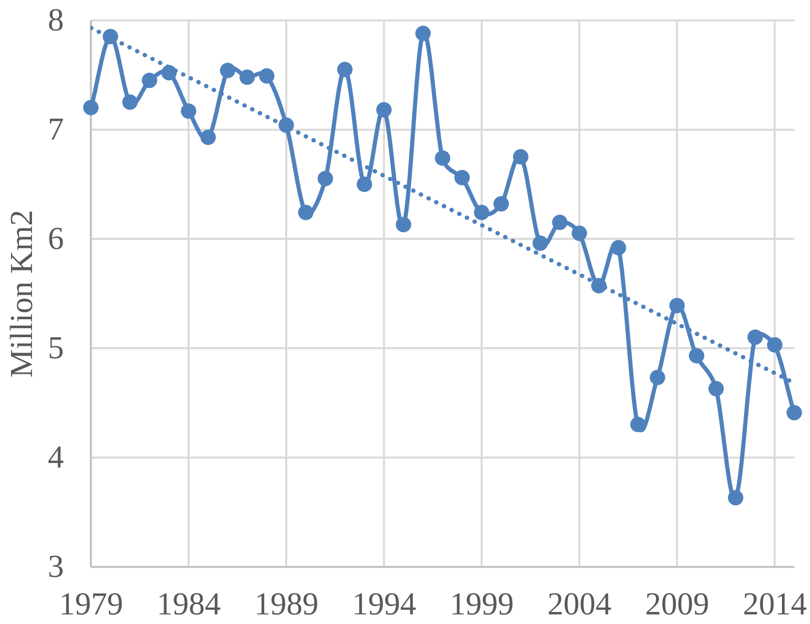
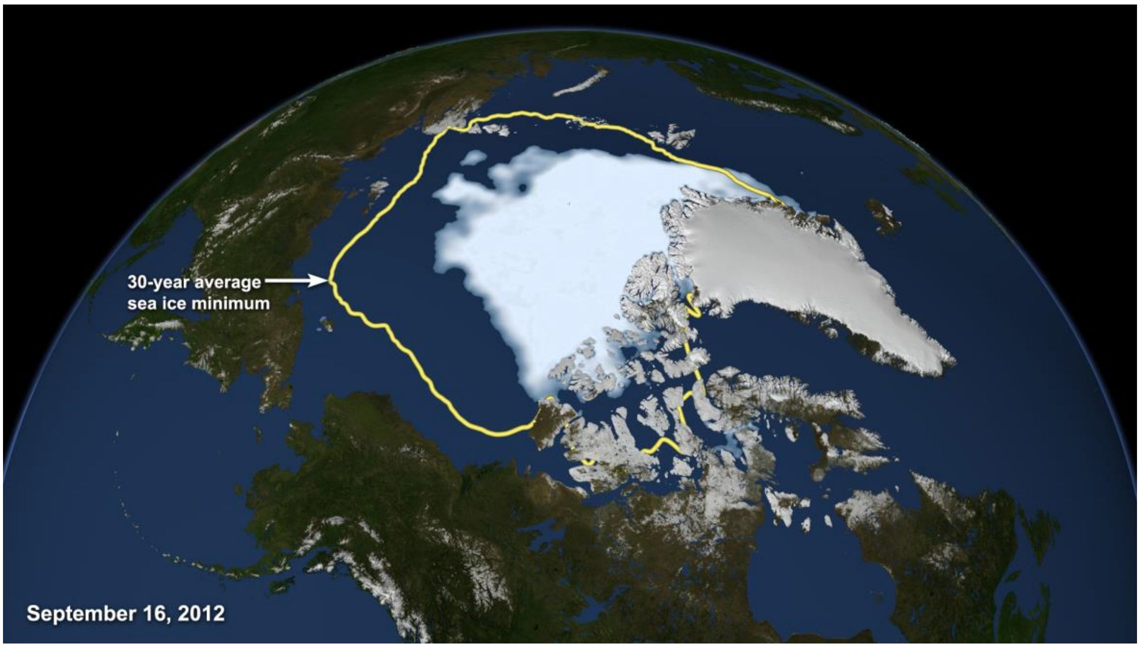
[13] Observed warming in the Arctic during the last 30 years has been between two and three times the global average (IPCC 2013a).
[14] Ice extent is defined as the area of the ocean with a fractional ice cover (i.e. an ice concentration) of at least 15%.

Figure 15. Average monthly Arctic sea ice extent in September 1979-2015 (Mkm^2)



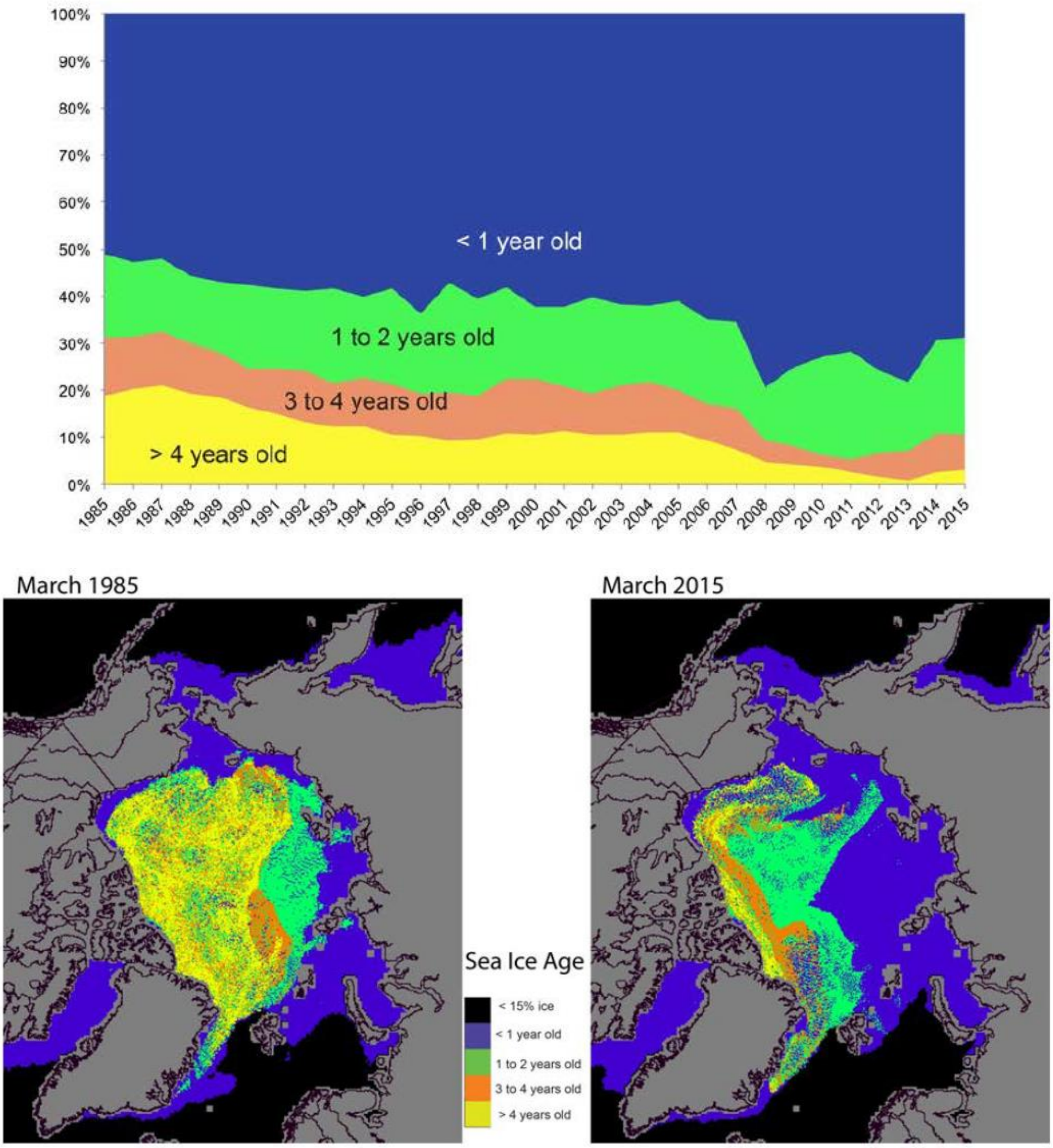
Source: National Snow and Ice data Centre (NSIDC)

Figure 16. Image of the minimum Arctic sea ice extension in 2012



Source: NASA

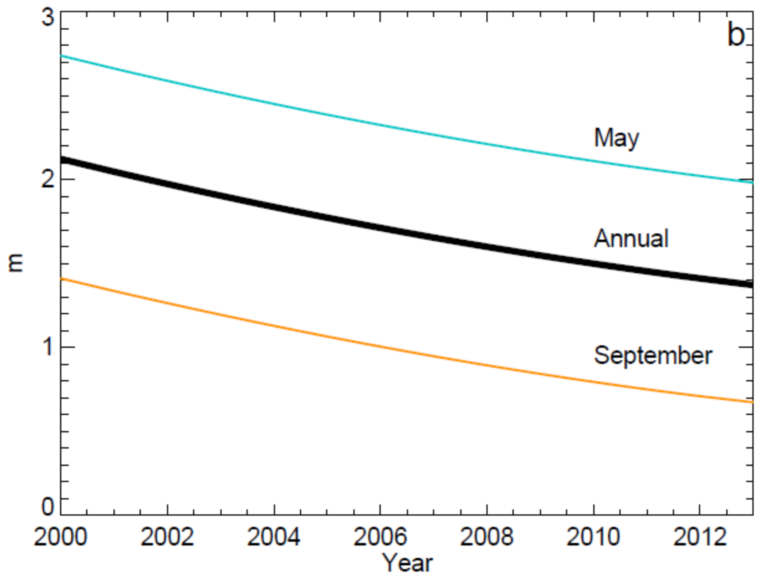
Figure 17. Arctic sea ice age in March 1979-2015



Source: Arctic Report Card (ARC 2015)

The annual mean ice thickness has been recently estimated (see Lindsay and Schweiger 2015) to have decreased from 3.5 m in 1975 to 1.2 m in 2012, a 65% reduction, and in September the mean ice thickness has thinned from 3 m to 0.44 m, an 85% decline. This trend is shown in Figure 18. Although there is some uncertainty in relation to the volume and thickness measures, most studies agree that the volume of ice has decreased around 70-80% since the 1980s and that most of this change may have occurred since 1995 (Maslowski et al. 2012).

Figure 18. Arctic sea ice thickness 2000-2012



Source: Lindsay and Schweiger 2015

An *ice-free summer*[15] in the Arctic is now expected to occur earlier than previously thought (Stroeve et al. 2007; J. C. Stroeve et al. 2012). Figure 19 provides estimations from IPCC AR4 and IPCC AR5 for the timing of the first ice-free summer. According to the IPPC AR5 models this may occur as early as 2040-2060 (IPCC 2013a) for an RCP8.5 scenario, although some models put it still earlier (Massonnet et al. 2012). An *ice-free summer* is also possible in an RCP2.6 scenario. In Hezel et al. 2014 this is the case for 3 out of 9 climate models with trends up to 2050 that are similar to[16] the trends in an RCP8.5 scenario. Other authors (Wang and Overland 2012; Overland and Wang 2013), who combine the information from climate models with observational data, suggest that an ice-free summer by the 2030s is more likely. Finally, using the estimated volume of ice as a trend for the future sea ice extent, some authors[20] project ice-free summers by 2020 or even earlier. Another possibility (Serreze, Holland, and Stroeve

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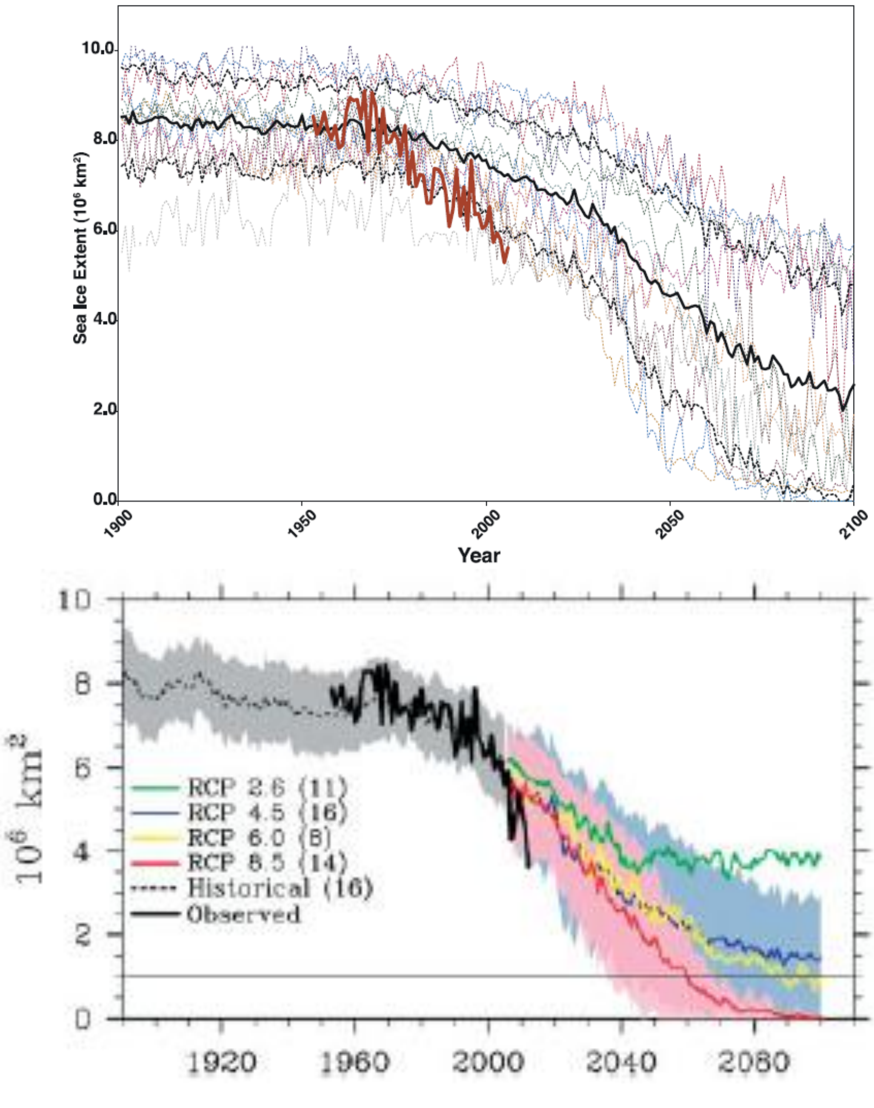
[15] "Ice free" is generally defined as a situation with less than 1.0 Mkm^2 of sea ice extension in the Arctic Ocean, as some ice will remain in the north of the Canadian archipelago and Greenland. However, notice that Hudson 2011 estimation later are based on fully free of ice.

[16] This is not the case for the second half of the century when the radiative forcing and global temperature will be very different. All of the 9 climate models that run RCP2.6 scenarios project an increase in sea ice extent in the second half of the century and beyond.

2007), due to the vulnerability of sea ice, is that an abrupt episode could trigger a faster transition.

Figure 19. Ice free summer protections by models in IPCC AR4 (2007) and AR5 (2013)



Source: Stroeve et al. 2007 and IPCC 2013

However, the relevant question that is starting to emerge (see Wang and Overland 2015) is not only when an *ice-free summer* will happen, but what will happen following such an event. Some authors (Barnhart et al. 2016; Wang and Overland 2015) provide estimations of the duration of open water in different areas of the Arctic and estimate that by 2050 the entire Arctic coastline and most of the Arctic Ocean will experience an additional 60 days of open water each year. The Barents, Nordic, Chukchi, and East Siberian Seas are expected to experience the biggest changes in the length and timing of the open water season (Barnhart et al. 2016). As stated above, one of the direct, important implications of ice-free or more open water conditions is the sea-ice albedo feedback effect.

The sea-ice albedo feedback (SIAF) refers to the process that is generated when ice (with high albedo/reflectivity) melts and more open water (with low albedo) is exposed to solar radiation, which absorbs more energy, generating a self-reinforcing warming mechanism. Although SIAF is not the only feedback mechanism associated to sea ice loss it has been identified to have a central role in recent Arctic temperature amplification (Screen and Simmonds 2010). Various studies have estimated the observed change in albedo due to sea ice melting (Riihelä, Manninen, and Laine 2013) and some have estimated the impact on regional or global radiative forcing. The global annually averaged radiative forcing caused by the observed sea ice loss in the Arctic between 1979 and 2007 is estimated (Flanner et al. 2011) to be around 0.11 Wm^{-2}. Hudson 2011 shows that a complete removal of Arctic sea ice would result in a forcing of about 0.7 Wm^{-2} and that "a more realistic ice-free summer[17] scenario", with no ice for one month (and linearly decreasing ice at all other times of the year), results[18] in a forcing of about 0.29 Wm^{-2}.

In this third part of the report we study the implications of mitigating climate change to below 2 ºC levels in the presence of rapid changes in artic sea-ice albedo. In line with other authors (Overland et al. 2014) who argue that in the first half of the century the sea ice process will not be affected much by the different mitigation pathways, we study the implications of sea ice-free month in September by 2050, as described in Hudson 2011. Although plausible given the current trends, this scenario can be considered to be a rapid transition by climate models. Based on the current debates about the potential recovery we consider three different pathways for the time beyond 2050: recovery, stabilisation or continued sea ice loss (or tipping-point).

5.2 Model

As in the second part of this report, we use the Dynamic Integrated Climate-Economy model (DICE version 2013R, Nordhaus and Sztorc 2013), an integrated assessment model (IAM) for analysis of the economic implications of different climate pathways

17 In Hudson 2011 the estimations are based on fully free ice extent in the Arctic.

18This effect only captures the sea-ice albedo feedback. Caldeira and Cvijanovic (2014) estimate that if all feedbacks (positive and negative) in the long-term are considered a totally sea-ice free situation will produce a net radiative global forcing of about 3 Wm-2.

(Nordhaus 1992; W. Nordhaus 2014; Moore and Diaz 2015; González-Eguino and Neumann 2016). The model weights the cost and benefits of investing in emission reduction and reducing present consumption, but preventing future damage from climate change. In our study an optimal path for fossil fuel and industrial CO_2 emission reduction is sought that maximises the net present value of cumulative economic welfare from 2010 to 2100 subject to a constraint on radiative forcing. In this approach economic welfare corresponds to net welfare, i.e. the damage[19] from climate change and the mitigation costs have already been deducted. We provide more detailed information about the model in the *Supplementary Materials* (in Appendix 1).

5.3 Scenarios

These scenarios explore the implications of a hypothetical and stylised transition towards an entire ice-free month in September by 2050, as described in Hudson 2011, with 3 different transitions after 2050: stabilisation, recovery and further sea ice loss (no-recovery). Figure 20 shows the extra radiative forcing from the sea-ice albedo feedback (SIAF) associated with each scenario. We focus on the additional efforts required to maintain a radiative forcing of 2.6 Watts per m^2 (Wm^{-2}) in 2100, which according to IPCC corresponds to *likely*[20] remaining below a 2°C temperature increase. The first scenario constitutes the baseline scenario whereas the following scenarios add additional forcing from the sea ice albedo changes. The scenarios can be summarised as follows:

- Scenario RCP2.6 is the baseline scenario and represents (van Vuuren et al. 2011) a mitigation scenario aiming to limit the increase in global mean temperature to 2°C until 2100. The scenario introduces the constraint that total radiative forcing should be equal to 2.6 Watts per m2 (Wm-2) in 2100. To be consistent with RCP scenarios from literature (van Vuuren et al. 2011; IIASA 2015) we consider that the exogenous radiative forcing from non-CO2 factors increases from 0.25 to 0.4 Wm-2 and that land-use emissions are reduced progressively to zero by 2100.

[19] The damage from climate change involves large uncertainties, especially for high emissions with large temperature changes (Pindyck 2013) However, here the choice of the damage function is less relevant as our analysis focuses on a low carbon emission scenario. For an analysis of the implications for a high carbon scenario see the Supplementary Materials (in Appendix 2).

[20] Note that according to some authors (Rockström et al. 2009) a 2.6 Wm^{-2} forcing could trigger "slow feedback" mechanisms or tipping points (Lenton et al. 2008) which may move the climate system beyond 2 °C.

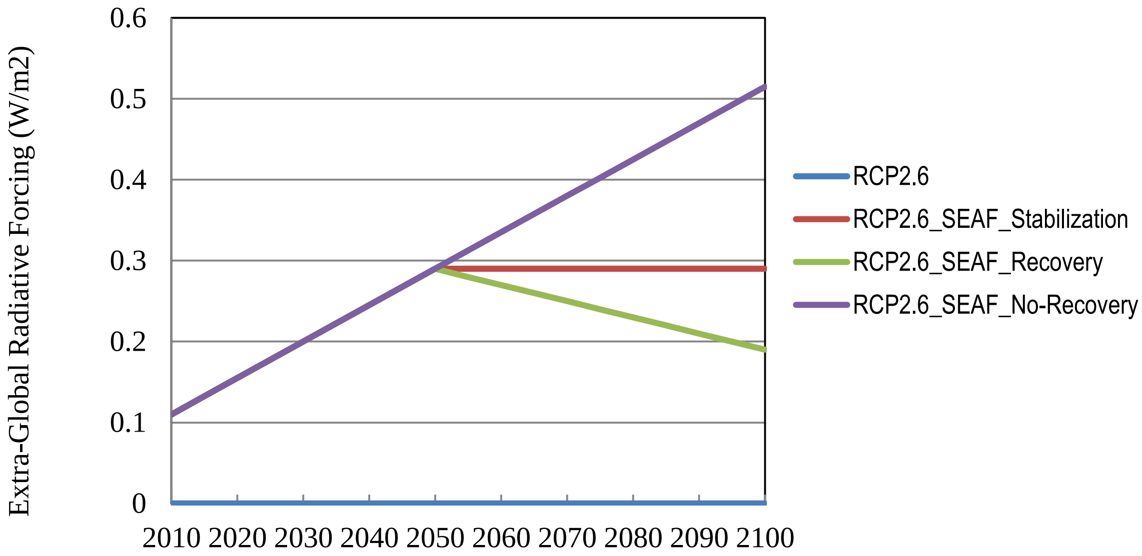
- Scenario RCP2.6_SIAF_Stabilisation: This scenario shows a linear increase from current extra radiative forcing due to sea ice loss (0.11 Wm-2) to a forcing of 0.29 Wm-2 in 2050, associated with an ice-free September, based on Hudson 2011. After 2050 the sea ice is assumed to stabilise at that level until 2100. The stabilisation process could be considered to be more consistent with the current climate models of a RCP2.6 scenario (Hezel, Fichefet, and Massonnet 2014) that show that the sea ice did not show recovery on timescales up through 2100.

- Scenario RCP2.6_SIAF_Recovery: This scenario is similar to Scenario RCP2.6_SIAF_Stabilisation, but shows a much faster recovery. Although different criteria could be used here, we assume a recovery that takes place at half of the speed of loss during the period of 1980-2050 (-0.0021 Wm-2y-1) leading to an additional forcing of 0.19 Wm-2 in 2100, as Figure 20 shows. This recovery process could be considered to be more consistent with current literature (Tietsche et al. 2011; Notz 2009; Serreze 2011) that shows that sea ice could be reversible and may recover quite quickly in a climate that is getting cooler as the ice–albedo feedback is offset by other large-scale recovery mechanisms.

- Scenario RCP2.6_SIAF_No-Recovery: This scenario is similar to Scenario RCP2.6_SIAF_Stabilisation, but with a continued trend of sea-ice loss. The extra radiative forcing levels increase to 0.51 Wm-2 in 2100. This could be considered to be more consistent with the current literature (Holland et al. 2008; Wadhams 2012) that shows that a threshold or a tipping point may exist in this process.

Given the uncertainty related to sea-ice melting we work with “stylized” scenarios that try to capture current debates in scientific literature on artic sea ice. These scenarios can be replaced as better estimates become available. We do not include in these scenarios the different sources of uncertainty discussed in Hudson 2011 (e.g. changes in cloud cover). The goal of our study is therefore to show how climate stabilisation would be affected due to these “stylised” scenarios of additional radiative forcing due to artic sea ice loss.

Figure 20. Extra radiative forcing from SIAF scenarios (Wm-2)



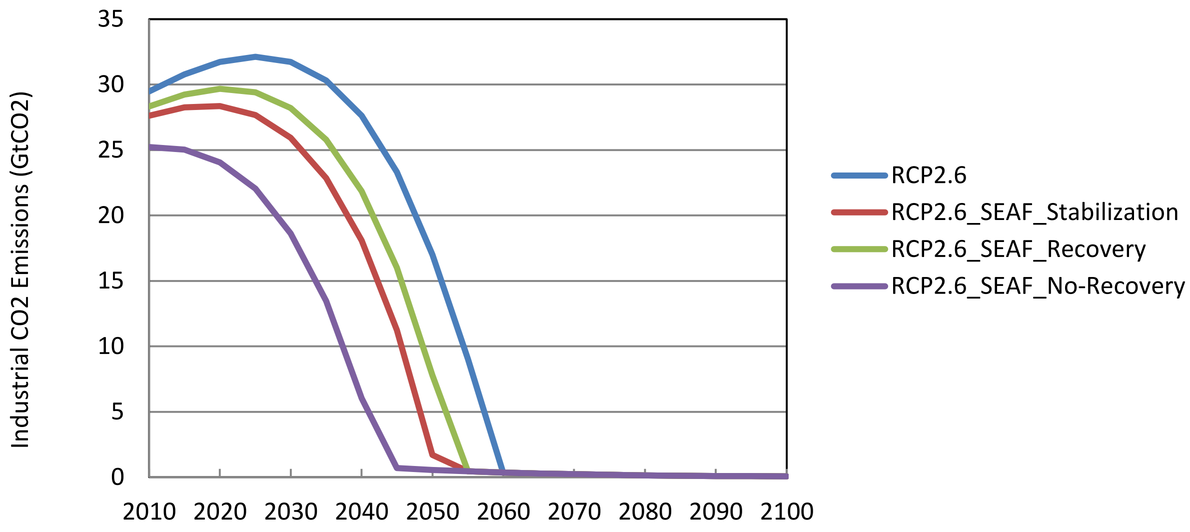
Source: Own work

5.4 Results

Figure 21 depicts the resulting CO_2 emission pathways to reach the 2.6 Wm^{-2} climate change control target due to the extra warming associated with one month free of ice by 2050. The results for fossil fuel and industrial CO_2 emissions need to peak around 10 years earlier in the case of a stabilisation transition (*RCP2.6_SIAF_Stabilisation*) and 5 years in the case of a recovery transition (*RCP2.6_SIAF_Recovery*). However, in the case of continued sea ice loss (*RCP2.6_SIAF_No-Recovery*) emission should have already peaked by now. Notice that as the model is solved for the period 2010-2100, the optimal path of emissions for all scenarios (also in the *RCP2.6 scenario*), emissions in the period 2010-2015 should be lower than the current emissions if the target is to be achieved at the least cost.

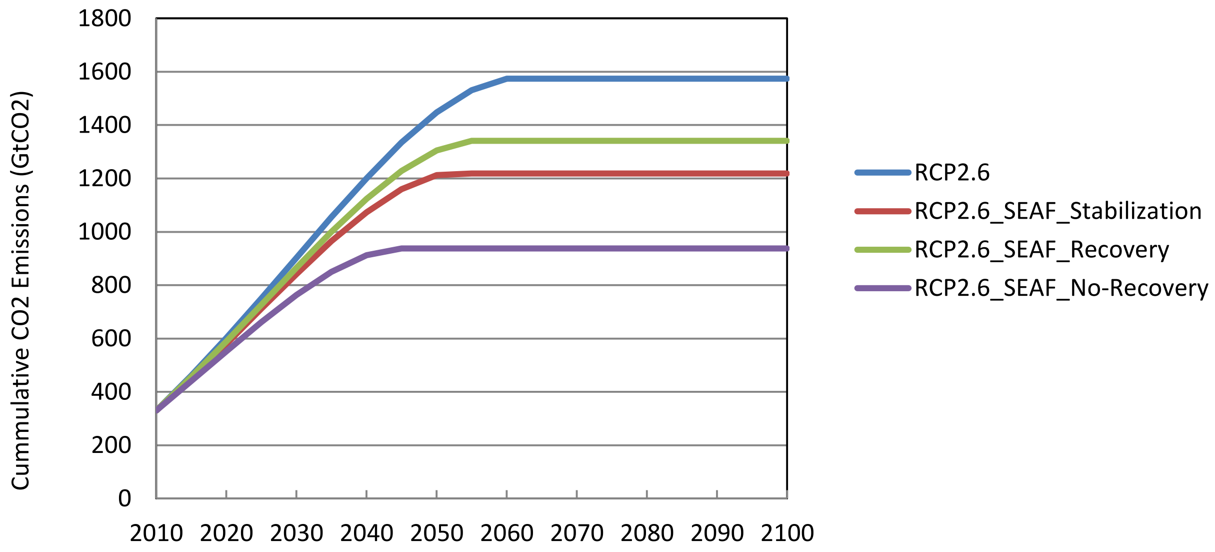
The carbon budget needs to be reduced from 1,570 $GtCO_2$ (*RCP2.6)* to 1,341 $GtCO_2$ (*RCP2.6_SIAF_Recovery*), to 1218 $GtCO_2$ (*RCP2.6_SIAF_Stabilisation*) and to 938 $GtCO_2$ (*RCP2.6_SIAF_No-Recovery*), equivalent to 14.8%, 22.6% and 40.4 % reductions (Figure 22). The CO_2 concentration in the atmosphere would need to peak earlier and be lower during the entire century (Figure 23). Only in the *RCP2.6_SIAF_Recovery* scenario can the CO_2 concentration surpass 450 ppm for a short period of time. This is possible because there is a larger overshooting potential in this scenario (see Figure 24), given that the extra-radiative forcing from SIAF is decreasing in the second half of the century.

Figure 21. Implication of SIAF for fossil fuel and industrial CO_2 emissions ($GtCO_2$)



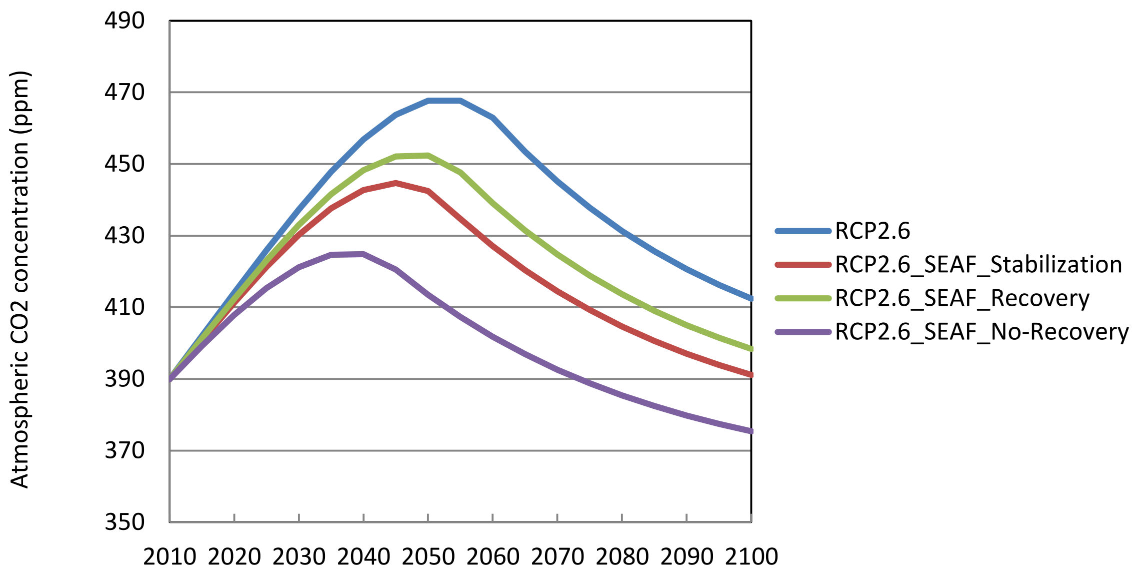
Source: Own work

Figure 22. Implication of SIAF for cumulative fossil fuel and industrial CO_2 emissions ($GtCO_2$)



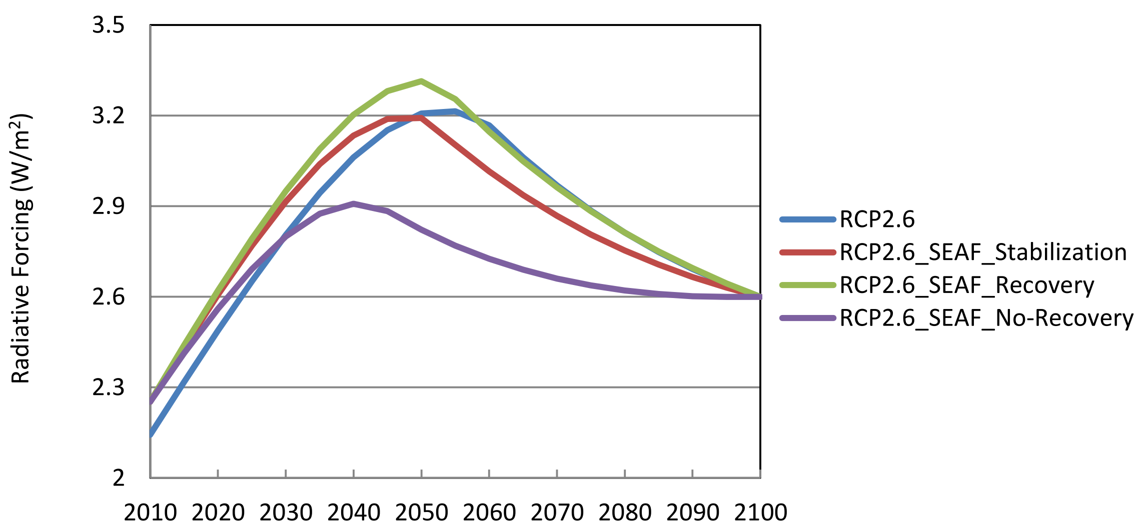
Source: Own work

Figure 23. Implication of SIAF for CO_2 concentration in the atmosphere 2010-2100 (pmm)



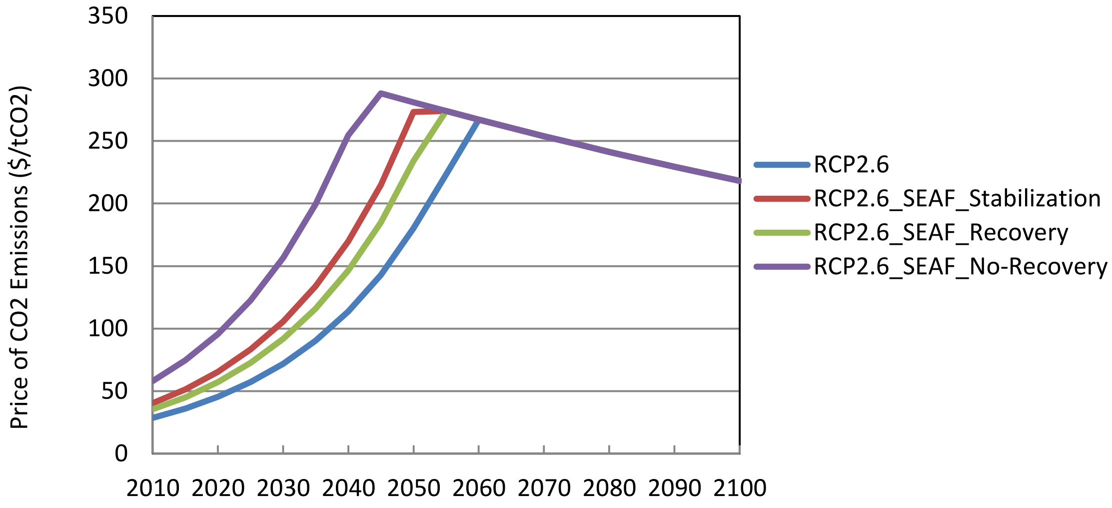
Source: Own work

Figure 24. Implication of SIAF for radiative forcing 2010-2100 (w/m^2)



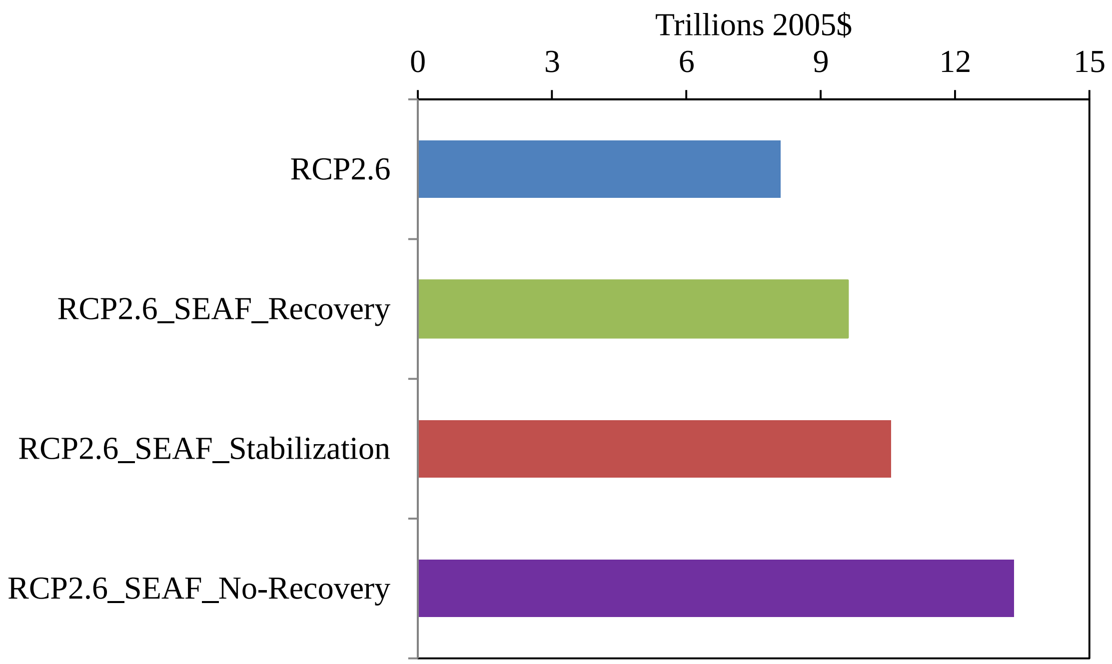
Source: Own work

Figure 25. Implications of SIAF for carbon prices ($/t$CO_2$)



Source: Own work

Figure 26. Implications of SIAF for mitigation costs (Trillion 2005$)



Source: Own work

In summary, the future sea ice melting and associated radiative forcing increase from sea-ice albedo feedback is translated directly into a more stringent reduction of fossil fuel and industrial CO_2 emissions. This also implies that the price of (tax on) carbon needed to achieve that transition must be higher, both now and in the future (Figure 25). Notice here again that the global price of carbon (or its equivalent in terms of regulation) for all scenarios should be much higher than today's price if the target is to be achieved at the least cost.

The stringent mitigation policy and the higher carbon price implies higher costs for society. The presence of sea-ice albedo feedback would increase the mitigation cost from US$8.1 trillion, to US$9.6 trillion (*RCP2.6_SIAF_Recovery*), US$10.6 trillion (*RCP2.6_SIAF_Stabilisation*) and US$13.1 trillion (*RCP2.6_SIAF_No-Recovery*), equivalent to cost increases of 19%, 30% and 64 % (Figure 26). The absolute mitigation costs obtained with the DICE model are in the low range of the literature (Clarke et al. 2014). One of the main reasons is the existing backstop technology[21], which puts an upper limit on the cost of CO_2 mitigation (as Figure 25 shows) and also the discount rate which are set to match the observed market values (around 4%).

Finally, devoting more resources to mitigation implies a reduction of consumption and investment, implying a loss in net welfare. Our results show that the net present value of total welfare from 2010 to 2100 is reduced due to sea-ice albedo feedback in our scenarios by US$8.3 trillion in *RCP2.6_SIAF_Recovery* (-4% with respect to *RCP2.6*), by US$12.5 trillion in *RCP2.6_SIAF_Stabilisation* (-6%) and by US$25.1 trillion (-25%).

5.5 Sensitivity analysis for timing of sea ice free conditions

As explained above, our scenarios are stylised scenarios with the aim of exploring the implications of a hypothetical transition towards a month free of ice in September 2050. However, there is much uncertainty in relation to this timing (Hudson 2011). In this section we perform a sensitivity analysis on the date for a full month free of ice between 2040 and 2060. The extra radiative forcing from Figure 20 is changed following a linear trend that would achieve a radiative forcing of 0.29 Wm^{-2} for each specific date and continuing until 2050. After 2050 the same recovery/stabilisation/no-recovery trend of scenarios of section 2 is applied, as the first column of Table 5 shows. The rows associated with the year 2050 correspond to the scenarios *RCP2.6_SIAF_Stabilisation*, *RCP2.6_SIAF_Recovery* and *RCP2.6_SIAF_No-Recovery*.

[21] In DICE, this backstop technology is available at US$344/t$CO_2$ (2005 US$, at 100% removal) in 2010 declining at 0.5% per year. This effect can be observed in Figure 25, where the carbon price cannot increase beyond that limit.

Table 5. Sensitivity analysis on the timing of month free of ice

	Extra-RF 2050/2100 (Wm-2)	Peak Emissions ($GtCO_2$)		Carbon Budget 2010-2100 ($GtCO_2$)		Carbon price 2020 (2005\$/tCO_2)	
RCP2.6	0/0	30.4		1573.6		45.4	
RCP2.6_Recovery							
2060	0.25/0.15	28.4	-6.7%	1386.0	-11.9%	54.4	+19.8%
2055	0.27/0.17	28.1	-7.7%	1366.1	-13.2%	55.7	+22.6%
2050	0.29/0.19	27.7	-8.8%	1341.3	-14.8%	57.3	+26.1%
2045	0.32/0.22	27.3	-10.3%	1309.4	-16.8%	59.4	+30.7%
2040	0.35/0.25	26.8	-12.0%	1267.2	-19.5%	62.2	+37.0%
RCP2.6_Stabilisation							
2060	0.25/0.25	26.7	-12.1%	1262.4	-19.8%	62.4	+37.5%
2055	0.27/0.27	26.5	-12.8%	1242.8	-21.0%	63.8	+40.4%
2050	0.29/0.29	26.2	-13.7%	1218.4	-22.6%	65.5	+44.2%
2045	0.32/0.32	25.9	-14.9%	1186.8	-24.6%	67.9	+49.5%
2040	0.35/0.35	25.3	-16.9%	1143.7	-27.3%	72.0	+58.6%
RCP2.6_No-Recovery							
2060	0.25/0.43	23.8	-21.8%	1039.5	-33.9%	82.3	+81.3%
2055	0.27/0.47	23.2	-23.6%	994.8	-36.8%	87.5	+92.7%
2050	0.29/0.52	22.4	-26.4%	938.0	-40.4%	95.8	+110.9%
2045	0.32/0.57	21.3	-29.9%	865.5	-45.0%	106.9	+135.4%
2040	0.35/0.65	19.7	-35.1%	768.1	-51.2%	127.3	+180.4%

Table 5 shows that mitigation needs to be more stringent the earlier the date of the first ice-free month. Fossil fuel and industrial CO_2 emissions need to peak at 28.4 $GtCO_2$ in the least stringent scenario and 19.7 $GtCO_2$ in the most stringent scenario, a reduction of 6.7 and 35.1% compared to RCP2.6. The carbon budget needs to be reduced from 1,386 $GtCO_2$ to 768.1 $GtCO_2$, a reduction of 11.9-51.2% compared to the RCP2.6.

5.6 Conclusions

Arctic sea ice is a key indicator of global climate change because of both its sensitivity to warming and its role in amplifying climate change due to the sea-ice albedo feedback effect. Recent trends in sea ice extent and volume in the Arctic have shown very rapid, unexpected losses. Our study shows the significant consequences for climate stabilisation using stylised scenarios of a rapid arctic sea ice loss.

Our results show that the sooner a sea-ice free month occurs and the less optimistic we are about the future recovery of sea ice the more difficult it will be to stabilize climate change as stated in the Paris Agreement. The emission reductions and carbon prices increase significantly. Sea ice extent is a very well-monitored process and if in the coming years events such as those in 2007 and 2012 are more recurrent, this study can provide valuable information on the window of opportunity that mitigation can offer and how the carbon budget should be affected.

It is important to realise that sea-ice feedback is not the only feedback occurring in rapid Arctic change (as we have seen in the second part of this report) and that these processes have not been captured by Integrated Assessment models (Stern 2016). It is also important to mention that some studies consider that the warming associated to sea-ice albedo feedback due to sea ice melting may be greater than current estimations[22].

[22] Some authors (Pistone, Eisenman, and Ramanathan 2014) have recently estimated that in 1979–2011 there was an average increase of 0.21 ± 0.03 Wm^{-2} over the whole planet, double the estimates by Hudson 2011 and Flanner 2011.

6 GENERAL CONCLUSIONS

In summary, this report shows the relevant economic implications of inaction, which are much higher than the cost of mitigation, even without considering its potential co-benefits. We show that the uncertainties associated with these estimations are very large and, unfortunately, are unlikely to decrease in the near future. In the second part, the report shows the effects of two major risks for climate change control to low levels of temperature change: permafrost thawing and summer sea ice melting in the Arctic. We show the relevant economic and mitigation implications of these two processes due to the extra warming effect that they will generate. If these two processes, which have not been considered to date in economic models, are factored into the analysis more stringent mitigation efforts and more acute climate policies will be needed in order to keep the rise in global temperatures below 2 ºC.

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7 APPENDIX

7.1 Appendix 1

We present here the major equations of the DICE model fully based on Nordhaus and Sztorc 2013 and Nordhaus 2014. DICE is a global integrated assessment model that represents the economic, policy and scientific aspects of climate change. It integrates the climate system in the framework of economic growth theory. In this approach, society invests in capital goods, thereby reducing consumption today, in order to increase consumption in the future. Investing in emissions reduces consumption today but prevents damage from climate change and increases consumption possibilities in the future.

The model optimises a social welfare function, W (Eq. 1), which is the discounted sum of the population-weighted utility of per capita consumption. In this function, c(t) is the per capita consumption, L(t) is the population, and $R(t) = (1 + \rho)^{-t}$ is the discount factor of utility or welfare. ρ is the pure rate of social time preference or generational discount rate. The utility function is a constant elasticity function with respect to consumption of the form $U(c) = c^{1-\alpha} / (1 - \alpha)$. The parameter α is interpreted here as the generational inequality aversion.

$$W = \sum_{t=1}^{T} U[c(t), L(t)]R(t). \quad (1)$$

Net output, Q(t) (Eq. 2), is the gross output, Y(t), reduced by damage, $\Omega(t)$, and mitigation costs, $\Lambda(t)$. This net output, a function of capital, labour and technology that explains economic growth, can be devoted to consumption, C(t), and investment, I(t). Labour is proportional to population, while capital accumulates according to an endogenous savings rate.

$$Q(t) = \Omega(t)[1 - \Lambda(t)]Y(t) = C(t) + I(t). \quad (2)$$

Damage from climate change, which is subject to large uncertainties, is represented in the DICE model by a quadratic function of globally averaged temperature change (T_{AT}). The damage function is defined as $\Omega(t) = D(t)/[1 + D(t)]$, where

$$D(t) = \psi_1 T_{AT}(t) + \psi_2 [T_{AT}(t)]^2. \quad (3)$$

The abatement cost (Eq. 4) is a function of the emissions reduction rate, μ(t), and is estimated to be highly convex, indicating that the marginal cost of reductions rises from zero more than linearly with the reduction rate:

$$\Lambda(t) = \theta_1 [\mu(t)]^{\theta_2}. \quad (4)$$

Total emissions, $E(t)$ (Eq. 5), are fossil fuel and industrial emissions plus land-use change emissions, ELAND(t) and $E_{PER}(t)$ is an exogenous forcing associated to the permafrost. Fossil fuel and industrial CO_2 emissions are determined by the level of carbon intensity, σ(t), times gross output, and reduced by the emissions reduction rate, μ(t). The only type of emissions subject to (endogenous) control in the DICE model is fossil fuel and industrial CO_2.

$$E(t) = \sigma(t) Y(t)[1 - \mu(t)] + E_{LAND}(t) + E_{PER}(t) \quad (5)$$

The geophysical equations link the greenhouse gas emissions to the carbon cycle, radiative forcing and temperature change. These equations are calibrated for the 21st century to large models or model experiments 2 and have been updated (version 2013R) in line with AR5 of the IPCC (for example, in the current version, the equilibrium climate sensitivity has been reduced from 3 to 2.9). Equation (6) represents the equations of the carbon cycle for three reservoirs (j = AT, UP, and LO): atmosphere, upper oceans and biosphere, and lower oceans. All emissions flow into the atmosphere and the parameters φij represent the flow of carbon between reservoirs per period.

$$M_j(t) = \varphi_{0j} E(t) + \sum_{j=1}^{3} \varphi_{i,j} M_i(t-1). \quad (6)$$

Finally, the relationship between CO_2 concentrations and increased radiative forcing is given by

$$F(t) = \eta\{\log_2[M_{AT}(t)/M_{AT}(1750)]\} + F_{EX}(t) + F_{EXARC}(t) \quad (7)$$

Where F(t) is the change in total radiative forcing of greenhouse gases from anthropogenic sources, FEX(t) is an exogenous forcing (which includes non-CO_2 emissions and aerosols) and $F_{SIAF}(t)$ is an exogenous forcing associated to the sea-ice albedo feedback effect. For simplicity and transparency, we keep all aspects of the original DICE model unaltered. In this way, our results can easily be compared to previous findings obtained with the same model.

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7.2 Appendix 2

Here we complement our analysis of the sea-ice albedo feedback effect of 1 month free of ice in September by 2050 with an estimation of the future damage that may result from it in a high carbon emission scenario (RCP8.5[23]). Recent studies (Hezel, Fichefet, and Massonnet 2014; Bathiany et al. 2016) indicate that in an RCP8.5 scenario 7 out of 9 climate models project nearly free ice condition in winter before 2200 and 3 of them by 2100. Therefore, we use the scenario with no-recovery (see Figure 1), which is more consistent with high emission pathways. The upper bound provided by Hudson of 0.7 $Wm^{-}2$ for a full year free of ice in the Arctic is still below the extra radiative forcing to achieve the selected scenario by 2100.

Estimations of the economic damage from climate change must be performed and interpreted with caution. Different studies have shown that these results are very sensitive (Pindyck 2013), for example, to the choice of the damage function (Moore and Diaz 2015), especially beyond 2 ˚C. Although these techniques have been helpful in illustrating the economic damage from climate inaction under different circumstances (Moore and Diaz 2015; Butler et al. 2014) and when different feedbacks are included (such as thawing permafrost(Whiteman, Hope, and Wadhams 2013; Chris Hope and Schaefer 2015)), these huge uncertainties and the possibilities of a tipping point or no linearities being crossed need to be addressed and recognised. Therefore, our analysis, following a similar approach to ref (Ackerman, Stanton, and Bueno 2010), uses three different well-known damage functions (Nordhaus_2013, Stern_2008[24] and Weitzman_2012[25]) and three values for the Equilibrium Climate Sensitivity[26]: 1.5, 2.9 (central value of DICE2013 model) and 4.5.

Table A1 shows the economic impact associated with the sea-ice albedo feedback (SIAF). The changes in temperature due to the SIAF effect (2.8 to 3.0 ˚C in ECS=1.5; 4.4 to 4.7 ˚C in ECS=2.9; and 5.5 to 5.9 ˚C in ECS=4.5) are translated into increasing damage. The Gross Domestic Product (GDP) losses by 2100 therefore increase as the values for ECS increase and with the steepness of the damage function. The damage per annum may increase by just 0.2% in the best case scenario (Nordhaus_2013 and EC2=1.5) and by 8.9% in the worst (Weitzman_2012 and EC2=4.5). Notice than in some situations the extra damages can be higher than the global economic growth.

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[23] This scenario is characterized as a business as usual scenario leading to a radiative forcing of 8.5 Wm^{-2} in 2100.

[24] The Stern Report uses the PAGE models, which perform a Monte Carlo analysis for the exponent of the function using a triangular probability distribution with a minimum of 1 and a maximum of 3. To simplify matters here we just take the maximum value of 3.

[25] Weitzman describes a function with large impacts beyond a 4-6 ˚C temperature increase. Weitzman motivates this function based on an expert panel study involving 52 experts according to which at this temperature change three out of five important tipping points(Lenton et al. 2008a) of major climate change events are expected to emerge.

[26] According to the IPCC's Fifth Assessment Report this is the *likely* range (>66%) for this parameter. Its uncertainty(Roe and Baker 2007) has not decreased much in the last few decades.

Table A1. Economic impact (% GDP in 2100) from a full month with the Artic free of ice in RCP8.5. The table shows the results for alternative damage functions and Equilibrium Climate Sensitivity (ECS) parameters

	ECS=1.5		ECS=2.9		ECS=4.5	
	No_SIAF	SIAF	No_SIAF	SIAF	No_SIAF	SIAF
Nordhaus_2013	2.1%	2.3%	5.1%	5.8%	8.1%	9.2%
Stern_2008	1.4%	1.7%	5.4%	6.5%	10.8%	12.9%
Weitzman_2012	2.3%	2.8%	13.5%	17.8%	37.3%	46.2%

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