The global economic impacts from permafrost thawing in the Arctic region

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This thesis is submitted for the degree of

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Abstract

The Arctic is warming at more than double the global average. This has resulted in physical impacts in the region including the melting of perennially frozen ground (permafrost) which holds almost twice the carbon in the atmosphere.

Permafrost thawing is not explicitly modelled in most of the latest climate models, which informs the Intergovernmental Panel on Climate Change Sixth Assessment Report (AR6). Hence, the temperature projections from AR6 which are extensively used to inform policymakers and stakeholders in the public and private sector, could underestimate the projected physical and economic impacts.

This thesis makes three contributions. First, it introduces a framework for assessing the global economic impacts from climate change in the Arctic region. Second, it describes PAGE22, an integrated assessment model which was developed to incorporate a permafrost carbon emulator and the persistent effects of temperature on economic production. The latter is complementary to the PAGE-ICE IAM which only includes level effects and smaller economic damage estimates than PAGE22. Third, it describes PAGE22-SCCO2, another version of PAGE22 to estimate the social cost of carbon dioxide - used as a proxy for carbon tax in policy.

The permafrost carbon feedback modelled in PAGE22 increases the mean temperature values in 2300 by 0.17-0.38 °C and the social cost of carbon dioxide by 2-9% under the SSPX-RCPY scenarios. The persistent effects of temperature on economic production increase the mean global impacts in 2200 from 1-53 USD trill. to 104-1,000 USD trill. and the social cost of carbon dioxide in 2020 up to almost 9 times under the SSPX-RCPY scenarios.

Through these contributions, this thesis expands the body of literature on climate change economic impacts. The tools developed can be used to assess how the physical impacts from climate change in the Arctic and beyond can translate into regional and global economic impacts.

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Author's declaration page

I declare that, to the best of my ability, this thesis is the result of my own work unless specified otherwise within. It has not been submitted in substantially the same form for the award of a higher degree elsewhere. Excerpts of this thesis have been published as indicated within. The word length of the thesis does not exceed the maximum permitted length of 80,000 words including appendices, references, and footnotes.

María Jimena Alvarez

For my beloved children, Félix and Delfina, and husband, Cristian

Chapter 1 - Introduction

1.1. Motivation

Global mean temperature has risen by 1.1°C since pre-industrial times due to an increase in greenhouse gases emissions mainly from anthropogenic activities (WMO,2020). This has resulted in a myriad of detrimental impacts on ecosystems and society as well as contributed to increase inequality (IPCC,2022). Future impacts will depend on how much more greenhouse gases result from anthropogenic activities as well as which positive climate feedbacks[1] are expected to contribute to further temperature increases.

1.1.1. Arctic amplification

In recent decades the Arctic region has been experiencing temperature increases more than double of the global average (IPCC, 2013; Overland et al., 2015). This is referred to as Arctic amplification and is driven by a series of positive climate feedbacks particular to the Arctic including the melting of sea ice and snow – surface-albedo feedback – and an increase in heat transport from the atmosphere and the ocean

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[1] *"An interaction in which a perturbation in one climate quantity causes a change in a second and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is enhanced. The initial perturbation can either be externally forced or arise as part of internal variability."* (IPCC, 2021b, page 2222)

towards the pole (Pithan and Mauritsen, 2014; Goosse et al., 2018; Dai et al., 2019; Feldl et al., 2020; Forster et al., 2021). The are several physical impacts stemming from Arctic change, including melting of the Arctic Sea ice, melting of the Greenland icesheet and glaciers, and permafrost thawing, all of which affect the Arctic and the rest of the world.

The melting of the Arctic Sea ice has increased substantially over the past four decades (Fox Kemper et al., 2021) and is projected to likely decrease to below 1 million square metres in September – "ice-free" – by 2050 (Notz and SIMIP Community 2020; Fox Kemper et al., 2021). The expected repercussions range from local impacts on ecosystems (Wassmann et al., 2011), particularly species that depend on the icesheet such as polar bears, through to global impacts on ocean acidification, caused by an increase in CO_2 uptake by the Arctic Ocean resulting from an increase in sea ice loss (Bates and Mathis, 2009).

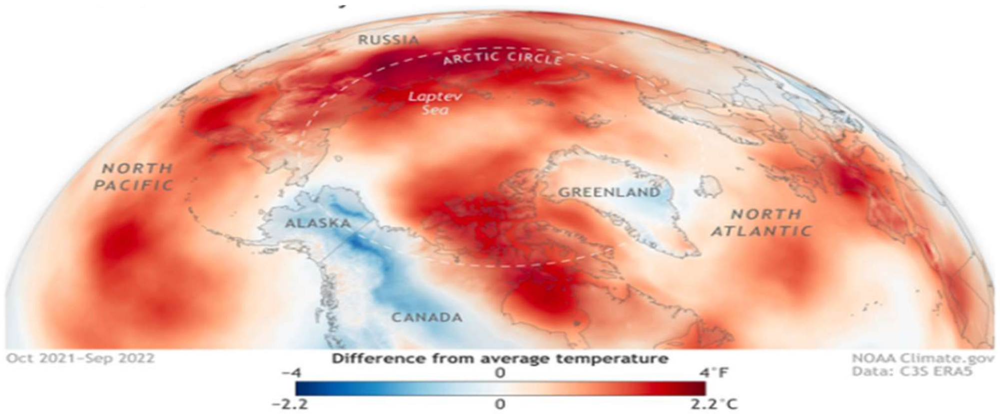

Figure 1.1: Arctic amplification. Source: NOAA

The melting of the Greenland icesheet and glaciers contributes to an increase in sea level rise (Chylek et al., 2009; Tedesco et al., 2011; Francis and Vavrus, 2012) and could also potentially affect the Atlantic

Meridional Overturning Circulation (AMOC)[2] (Bakker et al., 2016). The AMOC plays a crucial role in the global climate (Vellinga et al., 2008; Hu et al., 2009; Liu et al., 2017; Eyring et al., 2021).

Permafrost thawing refers to the melting of perennially frozen soils. This releases greenhouse gases emissions (carbon dioxide and methane) bound up in the frozen soil, acting as a positive global climate feedback (Schuur et al., 2009, 2015; Schaefer et al., 2011) as well as leading to local impacts (Hovelsrud et al., 2011).

Finally, there is a link between Arctic amplification and a potential increase in extreme weather events (Cohen et al., 2014; Coumou et al., 2014; Hall et al., 2015; Francis and Vavrus, 2015; Kug et al., 2015; Francis et al., 2017). As an example, Arctic amplification could influence mid-latitude extreme weather during the summer (Coumou et al., 2018). However, there is not scientific consensus around the link between Arctic amplification and extreme weather events and further research is needed (Cohen et al., 2020).

1.1.2. Climate change uncertainty

At the same time, future climate change is characterised by high uncertainty, spanning physical impacts, such as sea level rise and temperature and precipitation change, to socioeconomic impacts on economic growth, ecosystem services, and health, to name but a few (IPCC, 2022). This uncertainty comes from what is unknown and from

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[2] *"The main current system in the South and North Atlantic Oceans. AMOC transports warm upper-ocean water northwards and cold, deep water southwards, as part of the global ocean circulation system. Changes in the strength of AMOC can affect other components of the climate system."* (IPCC, 2021b, page 2238).

what is known. The former includes not knowing what the technological and social changes in the future will be (Chen et al., 2021) as well as unknown unknowns[3]. The latter includes errors from observations, models and internal variability (Eyring et al., 2021).

The IPCC Assessment Reports are periodically published every 4 to 6 years and consist of a detailed review of the status of climate change science. Each Report includes hundreds of scientists from a wide range of backgrounds as authors or editors of its chapters. Therefore, the Assessment Reports contain a thorough and robust analysis of the most recent scientific literature around climate change with a classification around its uncertainty. Ever since its second Assessment Report, the Reports have been structured in three Working Groups (WG): WGI focusses on the physical impacts from climate change, WGII on Impacts, Adaptation and Vulnerability and WGII on climate change mitigation.

Permafrost thawing is not explicitly modelled in most of the global climate models that took part in the sixth phase of the coupled model intercomparison project (CMIP6; Tebaldi et al., 2021), which is a multi-model experiment that informed the Intergovernmental Panel on Climate Change Sixth Assessment Report (AR6). Temperature projections presented in the AR6, which are extensively used to inform several stakeholders in the public and private sector, could underestimate the projected physical impact. In turn, this results in an underestimation of the potential global economic impacts from climate change.

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[3] *"The term 'unknown unknowns' (Parker and Risbey, 2015) is also sometimes used in this context to refer to events that cannot be anticipated with present knowledge or were of an unanticipated nature before they occurred." Chen et al. (2021), page 203*

1.1.3. Climate change impacts

Climate change is a public goods problem[4] in which a tonne of greenhouse gas emissions has a negative global effect independently of where in the world it is emitted (Stern, 2007). Yet, the impacts of climate change are felt disproportionately across the globe, with greater impacts expected to affect poorer communities which have less adaptative capacity, hence further reinforcing inequality (Meyer and Roser, 2010; Islam and Winkel, 2017). In addition to inequality issues around climate change impacts, there are two critical issues around intergenerational and intragenerational justice (Glotzbach and Baumgartner, 2012). Intergenerational justice refers to the responsibility of current generations towards future generations on the availability of natural resources (Meyer,2017). Intragenerational justice – also referred to as global justice – points to the principle of "common but differentiated responsibilities" in the Brundtland Report (World Commission on Environment and Development, 1987) given the developed countries' contribution to climate change through greenhouse gases emissions since the industrial revolution.

Different types of models play a crucial role in improving the understanding of how Arctic climate change can translate into regional and global impacts to inform policymakers on mitigation and adaptation (Alvarez et al., 2020). The next section will introduce integrated assessment models which have, amongst many other uses, been used to

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[4] *"A good or bad that is both nonrival and nonexcludable is a public good or bad." (Kolstad, 1997, page 95)*

assess the global economic implications from Arctic change (e.g.: Hope and Schaefer, 2015).

1.1.4. Integrated assessment models

Integrated assessment models (IAMs) are simplified representations of climate processes and the economy. They translate emissions of greenhouse gases into physical parameters (e.g., global mean temperature, sea level rise) to assess physical and socioeconomic impacts under different scenarios (Parson & Fisher- Vanden, 1997). Figure 1.1 shows a schematic of the general form of an IAM, emphasising how IAMs calculate socioeconomic impacts given different socioeconomic and/or emissions inputs.

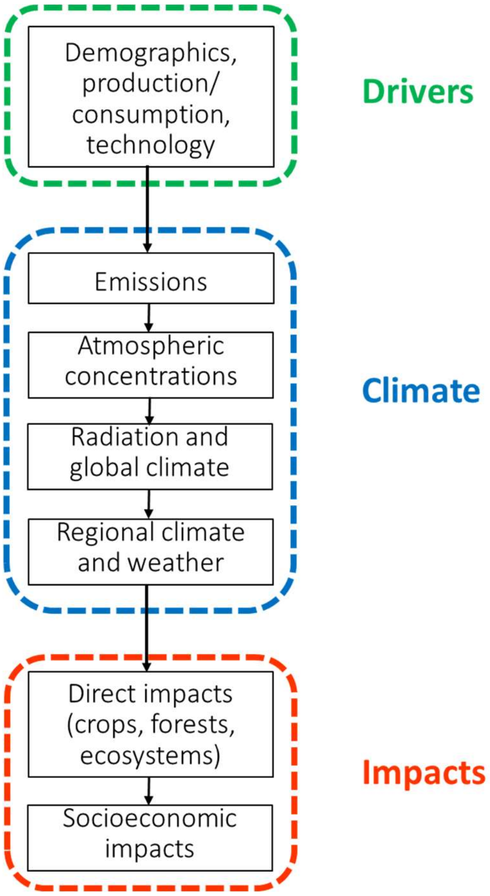

Figure 1.2. Integrated assessment model schematic.

[Adapted from Parson & Fisher-Vanden, 1997.]

To combine different systems within one model, assumptions and trade-offs are required in order that the model is tractable and solvable. IAMs can be divided into two types (Weyant et al., 1996): 1) policy optimisation models, which optimise key control variables given certain policy goals, and 2) policy evaluation models, which estimate the physical, environmental, and socioeconomic consequences of certain policies. Policy optimisation models can be further divided into three model subtypes: cost-benefit, target-based, and uncertainty-based. Policy evaluation models can be further divided into two model subtypes: deterministic projection and stochastic projection (Weyant et al., 1996).

Over the decades, there have been other IAM classifications (e.g.: Goodess et al., 2003; Ortiz and Markandya, 2009; Stanton et al., 2009; Füssel, 2010; Nikas et al., 2019). Some of these (e.g., Goodess et al., 2003; Füssel, 2010) do not differ much from Weyant et al. (1996) while the others do. Goodess et al. (2003) classification includes cost-benefit analysis models as those developed for policy optimisation analyses, bio-physical impacts models as those for policy evaluation analysis and tolerable windows approach as those for policy guidance analysis. Füssel (2010) classify IAMs based on their decision analytical frameworks (i.e., policy optimisation, policy evaluation and policy guidance) yet emphasize how there may be an overlap between them (e.g., using PAGE09, a policy evaluation model, in optimisation mode). Stanton et al. (2009) include five model categories based on model structure: welfare maximisation, general equilibrium, partial equilibrium, simulation (which includes

PAGE09), and cost minimisation. Ortiz and Markandya (2009)'s classification depends on whether the IAM includes four modules: climate, economy, energy sector and damage. Nikas et al. (2019) draw on these classifications and propose 6 categories based on how the climate, energy and impacts modules interact with the economy and how the latter is modelled. Weyant (2017) – 20 years past the initial classification – classifies them based on their level of aggregation into: detailed process and benefit-cost IAMs.

1.1.5. Social cost of carbon dioxide

The social cost of carbon dioxide is equal to the marginal increase in the net present value of climate change impacts from the emission of an extra tonne of carbon dioxide (Hope, 2013). Simplified IAMs like PAGE09 (Hope, 2011), DICE (Nordhaus, 2013) and FUND (Tol, 1996; Wadhoff et al., 2014) have been used to calibrate the social cost of carbon for the US government (IAWG, 2010; 2013). These reports included four value estimates over 2010-2050: average SCCO2 using different discount rates – 2.5, 3 and 5% – and a fourth estimate to incorporate high impact low likelihood events (SCCO2 value corresponding to the 95% percentile of the frequency distribution using a 3% discount rate, 95% f-3% hereafter).

The SCCO2 is calculated as the difference in the net present value of two different future cashflows which differ by one of them having an extra tonne of carbon dioxide emissions. The discount rate is the parameter used to estimate the value of the future cashflows into the present. As such, it has a substantial impact over results. For instance, in the estimates by US government, the average SCCO2 in 2050 ranged from 26, 69 to 95 USD 2007/tnCO$_2$ for 5%, 3% and 2.5% average rising to 212 USD 2007 /tnCO$_2$ for the 95% f-3% (IWG,2016). The highest the discount rate, the lower the SCCO2 impacts with some experts suggesting a discount rate of zero – which would place the same importance of future impacts as present ones – would address intergenerational issues (Stern, 2007).

In 2017, during Trump's presidency, the Interagency Working Group on the Social cost of Greenhouse Gases (IWG) was "disbanded" and the US government modified the SCCO2 methodology to only include domestic damages – as opposed to global – and 3% and 7% discount rates (E.O. 13783 of Mar 28, 2017). In 2021, during Biden's presidency, the IWG was re-established (E.O. 13990 of Jan 20, 2021). The latest SCCO2 estimates for 2050 are 200, 310 and 480 USD/tnCO$_2$ for 2.5, 2 and 1.5% discount rates respectively. Asides from lower discount rates (which increase SCCO2 estimates), a dynamic discounting rate is introduced (as opposed to the fixed discount rate in previous reports) (EPA, 2022).

1.2. Justification for research

IAMs have been used extensively to assess the potential global economic impacts from climate change and inform policy (see for example: Stern, 2007; IAWG,2010; IAWG, 2023). They are a useful tool to incorporate the climate feedbacks which are not widely represented in CMIP6, such as permafrost thawing, so that their climate change impacts estimates include these as well as other relevant metrics (e.g.:

temperature, sea level rise projections, remaining carbon budget for a given global warming level to name but a few).

Hope and Schaefer (2015) used PAGE09 to estimate the impacts from permafrost thawing by incorporating CO_2 and CH_4 emissions using SibCASA[5] (Schaefer et al., 2011), a land use model which simulates permafrost processes, exogenously to the model and found that the net present value[6] of climate change impacts by 2200 increased by 43 USD trillion (13%). In SibCASA (please see Schafer et al., 2011 for a detailed description), the permafrost carbon stock is only modelled for the top 3 meters which only represents 60% of the estimated total permafrost carbon pool in the northern hemisphere (Tarnocai et al., 2009). Yumashev et al. (2019) developed PAGE-ICE incorporating a permafrost carbon emulator and a surface albedo feedback emulator and found that the net present value of climate change impacts by 2300 ranged from 24.8-66.9 USD trillion under different scenarios. PAGE-ICE, unlike PAGE09 and PAGE22, has fixed in-built scenarios as opposed to user-definable ones. Other studies (Gonzalez-Eguino and Neumann; Kessler, 2017; Wirths, 2018) used DICE (Nordhaus, 2013) to estimate permafrost carbon feedback impacts and found an increase in impacts. A summary of each of these is presented in section 3.1, but a salient point is that the results in each of them do not incorporate uncertainty given that DICE is a deterministic IAM. None of the estimates presented so far are based on an IAM which includes a permafrost carbon emulator and, at the same

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[5] *"SiBCASA combines the biophysical Simple Biosphere model, version 3.0 (SiB3.0), with the carbon biogeochemistry from the Carnegie-Ames-Stanford Approach (CASA) model (Schaefer et al., 2008). SiBCASA has fully integrated water, energy and carbon cycles and computes surface energy and carbon fluxe at 10-min time steps. SiBCASA predicts the moisture content, temperature and carbon content of the canopy, canopy air space and soil (Sellers et al., 1996a; Vidale and Stockli, 2005). Fluxes of latent and sensible heat include the effects of snow cover, rainfall interception by the canopy, and aerodynamic turbulence (Sellers et al., 1996ª)."* Schaefer et al. (2011), page 167

[6] the sum of discounted future cashflows of an investment at the time of calculation

time, incorporates uncertainty and the user-definable flexibility around analysis time periods and mitigation and adaptation scenarios. PAGE22, and IAM which will be introduced in the thesis, meets these three criteria.

IAMs have been criticised for reasons including not incorporating the most recent climate change scientific and impact studies (Burke et al., 2016; Diaz and Moore, 2017; Rose et al., 2017); interdependent calibration of damage functions in simplified IAMs – like PAGE09, DICE and FUND (Rose et al., 2014; 2017); and that high temperatures only result in minor damages – e.g.: it takes a temperature increase of 18°C to lose 50% of global output in DICE (Dietz and Stern, 2014). PAGE22 was developed considering these criticisms. Two of the major structural developments in the model, incorporating the physical impacts from permafrost thawing (Burke et al., 2017; see Chapter 3) and the non-linear effect of temperature on economic production (Burke et al., 2015; see Chapter 4), are based on research derived from a physical permafrost model for the permafrost thawing emulator and an empirical study for the economic effect respectively. In addition, these are not dependent on other IAMs nor outdated. Unlike PAGE-ICE (Yumashev et al., 2019) which incorporates Burke et al. (2015) as a level effect, in PAGE22 the effects of temperature on economic production persist into the future (affect GDP in subsequent years). It is expected that damages from PAGE22 simulations included in this thesis will be larger than those in PAGE-ICE. These and other new developments made detailed in this thesis make PAGE22 state-of-the-art in terms of simulating the socioeconomic impacts of climate change.

In addition, this thesis introduces PAGE22-SCCO2, a new model version stemming from PAGE22 that was specifically developed to estimate the social cost of carbon dioxide. There are several estimates of the SCCO2 using IAMs with and without permafrost carbon feedback (e.g.: Kessler, 2017) and with and without growth effects (e.g.: Moore and Diaz, 2015). Similar to the justification for research on climate change damages, estimates using PAGE22-SCCO2 fill a gap in the literature as as they are based on a stochastic IAM which includes a permafrost carbon emulator, the persistent effect of temperature on economic growth and the user-definable flexibility around analysis time periods and mitigation and adaptation scenarios.

1.3. Research questions and thesis contributions

This thesis is structured around four research questions:

1. How can climate change in the Arctic region translate into local and global economic impacts?
2. How can the Arctic permafrost carbon feedback affect the temperature projections up to 2300?
3. How does incorporating the persistent effects of temperature on economic production affect climate change economic impact projections?
4. What are the potential economic impacts from the Arctic permafrost carbon feedback?

In addressing these research questions, the thesis makes three distinct contributions. First, it introduces a framework for assessing the global economic impacts from climate change in the Arctic region. This framework is used to understand which of the potential economic impacts are more urgent to study based on the combination of magnitude of impacts and availability of impact studies in the literature. Second, it describes PAGE22, an integrated assessment model which was developed to incorporate a permafrost carbon emulator and the persistent effects of temperature on economic production. Whilst the first contribution from this thesis addresses research question 1, the second contribution addresses research questions 2 to 4. Finally, the third contribution from this thesis is the development of another version of PAGE22 -PAGE22-SCCO2- to estimate the social cost of carbon dioxide which contributes to research questions 3 and 4. The two new IAMs introduced in this thesis which are used to address research questions 2 to 4, can be used to explore research questions beyond the scope of this thesis. For example, by using different emissions and socioeconomic scenarios as well as modifying different climate and/ or socioeconomic parameters. As such, the second and third contributions from this thesis make a bigger contribution to the field than the first contribution (framework).

Table 1.1 Model versions included in this thesis including specifications around permafrost carbon feedback, persistent effects, impact sectors, statistical value of civilisation, variable outputs and reference to thesis sections.

Model	Version	Permafrost carbon feedback	Persistent effects	Economic, non-economic, sea level rise, discontinuities impact sector	Statistical value of civilisation	Variable output and (thesis section)
PAGE22	1.0	off	off	on	Default	Global mean surface temperature (3.3.1, 3.3.2.,3.3.3, 3.3.4.), global impacts per year (4.4.1, 4.4.2)
	1.1	on	off	on		Global mean surface temperature (3.3.1, 3.3.2.,3.3.4); cumulative permafrost carbon emissions (3.3.4)
	1.2	off	on	on		Global impacts per year (4.4.2, 4.4.3); net present value of global total impacts (4.4.4)
	1.3	on	on	on		Net present value of global total impacts (4.4.4)
	1.4	off	on	off		Global mean surface temperature and ratio of unweighted impacts/ GDP (4.3.1.)
	1.5	on	on	on	High	Net present value of global total impacts (4.4.5)
PAGE22-SCCO2	1.0	off	off	on	Default	Social cost of carbon dioxide (4.4.5.)
	1.1	on	off	on		
	1.2	off	on	on		
	1.3	on	on	on		
	1.4	on	on	on	High	

Notes: for all model versions, the analysis time periods are the same (2020, 2030, 2050, 2050, 2075, 2100, 2150, 2200, 2250 and 2300). Statistical value of civilisation: "Default" has a mean value of 67,000 USD trill. (13,000, 63,000 and 130,000 USD trill. for the min, mode and max of the triangular distribution parameters respectively) based on Weitzman (2009), and "High" results from multiplying the parameters in "Default" by 1 exp^12.*

Throughout this thesis, 11 versions of the two models are used (6 for PAGE22 and 5 for PAGE22-SCCO2). As shown in table 1.1, the model versions differ on whether the permafrost carbon feedback emulator, the persistent effects impact sector, the other impact sectors (economic, non-economic, sea level rise and discontinuities) are switched on/off as well as the value used as input for the statistical value of civilisation. As explained in Chapters 3 and 4, each model version is run under a range of emissions and socioeconomic scenarios.

It should be noted that even though PAGE22 was developed with the aim of addressing research questions 2 to 4, it can be used to assess the impacts from user-definable climate mitigation and adaptation policies beyond those included in this thesis. As it will be explained in Chapters 3 and 4, the functionalities developed in this thesis as well as others in the model can be switched on and off by the user.

1.4. Thesis structure

This thesis is divided into five chapters, including this introductory one.

Chapter 2 presents the framework developed to assess the potential economic impacts from Arctic change. It starts with an introduction, followed by the framework with a section on each component, subsequently an analysis of existing quantitative methods and a discussion around future research and concluding remarks. It sets the landscape for identifying the research question number 2.

Chapter 3 presents PAGE22, a new version of the PAGE09 integrated assessment model (Hope, 2011), which can be used to assess the global potential economic implications from climate change under a range of scenarios and policies. This new model development was motivated by the objective of estimating the global economic effects of permafrost thawing, given that it is an important climate feedback which is seldomly included in CMIP6 models. Asides from an update to many parameters, PAGE22 introduces a new temperature forecasting variable and a permafrost carbon emulator. PAGE22 models the permafrost carbon feedback by calculating the permafrost thawing emissions of the greenhouse gases carbon dioxide and methane, which arise from the warming effect from increased anthropogenic greenhouse gases emissions. In turn, the additional greenhouse gases emissions from permafrost thawing further increase the global mean temperature and sea level rise. It includes a benchmark analysis of temperature projections vs. PAGE09 and another one vs. the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report (AR6) for a range of climate scenarios. It also includes an analysis of cumulative permafrost carbon emissions by 2100, 2200 and 2300 and a benchmark vs. other relevant impact studies. It follows by an estimate of the resulting temperature differentials from the permafrost carbon feedback, a discussion around the caveats around the permafrost carbon feedback modelling and results and concluding remarks.

Chapter 4 presents the inclusion of the persistent effects of temperature on economic production in PAGE22. It explains the rationale for this development as well as projections of climate change impacts by 2300 under a range of scenarios. It includes an analysis of the contribution from the permafrost carbon feedback and a section on the social cost of carbon followed by a discussion around caveats and concluding remarks.

Chapter 5 focusses on how the research questions posed in section 1.3. are addressed in this thesis, expands on caveats and includes a discussion around future research needs.

Chapter 2 – A framework for assessing the economic impacts of Arctic change

The following chapter was published as a peer review article in Ambio on 24th June 2019 (citation: Alvarez, J., Yumashev, D. and Whiteman, G., 2020. A framework for assessing the economic impacts of Arctic change. Ambio, 49(2), pp.407-418.). The author contributions are listed below.

Statement of contribution

This paper was written when Dmitry Yumashev and Gail Whiteman were my PhD supervisors with the objective of being included in my thesis. I created the framework that the study outlines and wrote all of the paper, with supervisory input and editorial comments from Dmitry Yumashev and Gail Whiteman.

2.1. Abstract

The scientific literature on physical changes in the Arctic region driven by climate change is extensive. In addition, the emerging understanding of physical feedbacks and teleconnections between the Arctic and the rest of the world suggests that the warming in the Arctic region is likely to cause impacts that extend well beyond the region itself. However, there is only limited research on how Arctic change may affect economies and individual industry sectors around the world. We argue that there is a pressing need for more research on this topic and present a conceptual framework to guide future research for assessing the regional and global economic impacts of Arctic change, including both possible benefits and costs. We stress the importance of a transdisciplinary approach, which includes an integration of the natural sciences, economics and social sciences, as well as engagement with a wide range of stakeholders to better understand and manage the implications of Arctic change.

Keywords

Arctic; climate change; economic impacts; transdisciplinary science

2.2. Introduction

The Arctic has been changing at unprecedented rates over the past three decades driven by climate change, with the average rate of warming in the region twice as high as the global average (IPCC, 2013; Overland et al., 2015). The changes in the Arctic are manifested by the decline in the sea ice, permafrost, glaciers and the Greenland ice sheet (Stroeve et al., 2012a; Van den Broeke et al., 2016; Chadburn et al., 2017).

In addition to the extensive scientific literature on physical changes in the Arctic region itself, there is an emerging scientific knowledge of physical feedbacks and teleconnections between the Arctic and the rest of the world (Burke et al., 2017; Francis et al., 2017). These physical processes will exacerbate the effects of climate change globally. Since climate change carries significant economic impacts worldwide (Stern, 2007; Tol, 2009; Hope, 2013; Nordhaus, 2013; Dietz and Stern, 2014; IPCC, 2014), Arctic-driven feedbacks and teleconnections are expected to cause additional economic impacts far beyond the Arctic region itself (Whiteman et al., 2013; Hope and Schaefer, 2015; Yumashev et al., 2019).

Yet economics research to date has focussed primarily on estimating economic opportunities due to Arctic change through increased oil & gas and mineral extraction, shipping, tourism and agriculture in the Arctic region (ACIA, 2005; Gautier, 2009; Hovelsrud and Smit, 2010; Hovelsrud et al., 2011; Emmerson and Lahn, 2012; Smith and Stephenson, 2013; Bekkers et al., 2016). While multiple authors started to recognize potential negative economic impacts of Arctic change, both regionally in the Arctic and globally (Whiteman et al., 2013; Euskirchen et al., 2013; Hope and Schaefer, 2015; Lam et al., 2016; González-Eguino et al., 2016, 2017; Melvin et al., 2017; Yumashev et al., 2019), the literature lacks a comprehensive framework for assessing the costs and benefits of an ice-free Arctic. Without such a framework, policymakers could underestimate the true cost associated with Arctic change. This is the key gap that we wish to address here.

Estimating the benefits and costs associated with Arctic change requires a number of complementary methodologies and models, including specialised climate and ecosystem models, Integrated Assessment Models (IAMs) and both regional and global macroeconomic models. This highlights the importance of a transdisciplinary approach to better understand and manage the implications of Arctic change, which brings together natural sciences, economics, social sciences and engagement with a wide range of stakeholders (Whiteman & Yumashev, 2018).

We build upon recent work in this area. For example, the European Union's project Arctic Climate Change, Economy and Society (ACCESS) delivered a transdisciplinary approach to assess physical impacts of climate change on the Arctic Ocean and the resulting socio-economic impacts within the Arctic region focussing on key economic activities: shipping, tourism, sea food production and natural resource extraction up to 2050 (Crépin et al., 2017a; Gascard et al., 2017; NERC, 2015). A key contribution from the project is highly relevant to the issue at hand: the development of "a framework for integrated ecosystem-based management" (Crépin et al., 2017a,b). The so-called 'integrated ecosystem-based management' (IEBM) was developed as a management tool with a focus on the Arctic Ocean, and it "accounts for complex interactions between society and nature, possible abrupt change, and substantial uncertainties" (Crepin et al., 2017b). Our proposed framework – though focussed on economics – extends the IEBM's scope of analysis to account for the indirect global impacts from Arctic change and the secondary impacts through knock-on effects in the global economy.

The paper is structured as follows: section 2.3 introduces a framework for assessing the economic impacts from Arctic change; section 2.3.1 focusses on the economic benefits resulting from a melting Arctic; sections 2.3.2 and 2.3.3 address the direct regional impacts and indirect global impacts from Arctic change respectively, followed by the existing quantitative methods and implications for future research in section 2.4 and concluding remarks in section 2.5.

2.3. A framework for assessing the economic impacts from Arctic change

Given the systemic nature of Arctic climate feedbacks, the global economic costs of Arctic-related climate change may counter-balance the economic benefits from shipping, tourism, natural resource extraction and other industries enabled by a warming Arctic region. Thus, a key outstanding question is whether the changing Arctic could result in significant economic impacts worldwide, and if so, how best one could quantitatively assess these impacts.

Based upon existing literature from a variety of disciplines, Figure 2.1 delineates how Arctic physical changes can trigger economic impacts – positive and negative – both on the regional and global levels. On the one hand, (i) new economic opportunities in the region associated with oil & gas and mineral extraction, commercial shipping, tourism, agriculture and fishing have the potential to generate multi-billion-dollar annual revenues (ACIA, 2005; Gautier et al., 2009; Dyck and Sumalia, 2010; Hovelsrud and Smit, 2010; Hovelsrud et al., 2011; Emerson and Lahn, 2012; Bekkers et al., 2016; Lam et al., 2016). On the other hand, (ii) changes in the Arctic have direct regional impacts on its climate, ecosystems and communities (ACIA, 2005; Hovelsrud et al. 2011; Wassmann et al., 2011; AMAP, 2015), (iii) as well as lead to indirect global impacts through Arctic climate feedbacks and teleconnections (Euskirchen et al., 2013; Hope and Schaefer, 2015; González-Eguino et al., 2016, 2017; Yumashev et al., 2019). In addition, (iv) the revenues and impacts associated with Arctic change could result in secondary impacts through economic knock-on effects in multiple countries around the world (Bekkers et al., 2016). Each of these four main components of Figure 2.1 are discussed in the subsequent sections.

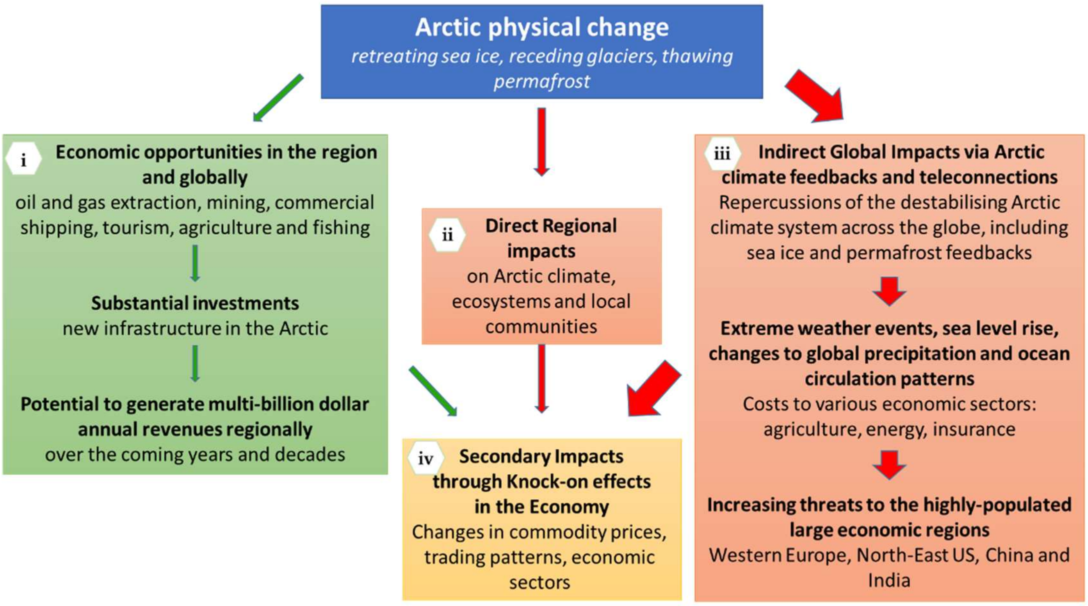

Figure 2.1. Benefits and costs of Arctic change.

Source: Alvarez, Yumashev and Whiteman (2020)

2.3.1. Economic opportunities from a melting Arctic

The profound physical changes that are underway in the Arctic are likely to lead to substantial investments into new infrastructure in the Arctic region, with the potential to generate multi-billion-dollar annual revenues over the coming years and decades (Emmerson and Lahn, 2012). However, investment decisions in the Arctic are particularly difficult due to its restricted geographic access, environmental concerns, highly contrasting seasons and constrained markets, as well as the fact that many projects are transborder in nature since they include several Arctic states (WEF, 2014), giving rise to sensitive geopolitical issues.

The short-term (years) and medium-term (until 2050) economic benefits of an Arctic change scenario include potential for oil & gas and mining exploration, increase in regional tourism, fishing, agriculture and commercial shipping to Arctic destinations (ACIA, 2005; Gautier, 2009; Hovelsrud and Smit, 2010; Hovelsrud et al., 2011; Lam et al., 2016), as well as medium- to long-term (beyond 2050) benefits from commercial shipping along transit Arctic routes (Hansen et al., 2016; Yumashev et al., 2017). An assessment by the United States Geological Survey of the area north of the Arctic Circle concluded "that about 30% of the world's undiscovered gas and 13% of the world's undiscovered oil may be found there, mostly offshore under less than 500 meters of water" (Gautier et al., 2009). In order to access these resources, substantial investment is needed: "except for certain areas of Norway and the western Russian Federation, the region remains vastly underserved by transportation, port and other critical infrastructure" (WEF, 2014). Furthermore, a recent scenario-based study on the European Arctic Seas concludes that, even if oil and gas exploitation were possible from a technological point of view, "under current prices and with competing fossil and renewable energy sources, an exploitation does not seem to be rational from an economic point of view" (Petrick et al., 2017). The lack of infrastructure coupled with the remoteness of the region pose additional challenges to the management of potential oil spills (Harsem et al., 2011). In addition, the decrease in sea ice might result in "greater areal coverage and increased shoreline exposure" in future oil spills (Nordam et al., 2017). In a region where extreme weather increases the risk of an oil spill, a good starting point would be Greenland's strategy of negotiating an upfront "clean-up bond" (Webb, 2010; Harsem et al., 2011).

Climate change is a driver of 'last-chance' tourism in some Arctic locations, resulting in short to medium term benefits to local communities and tour-operators in the region, which is a paradox considering that emissions associated with travelling to these remote locations tend to further reinforce the negative impacts of climate change (Lemelin et al., 2010). In addition, whilst sea ice decline could potentially increase cruise shipping in some Arctic regions (Dawson et al., 2014), a study based on a 37-year observational record in the Canadian Arctic stresses that hazardous sea ice conditions might prevent this from happening, at least in the near future (Stewart et al., 2007). Even for a modest increase of tourism in the region, infrastructure and regulatory modifications would be required (Lasserre and Têtu, 2015).

A study on the impacts of climate change on the Arctic fisheries' sector projects that total revenues may increase by 39% in 2050 vs. 2000 (33% when factoring in ocean acidification) which, in turn, is expected to have a positive "multiplier" effect of 3 on the whole Arctic economy (Dyck and Sumalia, 2010; Lam et al., 2016). Positive impacts have already occurred such as the unprecedented arrival of the Atlantic mackerel in Greenland in 2011 which, climbed from representing 0 in 2011 to 23% of its exports in 2014 (Jansen et al., 2016). On the other hand, the industrial fisheries might pose a threat to native Arctic marine fish species as it "turns up as unprecedented bycatch" (Christiansen et al., 2014). Hence, the extent to which Arctic fisheries will benefit from climate change is subject to a variety of factors: from the resulting socio-economic repercussions due to exploitation of the new species compositions, to the risk posed by unsustainable fishing practices, particularly given the role some non-Arctic fishing countries with "more efficient and higher-powered fishing fleets"– such as Japan and China – might play in the region (Lam et al., 2016).

Even though Arctic change is enabling the development of agriculture in the region, some impediments still remain such as: lack of infrastructure to promote commercial agriculture, water limitations, scant population, risk-averse behaviour of the farmers as well as inadequate governmental policies (ACIA, 2005; Hovelsrud and Smit, 2010; Hovelsrud et al., 2011). Even if climatic conditions were to enable enough agricultural produce to cover local demand and export the surplus, macroeconomic conditions are still likely to be the dominant factor. For instance, the competitiveness of prices might present an issue, in particular to the Arctic countries that are part of the European Union (ACIA, 2005).

Medium- to long-term benefits of Arctic change also include shorter albeit inherently difficult transit shipping routes that could have a positive effect on the trade between Asia and Europe as well as between the East and West coasts of the US (Smith and Stephenson, 2013; Bekkers et al., 2016; Aksenov et al., 2016; Hansen et al., 2016; Bensassi et al., 2016). It has been estimated that around 5% of the world's trade could be shipped through the Northern Sea Route (NSR) in the Arctic alone under a hypothetical year-round and unhampered navigability, generating additional income for many European and Asian countries (Bekkers et al., 2016). Despite the seemingly favourable near-term navigability trend dictated by sea ice retreat from NSR around the month of September in the coming decades (Aksenov et al., 2016), the shipping companies may delay investments in large-scale operations along NSR until profitability conditions are met (Hansen et al., 2016), which is likely to push the onset of large scale commercial operations on NSR to the second half of the 21st century even under the worst-case scenarios in terms of the sea ice loss (Yumashev et al., 2017).

The changing Arctic and its consequent effects on diverse economic sectors, have the potential to generate significant revenues. However, the extent to which such revenues materialise is subject to uncertainty. A holistic approach which factors in the repercussions from economic development on the Arctic ecosystems and communities seems crucial to ensure a sustainable development of the Arctic region.

2.3.2. Direct regional impacts from Arctic change

Without taking away the economic potential that could be unlocked by a warmer Arctic, one should acknowledge the likely negative impacts in the Arctic region itself as a result of the rapid climatic changes (IPCC, 2014). Climate impacts in the Arctic affect its ecosystems and influence the subsistence activities of local communities. These include impacts of thawing permafrost on local infrastructure, impacts from wildfires in tundra and boreal forests, and changes in wildlife and plant species distribution patterns (ACIA, 2005; Higuera et al., 2008; Hovelsrud et al. 2011; Mack et al. 2011; Melvin et al., 2017). According to AMAP's latest assessment on human health in the Arctic: "The most pronounced impacts of climate change in the Arctic occur in small communities in regions with infrastructure dependent on permafrost stability and where ice is needed for travel, hunting and the protection of the shoreline from coastal erosion." (AMAP, 2015, page 137).

Several areas around the Arctic Ocean were identified as high-risk potential hazard of thawing permafrost within the Northern Hemisphere (Nelson et al., 2001). Thawing permafrost can lead to several negative effects: "threatens coastal settlements; damage to poorly engineered and constructed infrastructure; release of legacy pollutants that affect the food chain and have negative health effects; tree death caused by drought; increased forest fire occurrence" (Hovelsrud et al., 2011). Socioeconomic impacts of thawing permafrost include damages to infrastructure. Even though the number of settlements in the Arctic tundra is below 400 and most of them are relatively small, some Russian cities in the region exceed 100k population (Streletskiy et al., 2015). With a tendency of Arctic settlements to be located in coastal areas, an increase in coastal erosion might force settlements to relocate (Streletskiy et al. 2015). A study in Prudhoe Bay Oilfield in Alaska – the first oilfield which was developed in the Arctic in ice-rich permafrost (IRP) terrain – showed a doubling in flooding and more than tripling in thermokarst across a number of areas in the period between 1980-2010 (Raynolds et al. 2014, fig. 6). With the prospect of continued negative impacts from thawing permafrost on infrastructure, mitigation strategies like thermosiphons could offer a valuable coping mechanism (Streletskiy et al. 2015).

According to ACIA (2005)'s report: "Large-scale forest fires and outbreaks of tree-killing insects are characteristic of the boreal forest, are triggered by warm weather, and promote many important ecological processes." For example, in 2007 over 1000 km^2 of Arctic tundra were burnt in the Anaktuvuk River fire in Alaska, "doubling the cumulative area burned in this region over the past 50 years" (Mack et al., 2011). Thawing of permafrost may increase the risk of late season fires – such as those in the Anaktuvuk river basin – in tundra regions (Hu et al. 2010). In addition to the potential release of significant amounts of organic carbon, another impact of increased fires is the change in vegetation from graminoid to shrub tundra which, in turn, could further reinforce climate change (Mack et al., 2011). Based on a study of paleorecords in Alaska, Higuera et al. (2008) implied that "ongoing shrub expansion and climate warming will result in greater burning within northern tundra ecosystems."

A review of over 50 reports on the effects of climate change on Arctic marine ecosystems concludes that there is "compelling evidence of impacts of climate change on almost all components of the marine ecosystems" and further stresses that it is likely that many other impacts have not been documented yet (Wassmann et al., 2011). A global projection of climate change impacts on a sample of 1000+ marine species identifies the Arctic as one of two regions with the highest species turnover by 2050 (Cheung et al., 2009). The potential development of commercial shipping routes through the Arctic could result in an increase of marine species invasion in the region (Whitman Miller & Ruiz, 2014). In addition, under continued warming, the Bering Strait could enable the passage of mollusks and other species from the Pacific to the Atlantic Ocean (Vermeij & Roopnarine, 2008).

Despite the economic benefits resulting from Arctic shipping and oil & gas extraction, a recent study along the Norwegian coast suggests that local emissions from oil and gas and shipping are already impacting air pollutant levels in the region (ozones and aerosols such as sulphates and black carbon (BC)) (Law et al., 2017). Furthermore, a substantial increase in Arctic shipping and oil and gas extraction is expected to lead to higher environmental risks from short-lived pollutants such as BC, as well as oil spills (AMAP, 2015b; Harsem et al., 2011). For example, the expected increase in shipping traffic along the NSR could result in a total climate feedback contribution of "0.05% (0.04%) to global mean temperature rise by 2100 under the RCP8.5 (RCP4.5) climate change scenario" partially offsetting the economic gains from shipping by a third and a quarter respectively (Yumashev et al., 2017).

These impacts add to the stresses that Arctic ecosystems and local communities are subject to from the rapidly changing regional climate. Even though Arctic communities have a track record of high adaptability to natural variability, "the rate and magnitude of such changes represent unprecedented challenges to the current adaptive capacity and resilience of Arctic residents" (Keskitalo et al., 2010; Hovelsrud et al., 2011). There is an urgent need to put policies in place that will help Arctic communities adapt to climatic changes in the region.

2.3.3. Indirect global impacts via Arctic feedbacks and teleconnections, and secondary economic knock-on effects

The rapid warming in the Arctic region is of global concern due to a number of Arctic-driven feedbacks and teleconnections, including an increase in global sea level rise from the melting of the Greenland ice sheet (Chylek et al., 2009; Tedesco et al., 2011; Francis and Vavrus, 2012), greenhouse gas emissions from thawing permafrost on land (Schuur et al., 2009, 2015; Schaefer et al., 2011) and subsea (Romanovskii et al., 2005; Shakhova et al., 2010, 2014, 2017; Nicolsky et al., 2012), increased solar absorption in the Arctic Ocean due to sea ice and snow retreat (Flanner et al., 2011), increase in ocean acidification (Bates and Mathis, 2009), changes to global precipitation patterns (Givati and Rosenfeld, 2013), and growing extreme weather events attributed to increased jet stream volatility (Cohen et al., 2014; Coumou et al., 2014; Hall et al., 2015;

Francis and Vavrus, 2015; Kug et al., 2015; Francis et al., 2017). These processes have accelerated dramatically over the past three decades and have the potential to affect the overall stability of the climate system both in the Arctic, in the entire northern hemisphere and globally (IPCC, 2013).

The magnitudes of these effects and the extent to which at least some of them stem from Arctic change are under debate (Barnes and Screen, 2015; Francis and Vavrus, 2015; Sapart et al, 2017). For instance, the possible link between Arctic warming and an increase in extreme weather events in mid-latitude regions would affect various economic sectors in Europe, North America and Asia, including agriculture, tourism and insurance (Francis et al., 2017). To put this in a perspective, global annual weather-related losses increased from around USD 50 billion in 1980 to around USD 150 billion in 2012 (Munich Re, 2013; The World Bank Group Experience, 2013), although a significant part of this increase has been attributed to socio-economic factors alone (Bouwer, 2011; Mohleji and Pielke, 2014).

Arctic climate feedbacks that carry economic costs globally include methane emissions from thawing permafrost. CO_2 and methane releases from land-based permafrost represent another potential threat (Schuur et al., 2015; Burke et al., 2017), and economic estimates suggest that the associated cost to global economy could be around 40 trillion dollars over the next two centuries (Hope and Schaefer, 2015). Euskirchen et al. (2013) estimate that "Between 2010 and 2100, the annual costs from the extra warming due to a decline in albedo related to losses of sea ice and snow, plus each year's methane emissions, cumulate to a present value cost to society ranging from USD7.5 trillion to USD 91.3 trillion."

One of the most extreme scenarios, for example, could occur when warming Arctic waters lead to the abrupt atmospheric release of methane from gas hydrates which are stored under the subsea permafrost on the Arctic shelf (Shakhova et al, 2010). This worst-case scenario could cost the global economy an estimated 60 trillion dollars over the next two centuries (Whiteman et al, 2013). While some natural scientists suggest that such sudden releases of vast quantities of methane are implausible (e.g., Archer, 2015), others argue that underwater methane release in the East Siberian Sea is a valid threat (Romanovskii et al, 2005; Nicolsky et al, 2012; Shakhova et al, 2017).

In addition to climatic feedbacks and teleconnections associated with Arctic change, economic developments in the Arctic region itself are likely to generate various costs and benefits globally through knock-on effects in the economy. These are manifested by Arctic-driven shifts in commodity prices and trading patterns, potentially leading to changes in economic sectors and social welfare in multiple countries around the world. It is a new field of research and there are very few relevant impact studies available, mostly concerning Arctic shipping. Bekkers et al. (2016) estimate that year-round navigability on NSR could increase the trade between EU and Asia by up to 6%, resulting in a 0.14% higher GDP in China, a 0.12% higher GDP in the EU (Belgium is the biggest winner among the EU countries with a 0.4% increase in the GDP), 0.15% in Japan and 0.23% in South Korea. However, the potential economic gains from increased shipping along the NSR may be offset partially by the climate-related costs from the associated changes in the GHG emissions (climate feedback of the NSR), with most of the climate costs expected to occur in the poorer regions such as Africa and India (Yumashev et al., 2017).

2.4. Existing quantitative methods and implications for future research

The framework presented in this paper calls for more efforts towards estimating the extent and range of economic impacts associated with Arctic change. We believe that transdisciplinary science is crucial here since physical impacts often need to be translated into economic benefits and costs in order to engage with businesses and policymakers.

Each of the four main categories of impacts (benefits and costs) due to Arctic change, summarised in Figure 2.1, requires different methodologies and models in order to perform quantitative assessment of the impacts. Estimating economic opportunities in the Arctic region and globally (category (i)) requires a combination of climate and ecosystem models and sector-specific impact models that translate changing climatic conditions into benefits and costs for each sector (Lam et al., 2016). The same applies to direct impacts in the Arctic region (category (ii)). Assessing indirect global impacts of Arctic climate feedbacks and teleconnections (category (iii)) calls for IAMs calibrated according to the latest results from climate models (Yumashev et al., 2019). Finally, estimating secondary economic knock-on effects due to Arctic development requires regional and global macroeconomic models with interlinkages between multiple economic sectors (Bekkers et al., 2016), based on either general equilibrium or input-output methodologies.

On the climate modelling side, efforts to better understand the possible futures of Arctic sea ice, land and subsea permafrost and Greenland ice sheet, as well as their climatic impacts on other world regions, are ongoing. One particular difficulty is associated with the coupling of ice sheet and permafrost models with atmospheric, ocean and land models, which has not yet been attempted in the current generation of earth system models (CMIP5) that feature in IPCC AR5. Even before such coupling could be attempted, consensus must be reached on several underlying physical processes, most importantly a growth in the extreme weather events associated with volatile jet stream and emissions of methane from subsea permafrost.

On the economic modelling side, the growing literature on global economic impacts associated with climate change has relied on IAMs extensively (Hope, 2013; IPCC, 2014b). IAMs help bridge the gap between climate science and policy (Ackerman and Stanton, 2013), and provide a widely-used methodology for assessing policy options under multiple uncertainties, which is achieved by combining simplified representations of the climate, economy and policy options (Parson and Fisher-Vanden, 1997; Weyant and Hill, 1999). Most climate policy studies based on IAMs employ the estimates of the regional and global costs of climate change represented as functions of the corresponding changes in mean annual temperatures and sea level. As a result, they do not include more sophisticated physical processes such as the decline in the Arctic sea ice cover or thawing of the permafrost that are evident from observations as well as from climate model simulations.[7] One of the biggest challenges for the IAMs like PAGE, DICE and FUND is to improve the so-called damage functions in order to provide a more defensible economic valuation of the indirect global impacts of Arctic climate feedbacks and teleconnections. Such an improvement is important for assessing the cost not just of Arctic change, but of climate

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[7] *Arctic permafrost and sea ice feedbacks have recently been implemented using model emulators in the new IAM PAGE-ICE (Yumashev et al., 2019).*

change in general. Damage functions have been criticised for a variety of reasons, including their overall opacity and the high levels of uncertainty of the impacts at higher temperatures (Howard, 2014; Pindyck, 2017).

Aside from IAMs, there is a need for specialised regional macroeconomic models for Arctic countries and states such as Greenland, Alaska and Arctic parts of Canada and Russia, that are capable of translating sector-level impacts (Melvin et al., 2017) into secondary socio-economic effects in these areas. Regional studies from other parts of the world, for example a study by Crawford-Brown et al. (2013) on economic impacts of climate-driven flooding in London, have used input-output models. These models could be further enhanced to resolve secondary economic effects (both indirect and induced) of climate change in the Arctic countries and states by incorporating social accounting matrices. However, as with the estimates of global costs of Arctic change using IAMs, the biggest challenge for the regional economic assessments in the Arctic is to provide an accurate description of primary climate-driven economic impacts for each sector, some of which were reviewed in the sections above.

Finally, one should remember that the services of the ecological life-support systems (ecosystems) are crucial to the economies of the Earth, and hence “their total value to the economy is infinite” (Costanza et al., 1997). Climate change poses a threat to these systems as “with increasing warming, some physical systems or ecosystems may be at risk of abrupt and irreversible changes” (IPCC, 2014c); thus, global policymakers seek appropriate ways of evaluation beyond the neo-classical economics framework. As an example, to depict the total value of the Arctic in the Earth system, economic impacts on their own would not suffice and alternative methods such as multicriteria analysis could be worthwhile (Keeney and Raiffa, 1993). We acknowledge that a "social-ecological systems approach is required to better facilitate resilience-building, a key component of sustainable development" (Arctic Council, 2016). Nevertheless, our understanding is that adapting both climate models, IAMs and macroeconomic models to include Arctic-driven effects and help estimate the associated economic costs is a logical starting point towards highlighting the urgency of preventing the worst effects of Arctic change.

2.5. Conclusion

The rate of Arctic change in the recent years causes negative impacts on climate, ecosystem and communities that extend well beyond the Arctic region (Bates and Mathis, 2009; Shakhova et al., 2010, 2014; Givati and Rosenfeld, 2013; Coumou et al., 2014; Hall et al., 2015). Existing research has focussed primarily on estimating economic impacts (usually opportunities) in the Arctic region itself (ACIA, 2005; Gautier, 2009; Emmerson and Lahn, 2012; Smith and Stephenson, 2013). However, given the direct physical relationship between Arctic change and the global climate system, economic impacts are not likely restricted solely to the Arctic region.

In this paper, we presented a new framework for an economic assessment of both regional and global impacts of Arctic change that could help advise businesses and policymakers. There have been several studies attempting to quantify some of these impacts in economic terms (Euskirchen et al., 2013; Whiteman et al., 2013; Hope and Schaefer, 2015;

Lam et al., 2016), and we argue that a transdisciplinary approach with strong integration of climate science, economics and policy studies is required. The new framework encourages a more balanced perspective on Arctic development, and both on regional and global risks associated with Arctic change.

Arctic change can cause socio-economic impacts both at the regional and global levels. Growing industrial activities in the region are closely related to negative environmental impacts, for example black carbon pollution from shipping and greater risks of oil spills (Harsem et al., 2011; AMAP, 2015b). Local Arctic communities thrive from the natural resources available in the region and hence climatic changes brings about new threats. Thawing permafrost poses a risk to existing infrastructure and requires adaptation of certain traditional activities – like hunting. A side-effect of thawing permafrost is the potential release of contaminants held in the frozen soil (AMAP, 2015). Since Arctic change poses a threat to food and water security for Arctic communities, there is a need for monitoring programmes comprising quantitative indicators (Nilsson et al., 2013). On the global level, the extent of Arctic-related effects is highly uncertain but could cause multiple losses associated with rising sea level from the melting Greenland ice sheet, additional carbon emissions from thawing permafrost, additional warming due to the loss of the sea ice and snow covers and growing extreme weather events due to increased polar jet stream volatility. In addition, the limits to adaptation funds and/ or political unwillingness to invest in mitigation could lead to political and economic tipping points both in the Arctic region and globally (Huntington et al., 2012).

Given the global and systemic nature of Arctic climate feedbacks, the additional economic costs of Arctic-related climate change may counter-balance and possibly outweigh the economic benefits arising from a warming Arctic region. A comprehensive framework for assessing the total economic effect of Arctic change presented here could help guide both individual investment decisions associated with Arctic change, and a wider climate policy.

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Chapter 3 - Developing PAGE22: climate

3.1. Introduction

The previous chapter presented a framework for assessing the economic impacts from Arctic change. It highlighted the need for further research into the potential global economic impacts resulting from climate change in the Arctic region and how improved and different methodologies and models are needed to further investigate this. One of the key physical impacts stemming from Arctic change is permafrost thawing. This is where perennially frozen soils thaw, impacting global climate change by releasing large amounts of greenhouse gases to the atmosphere (Canadell et al., 2021), while also affecting the livelihoods of local Arctic communities (Ramage et al., 2021) (as depicted in boxes iii and ii in figure 2.1 respectively). Permafrost generally occurs below an active layer, which is subject to annual thaw and freeze cycles and varying in depth from 1 m to more than 1 km (Abram et al., 2019). It extends over almost a quarter of the area in the Northern Hemisphere (Zhang et al., 1999; Chadburn et al., 2017). The estimated carbon stored in the northern circumpolar permafrost region ranges from 1460–1600 PgC[8], which is almost double the carbon in the atmosphere (Schuur et al., 2018). With this huge carbon store, permafrost thawing has been identified as one of the climate tipping points, which, through reinforcing climate warming, could jeopardise any effort to limit global mean surface temperature (Lenton et al., 2019).

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[8] *Does not include carbon stored in subsea permafrost and some deep sediments due to scarce data*

At the same time, the inclusion of the physical and chemical processes important for understanding permafrost carbon in the global Earth System Models (ESMs) that inform international climate assessments (e.g., IPCC reports) is still in early stages. Indeed, in the latest coordinated international ESM experiment (the sixth coupled model intercomparison project: CMIP6), only two out of 11 ESMs which include a carbon cycle – the so-called C^4MIP-CMIP6 ensemble (Friedlingstein et al., 2006; Jones et al., 2016) – contained interactive simulation of permafrost processes, an increase from none in the previous experiment (CMIP5) (Canadell et al., 2021). These two models' projections of future climate differed from the other models: a positive carbon feedback from the permafrost region in these two models compared to a negative climate feedback in the CMIP6 ensemble mean (Canadell et al., 2021). A positive carbon feedback is like a reinforcing loop: a warming temperature results in an increase in permafrost thawing which, in turn, reinforces the initial warming. As a result, most climate impact studies based on global circulation models which do not include the feedbacks from permafrost thawing likely underestimate the impacts and feedbacks from a warming Arctic (Yumashev et al., 2019).

Other tools, such as simplified integrated assessment models (IAMs), can be useful to assess the uncertainty around the global implications from permafrost thawing through the incorporation of permafrost thawing emulators (Yumashev et al., 2019). IAMs are used to assess the economic impacts from climate change and explore the benefits and costs of climate policies. However, the permafrost carbon feedback is not routinely represented in IAMs which results in an underestimation of the economic impacts from climate change which are used to inform policymakers.

This chapter introduces a new modelling tool to explore the economic impacts of permafrost thawing for a range of climate and socioeconomic scenarios up to 2300: PAGE22, an IAM. As well as simulating the economic impacts of climate change captured by its predecessor (PAGE09; Hope, 2011), PAGE22 enables the user to estimate the potential global impacts from permafrost thawing, incorporating uncertainty in both the physical processes and the impact sectors. The results in this chapter increase the pool of potential estimates of the permafrost carbon feedback. The description of the development of PAGE22 is presented across two chapters: the present chapter focusses on the physical process modelling and Chapter 4 focusses on simulating the persistent effects of temperature on economic production.

The few estimates of the potential global economic impacts from permafrost thawing emissions are from the recent literature, and, moreover, all focus on gradual permafrost thawing and do not assess other possible scenarios such as abrupt permafrost thawing (e.g., Turetsky et al. 2019, 2020). Hope and Schaefer (2015) used PAGE09 coupled to SiBCASA (Schaefer et al., 2011), a land surface model that simulates permafrost processes, and estimated that permafrost thawing emissions could add an extra 43 USD trillion, or 13%, to the mean net present value – the sum of discounted future cashflows of an investment at the time of calculation – of climate change impacts by 2200, under a scenario with rapid population growth and where the atmospheric concentration in 2100 is around 700 ppm (A1B scenario (IPCC, 2000)). That study, the first analysis of its kind, did not internally emulate the permafrost processes in PAGE09 but directly added the emissions from SiBCASA. Gonzalez-Eguino and Neumann (2016) used the IAM DICE (Nordhaus and Sztorc, 2013) to analyse the impact of permafrost thawing emissions on the available carbon budget (i.e., the amount of carbon that humanity can emit to stay below a given global warming level), finding that it needs to be reduced by between 6–17% for the global warming level to remain below 2 °C by 2100. Kessler (2017) integrated a permafrost carbon feedback module to DICE to assess a range of economic impacts, including climate damages, the social cost of carbon, and the optimal abatement path. They found that the extra damages reached 3.6 and 57.3 USD trillion in 2100 and 2300 respectively (mean annual values). Wirths et al. (2018) incorporated an endogenous permafrost carbon feedback into DICE2013-R and found that the net present value of losses of output ranges from 0.9–3.2 USD Trill. or 0.02–0.08 %. Yumashev et al. (2019) used PAGE09 as a starting point to develop PAGE-ICE, which includes, among other changes, a permafrost carbon feedback and a surface albedo feedback emulator to estimate the climate change impacts of these two phenomena. They found that both factors increase the mean net present value of impacts by 24.8 USD trillion under the 1.5 °C scenario, 33.8 USD trillion under the 2 °C scenario and 66.9 USD trillion under the mitigation efforts from the Nationally Determined Contributions by 2300. These values are considerable given that a recent analysis using PAGE09 showed that under a 1.5°C scenario avoided damages would be 20% than in a 2 °C, amongst other decreases in risks (Warren, 2021; 2022). Unlike PAGE09 and PAGE22, PAGE-ICE has fixed in-built scenarios as opposed to user-definable ones. None of the studies cited above include a permafrost carbon emulator into the model whilst incorporating uncertainty into parameters, results and enabling user-definable flexibility around analysis time periods and mitigation and adaptation scenarios. PAGE22 meets these three criteria.

It is crucial to quantify the climate processes not currently included in most climate models – like permafrost thawing – given that these will result in larger climate change costs than in model versions which do not factor these in. Given that IAMs results are used to inform policymakers on the costs and benefits from climate change (IAWG, 2010; 2013), not factoring in feedbacks like permafrost thawing not only underestimates economic impacts but also other important results, such as the remaining carbon budget for a given global warming level.

In 2015, almost 200 parties signed the Paris Agreement, a legally binding commitment to limit the global temperature increase vs. pre-industrial "*well below 2 °C*", preferably 1.5 °C, to limit climate change risks and impacts (UN, 2015). This agreement has spurred more stringent climate policies around the globe, including establishing Nationally Determined Contributions (NDCs) at the country level, a series of national plans to progress on climate mitigation (UN, 2015). Not only a strong decarbonisation of the economy is needed to cut down greenhouse gases emissions to meet the Paris Agreement targets, but also incorporating climate feedbacks – from processes like permafrost thawing – into GCMs and IAMs used by policymakers so that both climate change physical and economic impacts assessments are not based on underestimates.

PAGE09, DICE (Nordhaus, 2013) and FUND (Tol, 1996; Wadhoff et al., 2014) are all well-known IAMs which were used to calibrate the social cost of carbon for the US government (IAWG, 2010; 2013). One of the biggest criticisms to these is that they are outdated and interdependent due to calibration of certain parameters between each other (Burke et al., 2016; Rose et al., 2014). These criticisms were considered when developing PAGE22. Major new additions in PAGE22 include incorporating the physical impacts from permafrost thawing (Burke et al., 2017) and the non-linear persistent effect of temperature on economic production (Burke et al., 2015; see Chapter 4). These new additions are, respectively, based on the research derived from a physical permafrost model for the permafrost thawing emulator and an empirical study for the economic effect. Neither of these are outdated nor depending on other IAMs, hence addressing both criticisms. Combined, they make PAGE22 state-of-the-art in terms of simulating the socioeconomic impacts of climate change.

This chapter is organised as follows. Section 3.2 details each of the modifications made to PAGE09 to develop PAGE22 with a focus on physical impacts. Section 3.3 presents the first results from PAGE22 starting with a benchmark of temperature projections up to 2200 from PAGE22 against PAGE09. This is to understand how the modifications to PAGE09 to develop PAGE22 translate into changes in temperature projections. It also includes a comparison of the results from PAGE22 to PAGE-ICE and also to those presented in IPCC (2021c). It is followed by an analysis of cumulative permafrost emissions for different time frames and scenarios, how this sits in the literature and how they affect temperature projections. The discussion in Section 3.4 considers some of the limitations in developing PAGE22 as well as suggestions for future research. Finally, the chapter finishes with a summary and conclusions in section 3.5.

3.2. Building PAGE22

This section describes the development of PAGE22 from PAGE09 (Hope, 2011). It starts with an introduction to PAGE09, including some of the equations used in the climate module. PAGE22 was developed through changes made to the default version of PAGE09. These changes are described in more detail in individual subsections.

3.2.1. The PAGE09 model

PAGE09, on which PAGE22 is based, is a policy evaluation stochastic model. This means it evaluates climate policies by randomly variating the parameters in the model and estimating results as probability distributions. PAGE09 itself is an updated version of PAGE2002 model (Hope, 2006; Hope, 2008 a,b), which in turn, is an updated version of PAGE95 model (Plambeck and Hope, 1995, 1996; Plambeck et al., 1997). The acronym PAGE stands for Policy Analysis of the Greenhouse Effect. PAGE09 was one of three IAMs used to estimate the social cost of carbon dioxide (SCCO$_2$) by the United States government (IAWG, 2013). PAGE2002 was used in the previous SCCO$_2$ estimate by the United States Government (IAWG, 2010), to estimate the SCCO$_2$ and value climate change impacts in the Stern Review (Stern, 2007), as well as in a review on the economics of climate change in Southeast Asia (Asian Development Bank, 2009) and to assess the climate change impacts of deforestation in the Eliasch review (Eliasch, 2008; Hope, 2011).

PAGE09 was developed for evaluating the potential economic impacts from climate change as well as the mitigation and adaptation costs of different policies. It includes a climate module and an economic module. The climate module models greenhouse gases emissions and converts them into concentrations and then radiative forcing levels which are used to project temperature changes vs. pre-industrial and sea level rise. The economic module translates the projected physical impacts – temperature increase and sea level rise – into economic terms through damage functions. Impacts are aggregated to calculate the net present value of each policy and their difference.

In general use, the user defines two policies, which can include a mix of abatement and adaptation. The abatement portion of each policy consists of the projected changes in emissions for different greenhouse gases (GHGs) for the ten analysis time periods vs. 2008. The adaptation portion of each policy consists of defining seven parameters each for the sea level, economic and non-economic impact sectors (e.g., increase of the tolerable temperature in a region beyond which impacts are accrued).

The projected changes in emissions vs. the base year are used to calculate the projected emissions up to 2200, which are then converted into a time series of radiative forcing for each GHG. Radiative forcing is the net imbalance in energy at the top of the atmosphere, which can be affected by changes in solar output, volcanoes, and GHGs (IPCC, 2021). These time series of radiative forcing are then used to project the physical variables of near surface air temperature increase and sea level rise physical variables from the base year value.

The economic module includes four impact sectors: economic, non-economic, sea level rise and discontinuities as well as climate mitigation and adaptation costs. The impacts which are directly included in GDP are represented in the economic impact sector whereas the non-economic impact sector represents those which are not (e.g.: ecosystem services, health impacts). The discontinuities impact sector includes those large-scale abrupt and/ or irreversible events such as the melting of the Greenland icesheet (American Meteorological Society, 2022). Chapter 4 includes a more detailed explanation of each impact sector.

It is a Microsoft Excel-based IAM, using the @RISK plugin to perform Latin Hypercube sampling (LHS)[9] to perform probabilistic calculations. Each model simulation estimates the costs[10] from two user-definable policies plus their difference. In this model, the world is divided in eight regions: European Union, United States of America, Other OECD, Former Soviet Union and Rest of Europe, China and Central Pacific Asia, India and Southeast Asia, Africa and Middle East, and Latin America. The base year for calculations is 2008 and impacts are calculated for ten unequally spaced analysis time periods up to the year 2200.

One of the strengths of PAGE09 is the flexibility with which the user can modify the probabilistic distribution of the parameters in the model and/ or define the base year and analysis time periods. Even though the default version of PAGE09 uses 2008 and 2200 as its base and end year respectively, these years are not fixed and can be modified. Changing the base year would entail adjusting several scientific and economic parameters which are used as initial values to build projections from but modifying the rest of the years does not entail this effort.

For ease of reference, I am including the equations which show how projected changes in emissions vs. the base year translate into changes in global mean temperature in PAGE09; this is how they are described by the original developer of the PAGE model (Hope, 2006; Hope, 2011). The reason for including these equations is twofold: 1) to show the level of

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[9] *LHS (McKay, Beckman and Conover, 1979) is an alternative to Monte Carlo simple random sampling technique which "improves the coverage of the range of parameters" (Hope, 2006, page 47)*

[10] *Abatement costs, adaptation costs and damages*

complexity in the climate module in PAGE09 and 2) to introduce some of the equations which will be modified to develop the permafrost thawing emulator in PAGE22.

PAGE09 estimates physical and economic impacts from anthropogenic climate change measured vs. preindustrial times. PAGE09 includes explicit regional representations of the greenhouse gases CO_2, methane (CH_4) and nitrous oxide (N_2O), as well as "linear gases", which are those with an atmospheric concentration so low that their radiative forcing has a linear behaviour with respect to their concentration (hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride).

As a starting point for computing the temperature increases vs. pre-industrial, PAGE09 calculates the anthropogenic excess concentration (EXC) of each of these gases g as

$$EXC_{g,0} = C_{g,0} - PIC_{g,0} \qquad \text{[ppbv]} \qquad [3.1]$$

g= 1-4 ,

where $C_{g,0}$ is the concentration in the atmosphere in the base year *0* and $PIC_{g,0}$ is the pre-industrial concentration of each of the explicitly represented GHG, both input data in the model. In turn, the excess concentration of each GHG is used as an input to calculate the level of emissions remaining in the atmosphere in the base year (RE),

$$RE_{g,0} = EXC_{g,0} * DEN_g, \qquad \text{[Mtonne]} \qquad [3.2]$$

g= 1-4 ,

where DEN_g is the density of each explicitly represented GHG denoted by g [Mtonne/ppbv].

Emissions

Taking CO_2 as an example – denoted by suffix *1* in equations [3.3 to 3.16 below], PAGE09 takes the CO_2 emissions in the base year (2008) – $E_{1,0,r}$ in equation [3.3] – and the user-definable CO_2 emissions specified in the abatement policies (measured as a percentage of the base year emissions in each analysis time period and region) – $ER_{1,i,r}$ in equation [3.3] – to project regional emissions as

$$E_{1,i,r} = \frac{ER_{1,i,r} * E_{1,0,r}}{100} \qquad \text{[Mtonne]} \qquad [3.3]$$

i=1 to 10, r=1 to 8,

The regional emissions are then aggregated at the global level

$$E_{1,i} = \sum_r E_{1,i,r} \qquad \text{[Mtonne]} \qquad [3.4]$$

i=1 to 10, r=1 to 8,

and used to calculate the total emissions to air of CO_2

$$TEA_{1,i} = E_{1,i} * \frac{AIR_1}{100} \qquad \text{[Mtonne]} \qquad [3.5]$$

i=1 to 10,

where AIR_1 is the airborne fraction, which is the percentage of CO_2 emissions that gets into the atmosphere, acknowledging the initial decay of CO_2. The total emissions to air of CO_2 in each analysis period is approximated as a linear interpolation

$$TEAY_{1,i} = \frac{(TEA_{1,i} + TEA_{1,i-1}) * (Y_i - Y_{i-1})}{2} \qquad \text{[Mtonne]} \qquad [3.6]$$

i=1 to 10,

where $(Y_i - Y_{i-1})$ is the time between the analysis time years. The cumulative emissions to air of CO_2 are calculated as

$$CEA_{1,0} = CE_{1,0} * \frac{AIR_1}{100} \qquad [\text{Mtonne}] \qquad [3.7],$$

$$CEA_{1,i} = CEA_{1,i-1} + \ TEAY_{1,i} \qquad [\text{Mtonne}] \qquad [3.8]$$

i=1 to 10,

where $CE_{1,0}$ are the total anthropogenic emissions of CO_2 up to the base year (2008). PAGE09 includes a climate-carbon feedback factor – CCFF – from the effect of temperature increase on CO_2 concentration as a proxy for the release of soil carbon and decreased absorption from the ocean. The remaining emissions of CO_2 in the atmosphere before this carbon feedback are calculated as

$$RE\_NO\_CCFF_{1,i} = STAY_1 * \ CEA_{1,i-1} * (1\text{-}\ e^{\frac{-(Y_i - Y_{i-1})}{RES_1}}) + RE_{1,i-1} * (e^{\frac{-(Y_i - Y_{i-1})}{RES_1}}) + TEAY_{1,i} * (\ e^{\frac{-(Y_i - Y_{i-1})}{2 * RES_1}})$$

$$[\text{Mtonne}] \qquad [3.9]$$

i=1 to 10,

where RES_1 is the half-life (in years) of CO_2 atmospheric residence and $STAY_1$ is the % of emissions to the atmosphere. Remaining CO_2 emissions in year Y_i are increased by emissions to the atmosphere and decreased by interactions (chemical and others) since previous analysis year Y_{i-1}.

Concentration

The concentration of CO_2 before CCFF is calculated as

$$C\_NO\_CCFF_{1,i} = PIC_1 + \ EXC_{1,0} * \frac{RE_{1,i}}{RE_{1,0}} \qquad [\text{ppbv}] \qquad [3.10]$$

i=1 to 10,

The carbon cycle feedback gain and factor are calculated as:

$$GAIN_i = \min(CCF * RT\_G_{i-1} + CCFMAX) \qquad [\text{ppb}] \qquad [3.11]$$

i=1 to 10,

$$CCFF_i = (C\_NO\_CCFF_{1,i} - PIC_1) * \frac{GAIN_i}{100} \qquad [\text{ppb}] \qquad [3.12]$$

i=1 to 10,

where CCF is the stimulation of CO_2 concentration expressed as a percentage over temperature ratio, RT_G_{i-1} is the global realised temperature in the previous analysis time period and $CCFMAX$ is the CO2 stimulation limit, expressed in percentual terms. Both CCF and $CCFMAX$ are uncertain parameters represented by triangular distributions.

The concentration of CO_2 after the CCFF is calculated as:

$$C_{1,i} = C\_NO\_CCFF_{1,i} + CCFF_i \qquad [\text{ppb}] \qquad [3.13]$$

i=1 to 10,

Radiative forcing

The radiative forcing from CO_2 is calculated as

$$F_{1,i} = F_{1,0} + FSLOPE_1 * \ln\left(\frac{C_{1,i}}{C_{1,0}}\right) \qquad [\text{W/m}^2] \qquad [3.14]$$

i=1 to 10,

given the logarithmic dependency of radiative forcing to the concentration of CO2 (Baede et al., 2001), where $F_{1,0}$ is the radiative forcing from CO_2 in the base year and $FSLOPE_1$ is the forcing slope is the constant in CO_2 forcing formula.

The total extra anthropogenic forcing FT is calculated from the sum of the extra forcings from CO_2, CH_4, N_2O and linear gases and the forcing from other gases not explicitly represented in the model, EXF

$$FT_i = \sum_g F_{g,i} + EXF_i \qquad [\mathrm{W/m^2}] \qquad [3.15]$$

i=1 to 10, g=1 to 4,

Temperature

The radiative forcing from all these gases as well as from sulphates are inputs to calculate the equilibrium temperature ET,

$$ET_{i,r} = \frac{SENS}{\ln(2)} * \frac{FT_i + FS_{i,r}}{FSLOPE_1} \qquad [°C] \qquad [3.16]$$

i=1 to 10, r=1 to 8,

where $FS_{i,r}$ is the forcing from sulphates for each region and analysis time period and $SENS$ is the equilibrium warming for a doubling of CO_2. The latter is estimated using the transient climate response (TCR) and the feedback response time[11] (FRT). The TCR is the temperature increase resulting from a steady 1% per year increase in CO_2 concentrations at the point of CO_2 doubling.

The projected temperature and sea level rise are affected by the adaptation policies defined by the user, which raise the tolerable level above which impacts occur at the expense of adaptation costs, The resulting regional temperature and sea level rise are converted into monetary impacts through so-called impact functions (Hope, 2011).

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[11] *" the characteristic lifetime of the delay in reaching the equilibrium temperature increase triggered by an increase in radiative forcing" Hope (2013), page 535*

IAMs treatment of uncertainty can be split into two sources: climate change uncertainty and uncertainty stemming from socioeconomic sources (Heal and Milner, 2014). Future climate change and its attribution to anthropogenic drivers has several uncertainties, and the IPCC has developed its own "calibrated language" to describe the confidence that can be placed in particular statements (Chen et al., 2021). As an example, according to AR6 the best estimate of the equilibrium climate sensitivity (ECS) parameter[12] is 3 °C with a "*likely*" range of 2.5-4 °C and "*very likely*" range of 2-5 °C (Forster et al., 2021). Despite decades of research on this, the "*very likely*" range is quite large: from 33% lower to 66% higher than the best estimate. This range translates into a range of possible climate outcomes for a given emission of greenhouse gases, which then translate into uncertainties for our estimates of the future impacts of climate change. Socioeconomic uncertainties are apparent in, for example, the range of possible damage functions used to estimate future impacts (Stanton et al., 2009). In addition to the climate change and socioeconomic uncertainties, there are uncertainties in things like the capacity of (present and future) societies to adapt to climate change, which is essentially unknowable (Heal and Milner, 2014).

Unlike deterministic IAMs, which rely on sensitivity analyses around parameters to understand the effect of changes over results, the outputs from PAGE09 consist of probabilistic distributions. This results from including probability distributions associated to most of its parameters, both for climate (e.g., transient climate response) and socioeconomic (e.g.: economic impact at calibration temperature) ones and by using Latin

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[12] *"the equilibrium (steady state) change in the surface temperature following a doubling of the atmospheric carbon dioxide (CO2) concentration from pre-industrial conditions.", (IPCC, 2021b, page 2233)*

hypercube sampling to perform calculations. Using the model results with 10,000 simulations will include some parameter values close to the extremes of their ranges.

This Chapter describes a default version of PAGE22, which includes, aside from the structural changes on permafrost thawing representation as well as temperature forecasting, a set of fixed values to define each of the random parameter distributions. However, the probability distributions for each parameter are user-definable and can be modified to allow for different sensitivity analysis, including the use of fat-tailed distributions. In addition, PAGE22 no longer models “linear gases” explicitly but implicitly as part of excess radiative forcing. This modification simplifies the treatment of these gases and moves away from the need to assume that they are represented by a single molecular weight.

3.2.2. Base year and analysis time periods

The first step towards developing PAGE22 was defining a new base year (formerly 2008 in PAGE09) to start projections from. 2019 was chosen as the base year for two reasons. Firstly, it is the most recent year prior to the onset of the COVID-19 pandemic and it is in line with the 2016–2020 average in terms of GDP (3% above average). Secondly, it matches the base year for the IPCC Sixth Assessment Report, from which several parameters in PAGE are taken (e.g., cumulative emissions and concentrations of the GHG explicitly represented in PAGE, sea level rise in base year). A huge benefit of using IPCC data for parameters is that it has been extensively reviewed by the scientific community and hence the robustness is higher than using a single source.

IAMs need to balance two rather different time scales: the long-time scales of climate (~decades–centuries) and the shorter ones for the economy (~months–years). In PAGE22 time is represented in the same manner as PAGE09, using a base year and ten analysis time periods, which are future years in which different physical and socioeconomic variables are projected in order to estimate physical and economic impacts. However, the base year and analysis period years are different in PAGE22, as indicated in Table 3.1.

Table 3.1. Analysis time periods in PAGE09, PAGE22 and PAGE22-SCCO2 (all model versions). The 11 analysis time periods correspond to times when the model outputs results.

Analysis period/ Model	Base year	1	2	3	4	5	6	7	8	9	10
PAGE09	2008	2009	2010	2020	2030	2040	2050	2075	2100	2150	2200
PAGE22	2019	2020	2030	2040	2050	2075	2100	2150	2200	2250	2300

The development of PAGE22 particularly focuses on the thawing of the permafrost in the Northern Hemisphere (see Section 3.2.5). With that in mind, the default end analysis year in PAGE09 was extended from 2200 to 2300 in PAGE22 to analyse the long-term impacts from permafrost thawing (Schneider von deimling et al., 2012; Schaefer et al., 2014) in line with similar impact studies on the subject (e.g., Yumashev et al., 2019).

3.2.3. Climate and economic parameters

This section includes an analysis of the parameters in PAGE09 which were modified to develop PAGE22. It starts by focussing on the regional parameters and follows by the global ones. Hope (2011; his Appendix 2) includes the full set of parameter values in PAGE09 and Appendix A includes the full set of inputs for calculations for PAGE22.

Regional

Table 3.2 includes the regional split of several parameter values which were updated from 2008 in PAGE09 to 2019 in PAGE22. These regional base year parameters set the initial socioeconomic and climate conditions which are then projected into the future using both the global parameters and the user-definable abatement and adaptation policies.

Table 3.2. Regional parameters update in PAGE22 and PAGE22-SCCO2 (all model versions). ROE stands for Rest of Europe.

PAGE22 Region	GDP [USD Trill.]	Population [Mill.]	CO2 emissions [Mtonne]	CH4 emissions [Mtonne]	N2O emissions [Mtonne]	Sulphates emissions [TgS]	Natural sulphates' emissions [Tg/km2]	Regional temperature [degC]
European Union	19	513	3,634	19	0.9	3.6	3.0E-07	1.9
United States	21	329	5,805	27	0.9	1.8	7.2E-08	1.7
Other OECD	10	292	3,095	15	0.7	1.8	4.8E-08	1.6
Former Soviet Union and ROE	3	315	2,258	54	0.6	2.7	4.4E-08	2.4
China & Central Pacific Asia	15	1,616	12,387	63	2.1	11.8	3.7E-07	1.6
India & Southeast Asia	8	2,387	6,734	71	1.9	6.3	2.7E-07	1.3
Africa & Middle East	5	1,560	5,608	67	2.5	4.5	4.6E-08	1.2
Latin America	5	646	2,979	46	1.4	3.6	3.9E-08	1.2

The monetary units in the model are expressed in USD of the base year: 2008 USD in PAGE09 and 2019 USD in PAGE22. The global GDP increased from 63.2 USD Trill. (2008 USD) to 86.6 USD Trill. (2019 USD) (World Bank, 2022) and the global population increased from 6.8 billion to 7.7 billion

(World Bank, 2022) in PAGE09 and PAGE22 respectively. The average GDP per capita in the base year increased from 9,300 USD to 11,200 USD in PAGE09 and PAGE22 respectively. Out of this 21% increase, 16% is due to the consumer price difference between both base years: 215 in 2008 to 256 in 2019 (Federal Reserve Bank of Minneaopolis, 2022).

The 2019 emissions[13] – including those from land use, land use change and forestry (LULUCF) – totalled 42,500, 363 and 11 Mtonnes of CO_2, CH_4 and N_2O respectively which equals 55.6 $GtCO_2$ equivalent (Olivier and Peters, 2020; van der Werf et al., 2017). The regional split in the Olivier and Peters (2020) database does not include LULUCF at the country level which is why the regional split from the Climate Watch (2022) was used instead. The anthropogenic emissions from sulphates are estimated from sulphur dioxide emissions in 2015 of 100 $MtSO_2$/yr (IPCC,2021) and applying the 2015-2019 decrease from Dahiya et al. (2020). The latter was not used as a source for the 2019 emissions value as it does not account for sources which emit less than 30kt/yr. The natural emissions from sulphates are based on those from volcanic eruptions and totalled 27 $MtSO_2$/yr (Fischer et al., 2019).

The regional land temperatures are approximated based on the effective absolute latitude of the region (GISTEMP Team, 2022; Lenssen et al., 2019) and calibrated to match the 1.1 °C global mean temperature increase vs. pre-industrial (WMO, 2020).

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[13] *Olivier and Peters (2020) was used as a source for base year (2019) GHG emissions per gas as it is the most comprehensive source with yearly publications and a matching database and it is also cited in the UN's emissions gap report 2021. Given that it does not include a split for the CH4 and N2O LUC emissions from forest and peat fires, these were calculated from their cited source (van der Werf et al., 2017).*

Global

Table 3.3 includes the global climate parameters in PAGE22 which were modified from those in PAGE09.

Table 3.3. Global climate parameters updated in PAGE22 and PAGE22-SCCO2 (all model versions). Min, mode and max values in columns are used as inputs for triangular distributions of each parameter.

Parameter	Mean	Min	Mode	Max	Unit
Transient climate response	1.7	0.8	1.7	2.5	degC
Land excess temperature ratio to ocean	1.6	1.5	1.6	1.8	
Sulfate direct (linear) effect in 2019	-0.2	-0.6	-0.2	0.1	W/m2
Sulfate indirect (log) effect for a doubling of sulphates	-0.5	-0.9	-0.5	0.0	W/m2
Sea level rise in 2019	0.2	0.2	0.2	0.3	m
Half-life of global warming	29.3	5.0	8.0	75.0	years
Equilibrium warming for a doubling of CO2	2.7				degC
Tolerable before discontinuity	1.5	1.0	1.5	2.0	degC
Half-life of discontinuity	567	200	500	1000	years

The transient climate response parametrisation in table 3.3. results in a value of 1.7 [1.1,2.2] (mean, 90% CI) in line with AR6 estimate of a mean value of 1.7 [1.1,2.3] (mean, 90% CI) of the emergent constraints[14] method which is similar to the “combined assessment” estimates 1.8 [1.2,2.4] (mean, 90% CI) estimate (Forster et al., 2021). The half-life of global warming was parameterised so that the equilibrium warming for a doubling of CO_2 (the SENS parameter; see section 3.2.1.) was in line with the latest IPCC report as well. As a result, the equilibrium climate sensitivity of PAGE22 is 2.7°C

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[14] “Numerous studies have leveraged this spread in order to narrow estimates of Earth's climate sensitivity by employing methods known as “emergent constraints” (Chapter 1, Section 1.5.4). These methods establish a relationship between an observable and either ECS or TCR based on an ensemble of models, and combine this information with observations to constrain the probability distribution of ECS or TCR.” (Forster et al., 2021, page 106).

[1.5–4.5; 90% CI] in line with the emergent constraints approach of the IPCC of 2.4–3.3°C [1.5–5; 90% CI] (Forster et al., 2021).

The land excess temperature ratio to ocean[15] is used to project the global mean temperature after the equilibrium temperature projections following equation 3.16 in section 3.2.1. It was calibrated with minimum and mode values from Tebaldi et al. (2021) and maximum value from Gulev et al. (2021). The sulphates direct effect[16] parameterisation results in a 2020 radiative forcing of -0.2 [-0.49, -0.003] W/m^2 compatible with aerosols radiation interactions radiative forcing of -0.22 [-0.47, +0.04] W/m^2 in 2019 in Forster et al. (2021). The indirect effect of sulphates[17] parameterisation results in a 2020 radiative forcing of -0.84 [-1.44, -0.27] compatible with aerosols cloud interactions radiative forcing of -0.84 [-1.45, -0.25] in 2019 in Forster et al. (2021).

The sea level rise in 2019 was estimated based on the increase in global mean sea level rise between 1901-2018 (given the negligible effect in metres between 2018 and 2019) from Gulev et al. (2021). The "tolerable before discontinuity" and the "half-life of discontinuity" were parametrised as in Arctic-ready PAGE (a precursor to PAGE-ICE; Yumashev et al., 2016) based on AR5. The "tolerable before discontinuity" is the temperature threshold above which a discontinuity can be triggered (Hope and Schaefer, 2015, methods). The values were not modified from Arctic-ready PAGE given that these values are in line with AR6 which states that the AMOC will likely continue to weaken at 1.5 degC and limited evidence of Greenland

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[15] This parameter is needed given the difference in solar radiation absorption capacity between land and ocean (Sutton et al., 2007).

[16] The direct effect of aerosols reflects "*changes in the scattering and absorption of incoming solar radiation*" (Forster et al., 2021, page 948)

[17] The indirect effect of aerosols represents effects on "*cloud micro- and macro-physics and thus cloud radiative properties*" (Forster et al., 2021, page 948)

and West Antarctica ice sheets melt loss for a 2 degC temperature increase vs. pre-industrial (Arias et al., 2021). The "half-life of discontinuity" is the time (years) it takes for the discontinuity to unfold; e.g.: under high levels of warming the ice sheets would melt over millennia. The range is quite broad to encompass a range of different phenomena; from the weakening of the AMOC to the melting of the ice sheets. All the economic parameters were based on Arctic-ready PAGE and adjusted by the cumulative inflation of USD between 2013 and 2019. This includes a revision of the non-market impact sector – ecosystem services and health impacts – to align it with estimates from AR5 (WG2, Chapter 10).

3.2.4. Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) up to 2300

Climate models are numerical models which are used to project future climate across space and time (Chen et al., 2021). The most complex ones are Global Earth system models (ESMs), which are used together with regional models to downscale the global climate information (Chen et al., 2021). Given the broad range of ESMs and modelling teams, initiatives like the Coupled Model Intercomparison Project (CMIP) are crucial to harmonise the range of results from ESMs. CMIP, which has been running for over two decades, uses scenarios common to all climate modelling teams to create an ensemble of projections of different climate variables. In addition, the results from CMIP are widely used in the climate change impact literature and also inform IPCC reports. As a result, the scenario development process within the scientific community plays a crucial role in shaping the possible futures that will be studied and influence climate policies.

The existing scenarios in the default version of PAGE09 are based on the IPCC's Special Report on Emissions Scenarios (SRES) (IPCC, 2000), which were used to inform climate projections in the Third (IPCC, 2001) and Fourth (IPCC, 2007) Assessment Reports. PAGE22 includes an update from the SRES scenarios to the Representative Concentration Pathways (RCPs) and Socioeconomic Pathways (SSPs), which were developed and used by the scientific community to inform climate projections in the IPCC's Fifth Assessment Report (AR5) (IPCC, 2013). In addition, many of the recent impact studies on both permafrost thawing (e.g.: Yumashev et al., 2019) and economic impacts from climate change (e.g.: Burke et al., 2015) use the SSPX-RCPY scenarios which is useful for benchmarking purposes (section 3.3.4). The RCPs and SSPs are the first two stages of a new scenario framework (van Vuuren et al., 2014), and their implementation in PAGE22 and PAGE22-SCCO2, are briefly summarised below.

3.2.4.1. RCPs

The RCPs constitute four radiative forcing pathways and the numerical values in their names – RCP 2.6 (van Vuuren et al., 2011b), RCP 4.5 (Thomson et al., 2011), RCP 6.0 (Masui et al., 2011) and RCP 8.5 (Riahi et al., 2011) – result from the approximate radiative forcing value in 2100 (expressed in [W/m^2]) vs. pre-industrial times. They are the starting point of a parallel scenario development process established by the scientific community as an alternative to the traditional "sequential approach" with the aim of reducing the length of the process (Moss et al., 2010). Previously, each research community worked on its own discipline towards the overall scenario development and that input was used as input for the next research community team, which resulted in a lengthier process overall (Moss et al., 2010).

Each RCP is based on an independent pre-existing scenario developed by four IAM modelling teams – and different IAMs – and updated to harmonise[18] and downscale[19] the land-use and emissions data (van Vuuren et al., 2011a). The aim of the RCP development is to encompass the range of plausible forcing levels from the scenarios in the literature so that the resulting forcing can be used as input for the climate modelling and IAM communities to conduct climate experiments and develop new emissions and socioeconomic scenarios in parallel (van Vuuren et al., 2011a). As such, they are not "*policy prescriptive*" and could be achieved through different technological and socioeconomic scenarios (van Vuuren et al., 2011a).

The RCP database[20], which is hosted by IIASA, contains times series of greenhouse gas and pollutant emissions and concentrations, radiative forcing, and land cover projections for each RCP (RCP2.6: van Vuuren et al., 2007; RCP 4.5: Clarke et al., 2007; Smith et al., 2006; Wise et al., 2009; RCP 6.0: Fujino et al., 2006, Hijioka et al., 2008; RCP 8.5: Riahi et al., 2007). The data contained in the database was used to develop the RCP emission scenarios in PAGE22 using the criteria outlined below.

Analysis time periods

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[18] *"i.e.made consistent with a selected set of base year data" (van Vuuren et al., 2011a, page 10)*

[19] *"to a 0.5×0.5 grid" (van Vuuren et al., 2011a, page 10)*

[20] *RCP Database (iiasa.ac.at)*

PAGE22 calculates climate and impacts for particular time periods (Table 3.1). For emissions at the decades (2020, 2030 etc), PAGE22 uses values taken directly from the RCP database, with 2075 calculated by linear interpolation between 2070–2080. The RCP extension beyond 2100 is based on Meinshausen et al. (2011, their table 3), who describe the criteria for the development of the Extended Concentration Pathways (ECP) up to 2300. RCP 2.6 emissions are kept constant beyond 2100 for 2150, 2200, 2250 and 2300 resulting in the adaptation of ECP 2.6 into PAGE22. For incorporating ECP 4.5, 6.0 and 8.5 into PAGE22, the global emissions for 2150, 2200, 2250 and 2300 are estimated in terms of their projected change vs. 2100 for each CO2, CH4, N2O and sulphates using the datasets from Meinshausen et al. (2011) given that there is no regional detail. These are applied to the 2100 regional percentual changes vs. the base year for each gas. The excess forcing – an input at the global level which represents the radiative forcing from other climate forcers[21] – for the analysis periods beyond 2100 is estimated as the difference between the total radiative forcing in Meinshausen et al. (2011) and the total radiative forcing in PAGE22 from CO2, CH_4, N_2O and sulphates.

Regional detail

PAGE22´s regional split is the same as in PAGE09. The RCP database includes world values as well as a regional detail for Asia, Latin America, Middle East and Africa, OECD and Reforming Economies. The correspondence between these and the regional split in PAGE22 is as follows: OECD for EU, USA and Other OECD, Reforming economies for Former Soviet Union and Rest of Europe, Asia for China & CP Asia and

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[21] *Halogens, ozone, stratospheric water vapour, Contrail-cirrus, Black carbon on snow, land use, volcanic, solar*

India & SE Asia, Africa and Middle East and Latin America for their analogous regions.

Forcing agents

PAGE22 requires inputs for CO_2, CH_4, N_2O and sulphate aerosols for each region – expressed both as a % emission change over the base year – and a radiative forcing amount from other gases (W/m^2). Using linear interpolation and regional detail matching, described in the previous sections, the CO_2, CH_4, N_2O and sulphate emissions are calculated up to 2100 using the emissions data from the RCP database. The rest of the forcing agents are included as excess forcing. The resulting emissions and excess forcing values for each RCP/ ECP are detailed in Appendix B.

3.2.4.2. SSPs

The Shared Socioeconomic Pathways (SSPs) were developed as the second phase of the new scenario framework (van Vuuren et al., 2014). The aim of their development is to encompass a range of "*socioeconomic futures*" up to 2100 (O' Neill et al., 2014) that can be coupled with the climate projections resulting from the RCPs as well as the Shared Climate Policy Assumptions (SPAs) (Kriegler et al., 2014) to develop new "*integrated scenarios*" for impacts, adaptation and vulnerability (IAV) analysis (van Vuuren et al., 2014).

They are based on five different narratives around challenges to mitigation and adaptation (O' Neill et al., 2016) but do not include climate change impacts nor any new climate policy assumptions other than those in place at the time of their development (O'Neill et al., 2014). They were developed by six different IAM teams and their models, and five "*SSP markers*" were chosen as "*representative of the broader developments of each SSP*" (Riahi et al., 2017, p. 154) each corresponding to a different IAM. Table 3.3 includes a summary of each SSP marker.

Table 3.3. SSP marker scenarios. [Adapted from Riahi et al. (2017), their tables 1 and 2]

SSP marker	SSP narrative name	Mitigation challenges	Adaptation challenges	Main IAM	IAM modelling team	Reference paper
SSP1	Sustainability- Taking the green road	Low	Low	IMAGE	PBL	van Vuuren et al. (2016)
SSP2	Middle of the road	Medium	Medium	MESSAGE- GLOBIOM	IIASA	Fricko et al. (2016)
SSP3	Regional rivalry- A rocky road	High	High	AIM/ CGE	NIES	Fujimori et al. (2016)
SSP4	Inequality- a road divided	Low	High	GCAM	PNNL	Calvin et al. (2016)
SSP5	Fossil- fueled development- Taking the highway	High	Low	REMIND- MAgPIE	PIK	Kriegler et al. (2016)

GDP and Population growth rates were taken from the SSP scenario database[22] (Riahi et al., 2017; Samir and Lutz, 2017; Dellink et al., 2017) aggregating country level data to PAGE22 regional detail. In the default version of PAGE22, the growth rates are held constant from 2100 up to 2300. The resulting GDP and Population growth rates for each PAGE22 region and SSP marker are detailed in Appendix B.

According to the most recent population projections, global population is expected to grow to 10.4 Billion in 2100, the equivalent to 0.3% increase per year given the 8 Billion mark in 2022 (United Nations Department of Economic and Social Affairs, Population Division, 2022). As seen in Appendix B, the SSP encompass a range of population growth rates: the equivalent to a global population increase between 2019-2100 of 0.6% per year under SSP3 to -0.1% per year under SSP1.

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[22] *SSP Database (iiasa.ac.at)*

3.2.5. Modelling permafrost thawing in the Northern circumpolar permafrost region

This section includes a brief description of how the permafrost carbon emissions – both as carbon dioxide and methane – are parametrised as a function of global mean temperature (GMT). PAGE09 only includes climate change impacts from user-defined emissions scenarios and does not factor in the potential large impacts through the climate feedbacks (temperature increases) from permafrost thawing. The permafrost carbon emulator developed in PAGE22 is the second explicit climate feedback representation in the model. PAGE09 already includes one carbon-related climate feedback which reflects the decrease in CO_2 uptake by the oceans and land as temperature increases.

Permafrost emissions in the form of carbon dioxide and methane are parameterised in PAGE22 as a function of temperature, following Burke et al. (2017). The novelty of their approach is using complex land surface models – JULES (Best et al., 2011; Clark et al., 2011) and ORCHIDEE-MICT (Parton et al., 1992; Koven et al., 2009, 2011; Goutevin et al., 2012; Wang et al., 2013) – to develop a new metric: the frozen carbon residence time (FCRt).

Burke et al. (2017) define the frozen carbon residence time for any time as: "*the ratio of remaining permafrost carbon to the permafrost carbon loss rate at that time*" which "*can be used to estimate permafrost carbon loss given any pathway of global mean temperature and an assessment of the initial permafrost carbon*" (p. 3062).

$$FCR_t = FCR_{t0}\ e^{\left(-\frac{\Delta T}{\Gamma}\right)} \qquad [3.17],$$

where $\Delta T > 0.2$ °C and

"FCR_{t0} *is a reference timescale representing the permafrost carbon turnover time at the transition point from accumulation of soil carbon to loss of soil carbon*"

"ΔT *is the temperature above which this transition occurs*"

"Γ *represents the temperature change at which the number of years taken for all of the old permafrost carbon to be emitted reduces by 1/e of its initial value*"

[*Source: Equation 4 in Burke et al. (2017) and page 3063 for parameter description*]

Equation 3.17 is used to model the emissions from permafrost thawing into PAGE22. These emissions are additional to the anthropogenic carbon dioxide and methane emissions in the model, which are user definable as inputs. The total emissions for each gas are converted to radiative forcing and result in a higher mean global temperature. The latter, in turn, affects sea level equilibrium and translates into economic and non-economic impacts.

The ΔT in equation 3.17 are constrained between 0.2 and 5 °C in Burke et al. (2017). The upper threshold in temperature presents a limitation as many of the scenarios that are analysed in this thesis surpass the 5°C temperature increase vs. pre-industrial times at some point during the 2300 analysis range. The complete dataset[23] of temperature ranges in Burke et al. (2017) was analysed with different fitting methods and the FCR_{t0} and Gamma parameters were estimated for both the constrained (0.2< ΔT < 5°C) and the complete datasets and the R^2 value calculated. Following the

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[23] *Personal communication with Dr. Eleanor Burke (9th September 2020)*

results in Appendix C, the R^2 values do not change considerably between the constrained and complete datasets parameter fit. In consequence, equation 3.17 is assumed to be valid up to 10.5 °C, which is the maximum temperature change in the dataset. The forecasting temperature value which is used as an input to equation 3.17 in PAGE22 is capped at the 10.5 °C limit.

Table 3.4 includes the variables used for incorporating the carbon dioxide and methane emissions from permafrost thawing in the Northern circumpolar permafrost region in PAGE22 and its parameter values based on equation 3.17. In line with several parameters in PAGE09, PAGE22 samples these values from an assumed triangular distribution, with the minimum, mode and maximum values detailed in table 3.4.

Table 3.4. Permafrost thawing parametrisation in PAGE22 (versions 1.1, 1.3 and 1.5) and PAGE22-SCCO2 (versions 1.1 and 1.3)

Parameter	mean	min	mode	max	Unit
Feedback Carbon Residence time t_0	6666	5333	6666	7999	yr
Gamma	2.6	2.1	2.6	3.1	degC
Permafrost carbon initial stock	1005	830	1000	1186	GtC
CH4 fraction of total emissions	0.02	0.020	0.023	0.026	%

The relationship between permafrost emissions and temperature is based on the parametrisations of Burke et al. (2017). The mode values for the Feedback response time t_0 and Γ (Gamma) parameters correspond to one of the model versions in Burke et al. (2017), (JULES-deepResp; their Table 1). This was chosen over the other model version (JULES-suppressResp) as its permafrost carbon stock in the top 3m (Burke et al., 2017, figure 3b and d) is more in line with the literature review values from Mishra et al. (2021).

The min and max values are -/+ 20% from the mode which produces results in line with Burke et al. (2017).

The permafrost carbon stock in the Northern circumpolar region has previously been estimated as 1,672 PgC, with 1,024 PgC in the top 3 meters, 407 PgC in the Yedoma deposits[24] and 241 PgC in deltaic deposits in Alaska, Northwest Territories (Canada) and Northern Russia (Tarnocai et al., 2009). These values are in line with more recent studies which estimate a permafrost carbon stock of 1,014 PgC (839–1,208 PgC, 95% confidence interval) in the top 3 meters with 1,000 PgC (830-1,186, 95% confidence interval) in the northern circumpolar region and the rest in the Tibetan region (Mishra et al., 2021). Following Burke et al. (2017), who derive the feedback carbon response time equation using permafrost carbon stocks of the top 3 meters, the values from Mishra et al. (2021) were used for parametrising the permafrost carbon stock in PAGE22 over Tarnocai et al. (2009) given that they include an uncertainty interval.

Methane emissions are assumed to represent 2.3% (mean in % of total carbon) of the total permafrost emissions (carbon dioxide and methane) in PAGE22, ranging from 2.0–2.6% and with the uncertainty captured by sampling a triangular distribution (values based on Schuur et al., 2013's figure 1).

3.2.6. Forecasting global mean temperature change

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[24] "*These deposits, which were formed by the deposition of sediments in unglaciated areas during glacial periods, occur in areas that, at that time, were covered by a mammoth steppe-tundra ecosystem.*" (Tarnocai et al., 2009, page 7). These "*ice-rich permafrostdeposits containing large syngenetic (freezing shortly after deposition) ice wedges, called Yedoma deposits, which accumulated in vast unglaciated regions of Eurasia, Alaska, and Northwest Canada during the Pleistocene (Schirrmeister et al., 2013).*" (Strauss et al., 2017, page 76)

The permafrost emissions calculation at a given timestep requires the global mean temperature change at that timestep as an input. The simplest solution would be to use the temperature change from the previous analysis period, as per PAGE09. However, for longer analysis periods this would introduce long lags in permafrost thawing, with – for instance – thawing in 2150 driven by the temperature change in 2100. To address this, PAGE22 uses Holt's method with damped linear trend for irregular time series (Cipra, 2006; Hanzák, 2014) to forecast temperature at the next timestep. Full details of the model selection are included in Appendix D.

3.3. Results and discussion

This section presents the first results from PAGE22. It starts with a baseline comparison of temperature projections to PAGE09 and PAGE-ICE, followed by a benchmark against AR6 and then finishes with an analysis of projected cumulative permafrost emissions.

3.3.1. Baseline comparison of PAGE22 vs. PAGE09

This section compares the projections of global mean surface temperature for PAGE22 and PAGE09 over 2020–2200, the overlap period between both models. Temperature was chosen as the indicator for comparison given that it is affected by all the changes made to develop PAGE22 from PAGE09. Comparisons are made over four different SSPX-RCPY scenarios (SSP1-RCP2.6, SSP2-RCP4.5, SSP3-RCP6.0 and SSP5-RCP8.5), which encompass a wide range of emission and mitigation levels.

Figure 3.1. Projections of global mean surface temperature changes over 2020–2200, relative to the 1850–1900 mean, for (top left) SSP1-2.6, (top right) SSP2-4.5, (bottom left) SSP3-6.0, and (bottom right) SSP5-8.5. Each panel shows the PAGE09 (green) and PAGE22v1.1 (pink) projections, with the mean change indicated with solid lines and 90% confidence interval with dashed lines. PAGE09 and PAGE22v1.1 results from 10,000 simulations.

Figure 3.1 shows the global mean surface temperature projections (mean and 90% confidence intervals) for PAGE09 and PAGE22 under the four SSPX-RCPY scenarios. The mean values of PAGE22 are greater than those of PAGE09 for all time analysis periods and scenarios. As shown in table 3.5, the greatest differences in projected global mean temperature values between both models are for the SSP1-RCP2.6 and SSP3-RCP6.0 scenarios. The mean values in 2100 of PAGE22 are greater than in PAGE09 by 24% in SSP1-RCP2.6 (2.2 vs. 1.8 °C), 18% in SSP2-RCP4.5 (3.3 vs. 2.8 °C), 31% in SSP3-RCP6.0 (3.8 vs. 2.9 °C) and 4% in SSP5-RCP8.5 (5.7 vs. 5.4 °C), respectively. The mean values in 2200 of PAGE22 are greater than in PAGE09 by 38% in SSP1-RCP2.6 (1.9 vs. 1.4 °C), 23% in SSP2-RCP4.5 (3.9

vs. 3.2°C), 63% in SSP3-RCP6.0 (4.9 and 3.0 °C) and 19% for SSP3-RCP6.0 (9.6 vs. 8.0 °C).

Table 3.5. Global mean surface temperature changes relative to pre-industrial (°C) for PAGE09 and PAGE22v1.1. Shown are both the mean temperature changes and, in parentheses, 90% confidence intervals calculated over 10,000 simulations.

Time period and model	SSP1-RCP2.6	SSP2-RCP4.5	SSP3-RCP6.0	SSP5-RCP8.5
2100				
PAGE09	1.8 [1.1,2.8]	2.8 [1.7,4.3]	2.9 [1.8,4.5]	5.4 [3.5,8.1]
PAGE22	2.2 [1.6,3.0]	3.3 [2.3,4.4]	3.8 [2.7-5.0]	5.7 [4.0,7.4]
2200				
PAGE09	1.4 [0.7,2.3]	3.2 [1.7,5.2]	3.0 [1.6,5.2]	8.0 [4.8,12.3]
PAGE22	1.9 [1.2,2.6]	3.9 [2.6,5.3]	4.9 [3.3,6.7]	9.6 [6.8,12.6]

Several of the changes made to PAGE09 to develop PAGE22 have implications for the projections of global temperature change. These include modifications to certain variable parameters to reflect the latest scientific information from the IPCC Sixth Assessment Report (section 3.2.3) as well as the explicit representation of permafrost thawing (section 3.2.5). Table 3.6 details the influence of both factors over 2200 global mean temperature projections. In all SSPX-RCPY the new base year and parameter updates have a much larger impact on temperature results than the permafrost thawing carbon feedback. Incorporating permafrost thawing contributes to increases in global mean temperature in 2200 ranging from 2% in SSP5-RCP8.5 to 12% in SSP1-RCP2.6. On the other hand, the effect of new base year and parameters has a larger contribution ranging from 16% in SSP2-RCP4.5 to 58% in SSP3-RCP6.0. Given the significant number of changes towards developing PAGE22 it is useful to understand the contribution of different parameters. Both PAGE09 and PAGE22 run simulations using the @RISK software. One of the functionalities is the statistical analysis of how much different variables contribute to the overall result of a particular variable.

Table 3.6. Global mean temperature in 2200: from PAGE09 to PAGE22. PAGE22v1.0 for estimating the new base year and parameters contribution to temperature. PAGE22v.1.1 for estimating the permafrost thawing contribution.

SSP	RCP	PAGE09 v1.7 [degC]	New base year and parameters	Permafrost thawing	PAGE22 [degC]
SSP1	**RCP 2.6**	1.4	23%	12%	1.9
SSP2	**RCP 4.5**	3.2	16%	6%	3.9
SSP3	**RCP 6.0**	3.0	58%	3%	4.9
SSP5	**RCP 8.5**	8.0	17%	2%	9.6

Figure 3.2 shows which five variables have the greater influence on the 2200 global mean temperature projections and how changes to these variables in percentual terms (x axis) would affect the projected global mean temperature values in 2200 (y axis). For each scenario the top three variables which influence global mean temperature projections the most are the same in PAGE22 and PAGE09. The two most important variables are the transient climate response (TCR) and the feedback response time (FRT) in each case. Both parameters are used to calculate the equilibrium warming for a doubling of CO_2. The third variable is the indirect effect for a doubling of sulphates (IND), which is used as an input to calculate the contribution of sulphates to radiative forcing. The half-life atmospheric residence of CO_2 – RES_CO2 – is ranked fourth or fifth in all scenarios for both models.

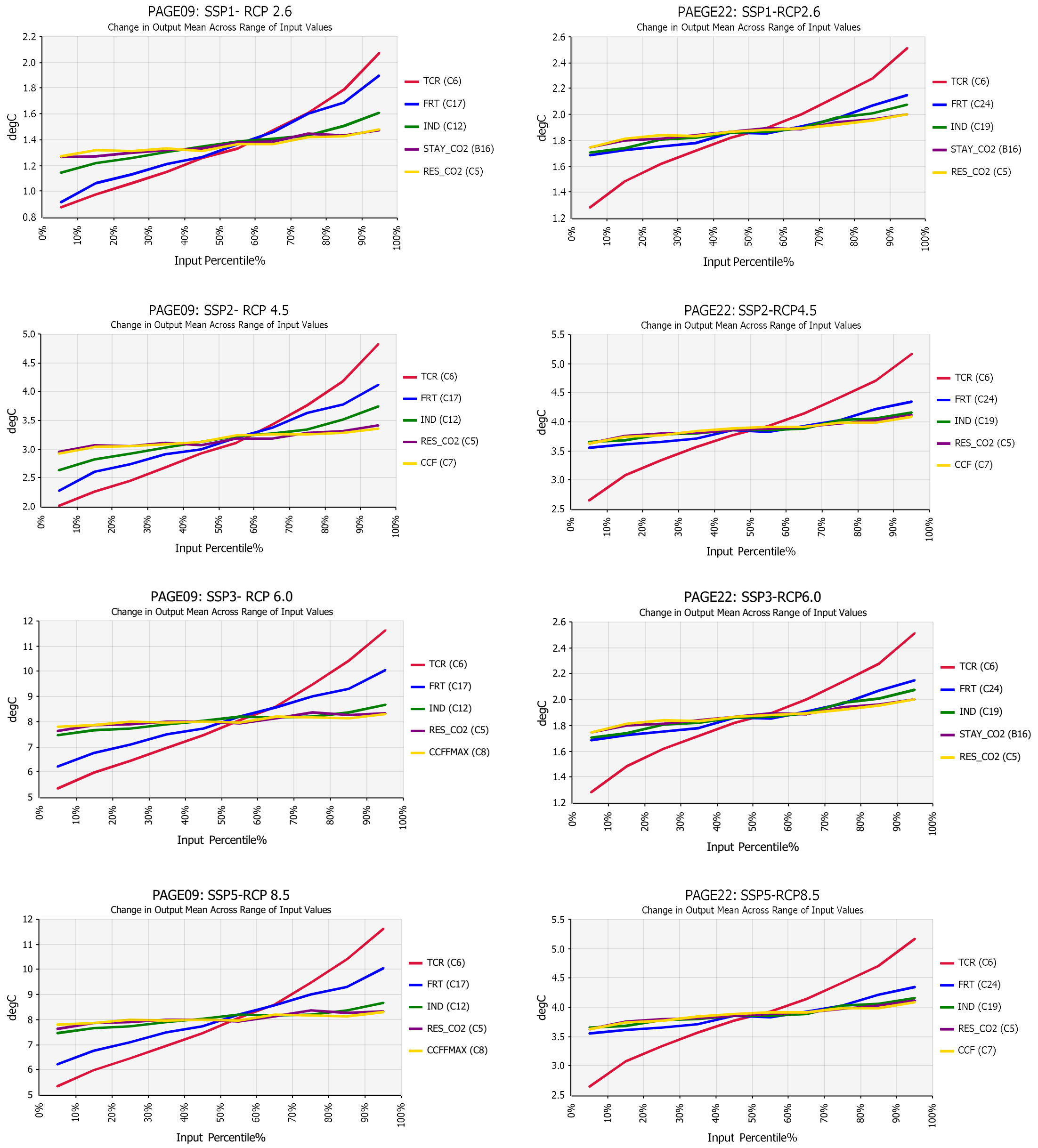

Figure 3.2. Main five variables affecting global mean temperature projections in 2200 in PAGE22v1.1 for the SSPX-RCPY scenarios (different panel for each scenario). Each coloured line represents a single variable (see legend) showing the resulting change in 2200 global mean temperature (y-axis) for a change in the given variable (x-axis). See the main text for discussion and definition of the different variables. PAGE09 and PAGE22v1.1 results from 10,000 simulations.

The other variable in the top five varies depending on the scenario and model combination and includes: the percentage of CO_2 which stays in air (STAY CO_2) and CCF and CCFFMAX. These latter two variables are used to estimate the climate-carbon feedback factor, which describes the resulting increase of CO_2 from the release of soil carbon and decreased carbon uptake by the ocean as temperature rises (see section 3.2.1.).

None of the variables listed in figure 3.2 are related to the explicit representation of permafrost thawing developed in PAGE22. This is not surprising considering the smallest influence of permafrost thawing explicit representation over the base year and new parameters changes as shown in Table 3.6. If figure 3.2 were extended to rank the top 10 variables (as opposed to the top 5), two of the variables which were added to PAGE22 to model permafrost thawing are ranked 9th or 10th at the most which reflects their minor impact on temperature projections. PAGE22 includes a conservative representation of gradual permafrost thawing by only emulating the emissions from the top three meters of permafrost carbon. Section 3.3.3 consists of an analysis of how the cumulative permafrost thawing emissions in PAGE22 change by scenario and the impact from them on temperature projections up to 2300.

3.3.2. Benchmark comparison of PAGE22 vs. PAGE-ICE

This section compares the projections of global mean surface temperature for PAGE22 and PAGE-ICE (Yumashev et al., 2019) over 2020–2300, the overlap period between both models[25]. A comparison is included here given that both PAGE22 and PAGE-ICE use PAGE09 as the basis for its model development. As in section 3.3.1, temperature was

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[25] *PAGE22 was developed independently from PAGE-ICE when Dr Yumashev was no longer my PhD supervisor and had left Lancaster University.*

chosen as the indicator for comparison given that it is affected by all the changes made to develop both models. Unlike PAGE22 and PAGE09, PAGE-ICE has in-built emissions and socioeconomic scenarios which constrain the scenario analysis that can be done using the model. In this section, comparisons are made over three different SSPX-RCPY scenarios (SSP1-RCP2.6, SSP2-RCP4.5 and SSP5-RCP8.5) given that PAGE-ICE has in-built scenarios which do not include SSP3-RCP6.0, SSP3-RCP8.5 nor the SSPX-Y scenarios which are included in this thesis.

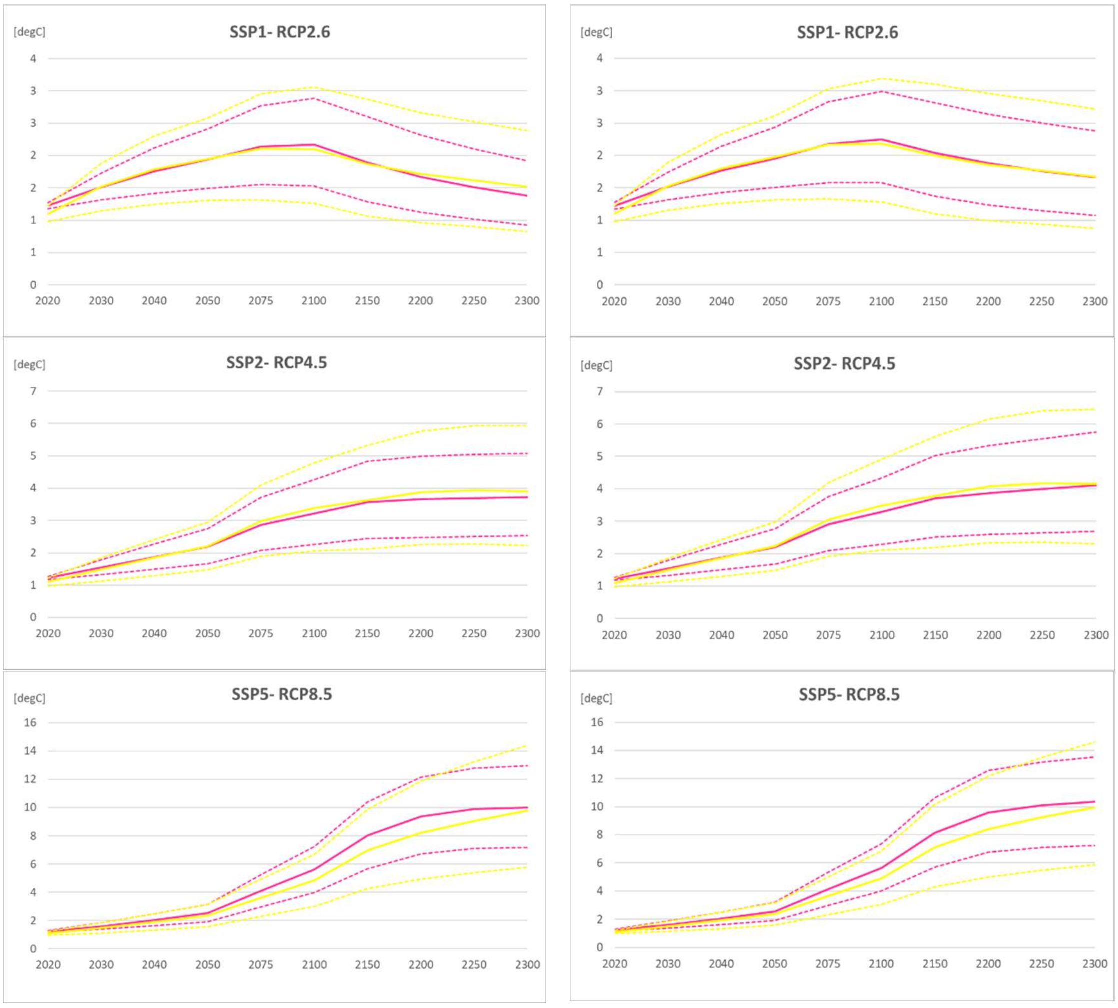

Figure 3.3 Projections of global mean surface temperature changes over 2020–2300, relative to the 1850–1900 mean, for (top) SSP1-RCP2.6, (middle) SSP2-RCP4.5, and (bottom) SSP5-RCP8.5. The left and right panel show results without and with permafrost carbon feedback respectively. Each panel shows the PAGE22v1.1 (pink) and PAGE-ICEv6.22 (yellow)

projections, with the mean change indicated with solid lines and 90% confidence interval with dashed lines. Model versions for results without permafrost carbon feedback: PAGE22v1.0 and PAGE-ICE with legacy PCF. Model versions for results with permafrost carbon feedback: PAGE22v1.1 and PAGE-ICEv6.22 with non-linear permafrost carbon feedback. Results from 10,000 simulations

Figure 3.3 shows the global mean surface temperature projections (mean and 90% confidence intervals) for PAGE22 and PAGE-ICE under three of the SSPX-RCPY scenarios. The temperature projections are in line between both models. For the model simulations without the permafrost carbon feedback, the mean values' differences between models ranges from -9/+16% depending on the scenario and analysis time period. For the model simulations with the permafrost carbon feedback, the mean values' differences between models ranges from -6/+15% depending on the scenario and analysis time period.

Table 3.7 Global mean surface temperature changes relative to pre-industrial (°C) for PAGE22 and PAGE-ICE with and without the permafrost carbon feedback. Shown are both the mean temperature changes and, in parentheses, 90% confidence intervals calculated over 10,000 simulations. Model versions for results without permafrost carbon feedback: PAGE22v1.0 and PAGE-ICE with legacy PCF. Model versions for results with permafrost carbon feedback: PAGE22v1.1 and PAGE-ICEv6.22 with non-linear permafrost carbon feedback.

Time period and model	SSP1-RCP2.6	SSP2-RCP4.5	SSP5-RCP8.5
WITHOUT PERMAFROST CARBON FEEDBACK			
2200			
PAGE22	1.7 [1.1,2.3]	3.7 [2.5,5.0]	9.4 [6.7,12.2]
PAGE-ICE	1.7 [1.0,2.7}	3.9 [2.3,5.8]	8.2 [4.9,11.9]
2300			
PAGE22	1.4 [0.9,1.9]	3.7 [2.5,5.1]	10.0 [7.2,13.0]
PAGE-ICE	1.5 [0.8,1.5]	3.9 [2.2,5.9]	9.8 [5.8,14.4]
WITH PERMAFROST CARBON FEEDBACK			
2200			
PAGE22	1.9 [1.2,2.6]	3.9 [2.6,5.3]	9.6 [6.8,12.6]
PAGE-ICE	1.9 [1.0,3.0}	4.1 [2.3,6.2]	8.4 [5.0,12.2]
2300			
PAGE22	1.7 [1.1,2.4]	4.1 [2.7,5.8]	10.3 [7.2,13.5]
PAGE-ICE	1.7 [0.9,2.7]	4.2 [2.3,6.5]	9.9 [5.9,14.6]

As shown in table 3.7, incorporating the permafrost carbon feedback increases the mean temperature values in 2200 and 2300 in PAGE22. In PAGE-ICE, incorporating the permafrost carbon feedback increases the mean temperature values in 2300 by 10%, 6% and 2% in SSP1-RCP2.6 and SSP2-RCP4.5 and SSP5-RCP8.5 in line with results from PAGE22 of 20%,10% and 3%.

3.3.3. Benchmark vs. IPCC's Sixth Assessment Report

The IPCC Assessment Reports have been used both as a source for input parameters in different versions of PAGE as well as to compare against the results of the model (Hope,1992, 2006, 2011, 2013; Plambeck, Hope and Anderson, 1997). PAGE22 uses the IPCC Sixth Assessment Report (AR6) as a source for many of the revised parameter values and also as a benchmark for the temperature projections.

This section contains an analysis of the temperature projections between PAGE22 and AR6 over the 2020–2100 period. The temperature projections included in AR6 are based on CMIP6 model simulations (Tebaldi et al., 2021) for four scenarios: low (SSP1-2.6), intermediate (SSP2-4.5), high (SSP3-6.0) and very high (SSP5-8.5) emissions scenarios. These scenarios are different from the ones included in the default version of PAGE22. The latter includes the so-called SSPX-RCPY scenarios (Chen et al., 2021) which is the combination of the RCPs (section 3.2.4.1.) and SSPs (section 3.2.4.2.). As detailed in section 3.2.4., these were developed individually. PAGE22 includes the SSPX-RCPY – with X from 1 to 5 and Y denoting the approximate radiative forcing by 2100 – scenarios in the default version as these are extensively used in the literature on climate change impacts (Chen et al., 2021). On the other hand, the AR6 results from CMIP6 include the SSPX-Y scenarios – with X and Y analogous to the SSPX-RCPY – which were developed using the SSPs pathways as a starting point to project GHGs emissions by linking them with different assumptions around climate change mitigation (Rogelj et al., 2018; Gidden et al., 2019; Tebaldi et al., 2021). Unlike the SSPX-RCPY, each SSPX-Y scenario was developed by an IAM team which ensures greater consistency throughout the process (Chen et al., 2021). Given that most of the ESMs in CMIP6 do not include a representation of permafrost thawing, the PAGE22 temperature projections in this section were performed with the permafrost emulator switched off.

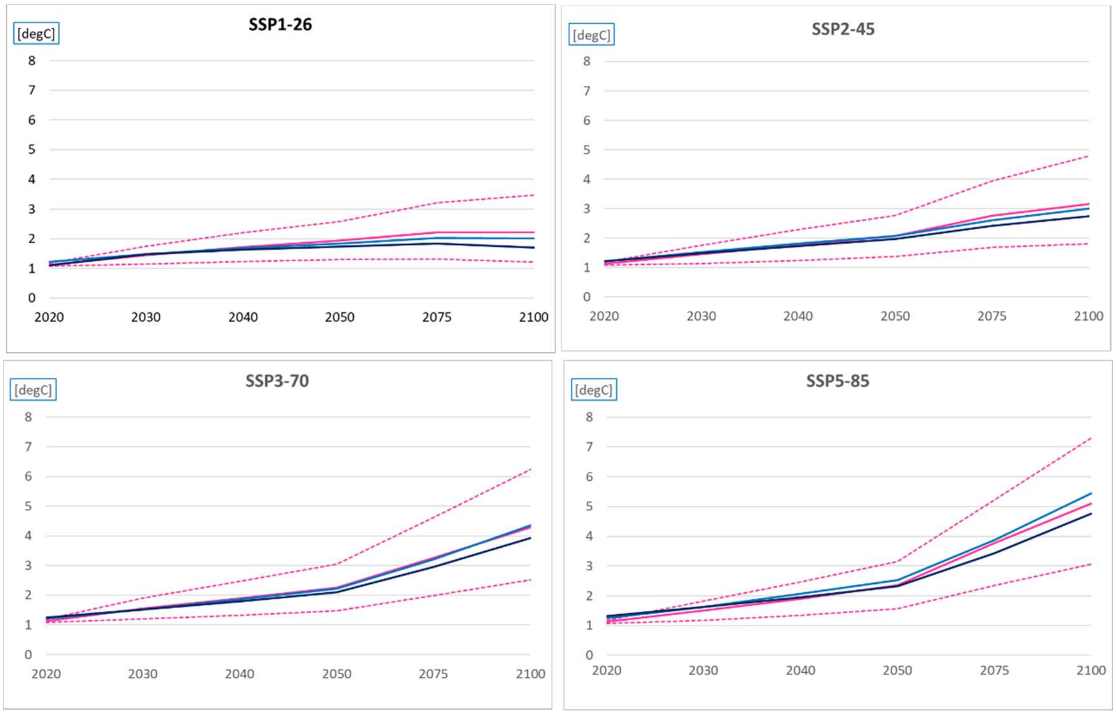

Figure 3.4. Projections of global mean surface temperature changes over 2020–2100, relative to the 1850-1900 mean, for the (top left) SSP1.26, *(top right) SSP2-45, (bottom left) SSP3-70, and (bottom right) SSP5-85* scenarios. *Projections are shown for PAGE22v1.0 (pink), the CMIP6 constrained ensemble (blue) (Lee et al., 2021), and the CMIP6 unconstrained ensemble (dark blue) (IPCC, 2021). For PAGE22v1.0, the figures show the mean (full lines) and 90% confidence interval (dashed lines). PAGE22v1.0 results from 10,000 simulations.*

Figure 3.4 shows the AR6 temperature projections vs. the results from PAGE22. The starting point for the simulations is the year 2019 in which the global surface air temperature – GSAT, a combination of the land surface air temperature (LSAT) and the marine air temperature (MAT) (Gulev et al., 2021) – is 1.1 °C above 1850-1900 (WMO, 2020). Figure 3.4 includes two results from AR6: mean temperature projections from constrained CMIP6 model simulations to match the observational record in light blue and mean temperature projections from unconstrained CMIP6 model projections in dark blue. In all the SSPX-Y scenarios, the projections from PAGE22 are in line with both CMIP6 constrained and unconstrained projections which is not a trivial result. The fact that PAGE22 can result in similar projections to those from CMIP6 attests that all the developments made from PAGE09 to create PAGE22 have been soundly made. In addition, it validates that the model can be used to investigate other scenarios.

In SSP1-26, the projections from PAGE22 are almost identical to both CMIP6 projections up to 2040 and then remain slightly above from 2050 onwards reaching a mean value of 2.21 °C in 2100 vs. 2.01 °C in CMIP6 unconstrained projection. The mean temperature in 2100 in PAGE22 is within the CMIP6 90% confidence interval for 2081-2100 [1.3, 2.8] °C (Lee et al., 2021, their Table 4.2). In SSP2-45, the projections from PAGE22 are almost identical to both CMIP6 projections up to 2050 and then remain slightly above from 2050 onwards reaching a mean value of 3.16 °C in 2100 vs. 3.00 °C in CMIP6 unconstrained projection. The mean temperature in 2100 in PAGE22 is within the CMIP6 90% confidence interval for 2081-2100 [2.1, 4.0] °C (Lee et al., 2021). In SSP3-70, the projections from PAGE22 are almost identical to CMIP6 unconstrained projections reaching a mean value of 4.28 °C in 2100. In SSP5-85, the projections from PAGE22 are slightly below those from CMIP6 up to 2040 and then fall between both CMIP6 projections from 2050 onwards reaching a mean value of 5.1 °C in 2100 vs. 5.44 and 4.76 °C in 2100 for CMIP6 unconstrained and constrained respectively.

3.3.4. Cumulative permafrost carbon loss in 2100, 2200 and 2300

This section consists of three parts. First, it presents an analysis of the cumulative permafrost carbon loss by the years 2100, 2200 and 2300 under the SSP1-RCP2.6, SSP2-RCP4.5, SSP3-RCP6.0 and SSP5-RCP8.5 scenarios and how these compare to Burke et al. (2017). Second, it includes an analysis of the effect of the permafrost thawing emulator in PAGE22 on climate change impacts expressed as differential temperature increases between PAGE22 with the permafrost thawing emulator switched on and off. Third, it finishes with a benchmark of the results from PAGE22 cumulative permafrost emissions against the literature.

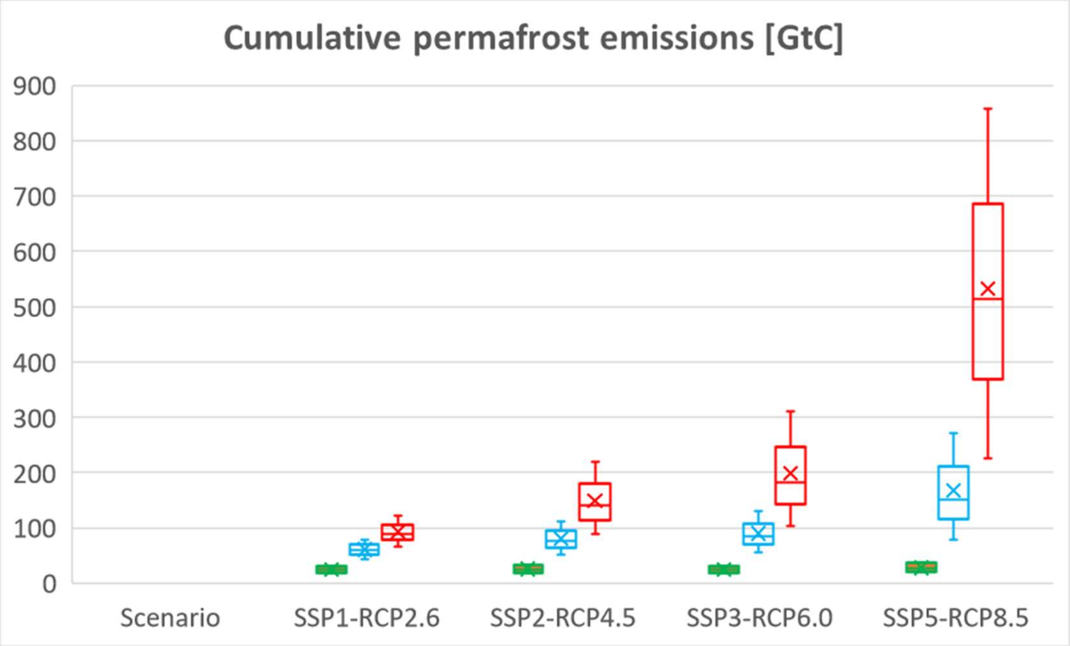

Figure 3.5. Cumulative permafrost carbon loss under different scenarios for 2100 (green), 2200 (light blue) and 2300 (red). Crosses represent mean values and error bars 90% confidence interval values. PAGE22v1.1 results from 10,000 simulations.

As can be seen in figure 3.5, the mean values of the cumulative permafrost carbon loss from gradual permafrost thawing range from 24–27, 59–151 and 90–513 GtC in 2100, 2200 and 2300 respectively. These values, which include both emissions from CO_2 and CH_4, fall within range of Burke et al. (2017) results for 2100 and 2200 (their figures 10a and 10b). The mean range for 2300 in PAGE22 – 513 GtC – is above the range for Burke et al. (2017). This is due to their figures only including simulations from two model specifications – JULES_suppressResp and JULES_deepResp – which include a permafrost carbon stock in the top three meters than the stock in PAGE22: 314 and 488 GtC (Burke et al., 2017, their figures 3b and d) vs. a mean value of 1000 GtC in PAGE22. The other model included in Burke et al. (2017), ORCHIDEE-MICT, has a permafrost carbon stock in the top three meters of 959 GtC (Burke et al., 2017, figure 3f) but the cumulative emissions up to 2300 of the latter are not included. Re-running PAGE22 with an initial permafrost carbon stock of 488 GtC under SSP5-RCP8.5 results in a mean of 246 GtC cumulative permafrost emissions by 2300, in line with Burke et al. (2017)´s figure 10c (75-325 GtC for JULES_deepResp).

The 90% confidence interval of cumulative permafrost carbon emissions throughout the scenarios and years in PAGE22 spreads from 22% lower than the mean – 18 GtC in 2100 in SSP1-RCP2.6 – to 80% higher – 272 GtC in 2200 in SSP5-RCP8.5. The mean cumulative emissions in 2300 range from 52% to almost double those in 2200 for SSP1-RCP2.6 and SSP2-RCP4.5 and to more than triple values in SSP5-RCP8.5 stressing on the importance of extending the analysis period from 2200 to 2300 in PAGE22.

Figure 3.6. Projections of global mean surface temperature changes over 2020–2300, relative to the 1850-1900 mean, for the (top left) SSP1-RCP2.6, *(top right) SSP2-RCP4.5, (bottom left) SSP3-RCP6.0, and (bottom right) SSP5-RCP8.5* scenarios. *Projections are shown for PAGE22v1.0 (pink) and PAGE22v1.1 (purple). The figures show the mean (full lines) and 90% confidence interval (dashed lines). PAGE22v1.0,1.1 results from 10,000 simulations.*

Figure 3.6 shows how the cumulative permafrost carbon emissions emulator affects temperature projections by 2300 under the four SSPX-RCPY scenarios. The mean values temperature projections in 2300 when including the feedback from permafrost carbon emissions increases by 20% (0.28 °C), 10% (0.38 °C), 4% (0.17 °C) and 3% (0.34 °C) in SSP1-RCP2.6, SSP2-RCP4.5, SSP3-RCP6.0 and SSP5-RCP8.5 respectively. The temperature projections in SSP5-RCP8.5 go beyond 10.5 °C after 2100 and the permafrost carbon emissions are capped at that limit following Burke et al. (2017). These estimates are conservative given that, as explained in section 3.2.5, the permafrost carbon stock included in the emulator is that of the top 3 meters of permafrost soil in the Northern Hemisphere. The effect of the permafrost feedback on temperature projections by 2300 is in line with results from Burke et al. (2017)'s figure 7 but towards their higher uncertainty ranges.

Table 3.8. Comparison of projected permafrost carbon emissions in 2100, 2200 and 2300 [GtC] with impact studies in the literature. PAGE22 results for model version 1.1.

Reference	2100	2200	2300	Notes
SSP1-RCP2.6				
PAGE22	24 [18-30]	59 [44-79]	90 [65-122]	mean, [90%CI]
Burke et al. (2017)-JULES-deepResp	25-50	40-70	45-95	Based on figure 10 a-c
Burke et al. (2017)-JULES-suppressResp	15-20	20-30	25-35	Based on figure 10 a-c
Yumashev et al. (2019)- JULESdR	39 [30-50]	59 [43-73]	74 [55-92]	Figure 1b
Gasser et al. (2018)	27 [6- 62]	39 [11- 82]	47 [15- 93]	
MacDougall et al. (2015)	103	153	169	CO2 only simulations
SSP2-RCP4.5				
PAGE22	25 [19-32]	77 [52- 112]	140 [88- 219]	mean, [90%CI]
Burke et al. (2017)-JULES-deepResp	25-55	45-110	50-145	Based on figure 10 a-c
Burke et al. (2017)-JULES-suppressResp	15-25	20-35	30-40	Based on figure 10 a-c
Koven et al. (2015)	21 [12-33]			
Yumashev et al. (2019)- SiBCASA	40 [26-70]	81 [49-154]	101 [62-196]	Figure 1a
Yumashev et al. (2019)- JULESdR	42 [31-57]	72 [47-97]	98 [62-129]	Figure 1b
Schneider von Deimling et al. (2012)	27	74	106	
Gasser et al. (2018)	35 [7-83]	64 [16- 130]	89 [26- 163]	
MacDougall et al. (2015)	156			
Schaefer et al. (2014)	27- 100			
SSP3-RCP6.0				
PAGE22	24 [19-31]	85 [55-129]	183 [104-310]	mean, [90%CI]
Gasser et al. (2018)	42 [8-102]	99 [23-203]	145 [39- 265]	
MacDougall et al. (2015)	166			
Schaefer et al. (2014)		190 +/- 24		
Schneider von Deimling et al. (2012)	33	55	62	
SSP5-RCP8.5				
PAGE22	27 [20-36]	151 [79-272]	513 [226-857]	mean, [90%CI]
Burke et al. (2017)-JULES-deepResp	25-60	50-200	75-325	Based on figure 10 a-c
Burke et al. (2017)-JULES-suppressResp	15-25	25-40	40-60	Based on figure 10 a-c
Koven et al. (2015)	57 [28-113]			
Yumashev et al. (2019)- SiBCASA	108 [65-174]	327 [174-460]	433 [242-525]	Figure 1a
Yumashev et al. (2019)- JULESdR	49 [32-71]	122 [62-188]	201 [95-299]	Figure 1b
Burke et al. (2013)	50			
Schneider von Deimling et al. (2012)	63	302	380	
Burke et al. (2012)	150			
Schuur et al. (2013)	158		345	
MacDougall et al. (2012)	174			
Harden et al. (2012)	218		436	
Schuur et al. (2015)	37- 174		100- 400	
Turetsky et al. (2020)			80 +/- 19	Abrupt thawing
McGuire et al. (2018)			208	
Gasser et al. (2018)	59 [11- 143]	150 [34- 297]	212 [55- 376]	
MacDougall et al. (2015)	226	611		
Schaefer et al. (2014)	37- 347			

Table 3.8 includes a comparison of how the cumulative emissions in 2100, 2200 and 2300 align with other estimates from the literature for the SSPX-RCPY scenarios. As can be seen in Table 3.8, the spread of results across scenarios and time periods is more concentrated around 2100 projections and the RCP4.5 and RCP8.5 scenarios. PAGE22 cumulative permafrost thawing projections are in line with other impact studies across the four scenarios for 2100 and 2200 with higher projections in 2300 for RCP4.5, RCP6.0 and RCP8.5. Gasser et al. (2018) include permafrost thawing projections for the four scenarios using an ESM coupled with a permafrost module which emulates four land surface modules including the three used in Burke et al. (2017). The mean values from PAGE22 are always within the uncertainty interval in Gasser et al. (2018) except for the RCP8.5 in 2300 in which PAGE22´s mean estimate is 513 GtC, considerably higher than the upper limit of 376 GtC in Gasser et al. (2018). This difference could be a result of the latter using a lower carbon stock than in PAGE22 (their supplementary table 4).

3.4. Limitations and conclusion

This section will expand on why the results from PAGE22 presented in Section 3.3. are conservative and present concluding remarks stemming from the analysis in this chapter. IAMs like PAGE22 can be useful for assessing the potential global impacts from climate change under a lens of uncertainty by incorporating probability distributions as inputs to many of its climate and socioeconomic parameters and running simulations that results in probabilistic outputs. The latter is crucial given the uncertainty around projecting physical and economic variables into centuries from now.

Tackling climate change may not only be fair to future generations (World Commission on Environment and Development, 1987) or those from developed countries which may be affected the most by impacts (Burke et al., 2015) despite their contribution to the problem is miniscule in comparison to the developed world (Frischmann et al., 2022; Okereke, 2018; Klinsky et al., 2017), analysing the results from tools like PAGE22 can help policymakers understand how expensive not doing so could be (Nordhaus, 2018). Despite the value in developing these tools, there are limitations to them (Diaz and Moore, 2017). This thesis addresses some of these under three groups: limitations related to the physical modelling with a focus on permafrost thawing in this section, limitations to economic modelling in section 4.5 and societal impacts in chapter 5.

One of the main issues around modelling permafrost thawing is that data is scattered and aggregation for different site-measurements is difficult considering the large extent and heterogeneity of the permafrost region (Canadell et al., 2021). In particular, the Yedoma region and deltaic deposits are not included in recent permafrost carbon stock estimates due to data constraints (Mishra et al., 2021). Also, there are regions like the shallow Arctic Ocean shelves where the uncertainty around emissions estimates is quite large (Canadell et al., 2021). Another issue is that this Chapter and the default model version of PAGE22 focus on gradual permafrost thawing. Abrupt thawing of permafrost poses an additional threat and research on quantifying the potential impacts is incipient (Schuur et al., 2015; Olefeldt et al., 2016; Meredith et al., 2019). New studies estimate that abrupt thawing could increase emissions from permafrost by 60–100 PgC by 2300 (Turetsky et al., 2019; 2020). In addition, the permafrost thawing emulator includes the top 3 meters of the permafrost carbon stock in the Northern circumpolar permafrost region with a mean value of 1,000 PgC (Mishra et al., 2021) vs. an estimated total of 1,672 PgC permafrost carbon stock in the Northern circumpolar permafrost region (Tarnocai et al., 2009).

In addition, aside from CO_2 and CH_4 emissions from permafrost thawing, recent studies documented for the first time N_2O emissions from permafrost (Abbott and Jones, 2015; Karelin et al., 2017; Wilkerson et al., 2019). These could be a non-negligible non-carbon feedback and a recent review on the subject pointed that further research is needed (Voigt et al., 2020). The scientific understanding of these physical processes behind the N_2O emissions is in its infancy and, as such, the economic impact assessments are very limited or non-existent. Estimating the economic effect of N_2O emissions would not be inherently difficult given PAGE22´s explicit representation of this GHG but it would depend on the availability of N_2O emissions projections under different scenarios. Despite the uncertainty revolving the science, it could be argued that there is value in assessing the potential global economic impacts from these processes precisely using tools like PAGE22 which result in estimates with large uncertainty ranges.

There are other physical phenomena related to permafrost thawing which are not included in PAGE22: the effect of fire as both a result and cause of permafrost thawing, subsidence, soil erosion (Meredith et al., 2019) and the release of pollutants and its subsequent impact on freshwater ecosystems (Hock et al., 2019). The level of granularity of these impacts requires more detailed models to analyse the impacts and feedbacks from them. Despite PAGE22 not being the appropriate tool to assess these implications, it reinforces why the permafrost carbon feedback impacts estimated by PAGE22 are conservative.

Limitations to economic modelling will be addressed in detail in Chapter 4 following the analysis on the global economic impacts from permafrost thawing. Lastly, limitations on societal impacts include qualitative impacts which can be very detrimental to local communities which experience the consequences from permafrost thawing.

Section 3.3 included an analysis of results on three fronts: a comparison of PAGE22 vs. PAGE09, a benchmark against the IPCC's Sixth Assessment Report and an analysis of permafrost thawing cumulative emissions over different time periods and their contribution to temperature projections. and the feedback response time – both related to climate sensitivity.

Section 3.3.3. included an analysis of the temperature projections between PAGE22 and AR6 for the 2020-2100 analysis period. The results from PAGE22 were compared to both CMIP6 constrained and unconstrained model simulations to make a more robust analysis of results. The mean values in all scenarios were aligned with AR6 with PAGE22 mean values being slightly higher than those from AR6 in SSP1-RCP2.6 and SSP2-RCP4.5.

The permafrost carbon feedback is largely underrepresented in CMIP6 and, in turn, temperature projections from the latest IPCC Sixth Assessment Report which inform policymakers worldwide. Section 3.3.4. on the cumulative permafrost carbon loss in 2100, 2200 and 2300 assessed how the projections from PAGE22 compared vs. the results from Burke et al. (2017), the paper used to explicitly model permafrost thawing in PAGE22. This validation is a necessary step to show that PAGE22 is correctly emulating the results from the paper that was used to develop the permafrost carbon emulator into the IAM. The cumulative permafrost emissions in 2300 ranged from 50% larger to more than three times those in 2200 which validates the importance of extending the analysis period from 2200 in PAGE09 to 2300 in PAGE22. The resulting temperature differentials from the permafrost carbon feedback ranged to 3-20% higher mean values by 2300 for the SSPX-RCPY scenarios. Given that the permafrost carbon emulator only includes the permafrost for the top three meters o permafrost soil in the northern circumpolar permafrost region – close to 60% of estimated total permafrost carbon stock, these estimates are conservative.

The aim of PAGE22 is to estimate the potential economic impacts from permafrost thawing under a range of scenarios to highlight the magnitude of impacts and push for more stringent climate policies. Following from Section 3.4, the results presented on this chapter point to these estimates being conservative. Chapter 4 will introduce the structural changes to economic impacts modelling in PAGE09 to develop PAGE22 and use the model to assess the potential economic implications from permafrost thawing under a range of scenarios.

Chapter 4 - Developing PAGE22: economics

4.1. Introduction

Whilst Chapter 3 focussed on the structural changes and updates to the physical modelling in PAGE22, the present chapter describes how PAGE22 simulates the persistent effects of economic production on temperature based on an econometric study by Burke et al. (2015). As a result, a new impact sector – persistent economic effects – is added to the model. In doing so, it addresses three of the most recurrent criticisms to IAMs estimates of damages: first, that IAMs are not updated with the latest scientific and impact studies on all things climate change (Burke et al., 2016; Diaz and Moore, 2017; Rose et al., 2017); second, that simplified IAMs – like PAGE09, DICE and FUND – damage functions are calibrated interdependently (Rose et al., 2014; 2017); and third, that damage functions in IAMs result in implausible damages at high temperatures. As an example of this latter criticism, in DICE´s quadratic damage function it takes a temperature increase of 18°C to lose 50% of global output (Dietz and Stern, 2014). If IAMs underestimate damages and are used to inform climate change policy metrics like the social cost of carbon dioxide (SCCO2) (IAWG, 2010, 2013), they will hinder the efficacy of the policies to meet the climate targets.

The capability of simplified IAMs like PAGE22 to be a useful tool also depends on the availability of impact studies that are methodologically accepted by experts in the field, have a regional split which can be matched to the regions in the model and include mathematical representations that can be applied to different climate and socio-economic scenarios and projected into centuries from now. It could be argued that using expert elicitation to parametrise damage functions in simplified IAMs in the past was a result of a lack of these impact studies.

Due to their low computational cost, simplified IAMs like PAGE22 can be run multiple times enabling estimation of the potential impacts from climate change for a large amount of the parameter space (i.e., simultaneously varying several parameters within their confidence bounds), allowing a thorough exploration of uncertainty. Unlike big climate models, that need days to run, PAGE22 can complete 100,000 simulations in a few hours. However, while climate models can use physical observations from the historical period to validate how well they replicate the past, there are scant measurement records of economic impacts to compare IAMs against. Hence, the validity of IAM results depends on what the information incorporated into the model from other studies and how well these are represented in the model through equations and parameters.

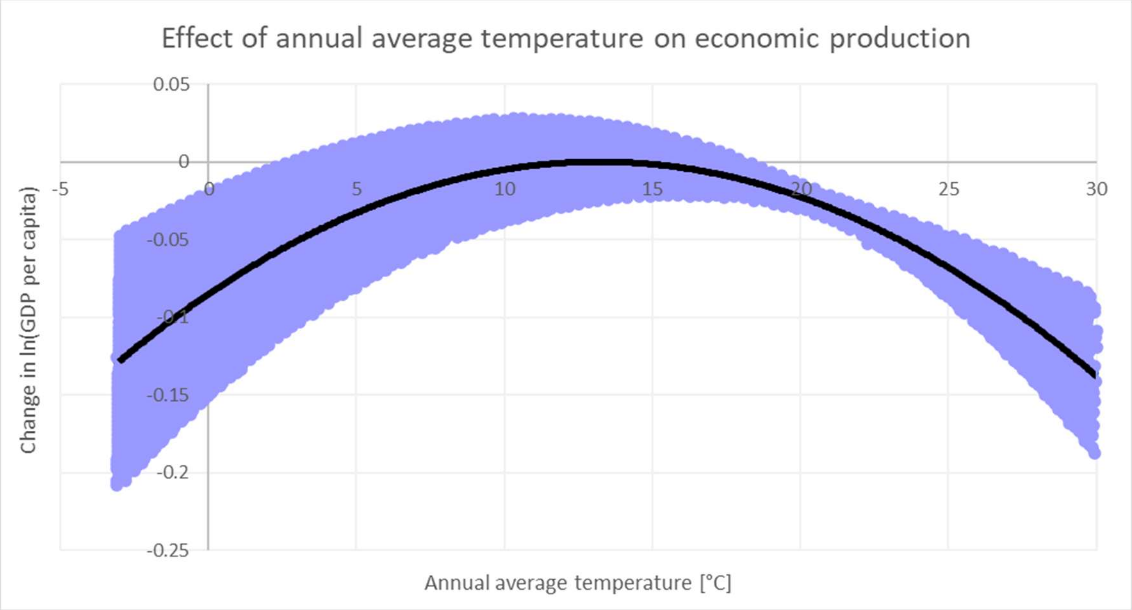

Figure 4.1. Statistical estimate of the effect of annual temperature on economic production during 1960-2010 (thick black line relative to optimum, 90% confidence interval in blue). Figure redrawn from Burke et al. (2015; their figure 2a).

One key aspect of climate-economy links that IAMs need to model is how temperature increases can affect the economy. Some studies have focussed on empirical analyses between temperature and economic output (Dell, Jones and Olken, 2012; Burke et al. 2015; Burke, Davis and Diffenbaugh, 2018; Colacito, Hoffman and Phan, 2019; Barnett et al., 2020). Burke et al. (2015) revealed a linkage of apparently contradictory results among non-linearity between micro and macro scale studies on climate change impacts. Figure 4.1 (from Burke et al., 2015) shows that there is a non-linear relationship between local temperature and the change in GDP per capita (as a natural log) – a proxy for growth rate – with a peak at 13 °C. This figure is based on data for 166 countries on economic production for the period 1960-2010. The resulting curves from the 1960–1989 and 1990–2010 analysis of Burke et al. (2015) are very similar to each other, which indicates that wealth, experience and technological changes between both periods have not considerably affected this productivity and temperature connection whilst also suggesting that climate change adaptation may be harder than formerly thought (Burke et al., 2015). The fact that their results are irrespective of the country's wealth points to wealth not being a substitute for natural capital (Burke et al., 2015).

Based on figure 4.1, global GDP is projected to decrease by 23% by 2100 under the SSP5-RCP8.5 scenario vs. a world with no climate change, assuming adaptation remains unchanged. As a reference, this value is considerably larger than the 5% GDP loss from the Great Recession in 2008-9 and the 3% GDP loss from the COVID-19 pandemic in 2020 (IMF, 2020; 2021; O'Neill et al., 2022). Burke et al. (2015) also projected that over 75% of the countries in their analysis would be poorer because of climate change, further enhancing climate change induced inequality (Diffenbaugh and Burke, 2019). These projected losses are much larger than those resulting from previous IAMs studies such as DICE and PAGE which project a 1% GDP loss by 2100 in a 2°C warmer world vs. pre-industrial (Nordhaus, 2013; Diaz and Moore, 2017). Building on this argument, some scientists find models like DICE unfit for policy analysis of climate change damages (Keen et al., 2021).

Incorporating the effects of temperature on economic production from Burke et al. (2015) partly addresses the criticism to IAMs on the lack of empirical foundation for their damage functions (Moore and Diaz, 2015; Pindyck, 2012; Stern, 2013; Revesz, 2014). Previous studies have followed a similar approach incorporating empirical studies to IAMs and resulted in considerably larger losses than from previous damage function configurations (Moore and Diaz, 2015; Yumashev et al. 2019). The analysis of Moore and Diaz (2015) incorporated the empirical estimates from Dell, Jones and Olken (2012) to DICE, which describes a linear relationship between temperature and economic output but only in poor countries. They found that including this relationship increases the social cost of carbon considerably: from 33 to 220 USD/tn in 2015, and from around 30 to almost 500 USD/tn in 2100. In contrast to Dell, Jones and Olken (2012), Burke et al. (2015) analysis shows that the effect of temperature on economic production is irrespective of a country's wealth. As such, it is expected that the effect of adding Burke et al. (2015) to PAGE22 will be larger that in Moore and Diaz (2015). Yumashev et al. (2019) incorporated the findings from Burke et al. (2015) to PAGE and found that under SSP5- RCP8.5 the SCCO2 in 2020 increases from around 150 USD/tn in PAGE09 to 165-250 USD/tn in PAGE-ICE. The inclusion of Burke et al. (2015) into PAGE22, as described in this chapter, is completed differently from Yumashev et al. (2019). Here, the effect of annual average temperature on economic production carries on into the future, whereas Yumashev et al. (2019) interpret their findings as level effects[26] which do not affect GDP projections into future years. As such, it is expected that economic results from PAGE22 will be larger than those in Yumashev et al. (2019).

This chapter is organised as follows. Section 4.2 details the economic modelling structure in PAGE09. Section 4.3 introduces the analysis in Burke et al. (2015) which ignited the structural changes to incorporate the persistent economic impacts quantification in PAGE22, details the methodology and presents a benchmark of key outputs to depict how the new development in the latter emulates the results in the former. Section 4.4. presents a range of results for PAGE22. First it compares PAGE09 to

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[26] Incorporating Burke et al. (2015) in PAGE-ICE as level effects means that the damages in any given year do not affect the GDP in the following year and are only determined by the exogenous GDP growth rates. In PAGE22, Burke et al. (2015) is modelled as a persistent effect in which GDP in any given year is determined by both the exogenous GDP growth rates (as in PAGE09 and PAGE-ICE) but also by the projected effect of warming on growth in that year.

PAGE22 without the persistent effects from Burke et al. (2015) and with the permafrost carbon emulator switched off under the SSPX-RCPY scenarios. Second, it compares PAGE22 with and without the persistent economic impacts under the SSPX-RCPY scenarios, with both model configurations with the permafrost carbon emulator switched off. Third, PAGE22 with the persistent effects from Burke et al. (2015) and with the permafrost carbon emulator switched off is used to estimate the economic impacts from climate change up to 2300 for the SSPY-X scenarios. Fourth, it contains an analysis on the global economic impacts from permafrost thawing in the Arctic region. Fifth, it concludes with estimates for the SCCO2 for different years. The discussion in Section 4.5 considers some of the limitations in incorporating the persistent effects to PAGE22 as well as suggestions for future research. Finally, the chapter finishes with a summary and conclusions in section 4.6.

4.2. Economic modelling in PAGE09

Integrated assessment models are used for a range of purposes including developing scenarios for the scientific community to assess climate change impacts – such as the SSPs – and estimating the social cost of carbon for policymakers to use as input to set pollution standards (IAWG, 2010, 2013; Burke et al., 2016). This section focusses on introducing the economic modelling in PAGE09; in short, how PAGE09 translates physical impacts into monetary units. The aim of this section is to present a summary of the economic modelling in PAGE09 before introducing the new development in section 4.3 whilst depicting the level of complexity in the model.

PAGE09 enables the user to calculate the climate change impacts from two policies and their difference via specifying emissions and socioeconomic scenarios. The former is specified as projected changes in emissions and radiative forcing levels vs. the base year of the model – 2008 – and the latter as projected as exogenous GDP and population growth rates for each region and time analysis period. As a starting point for estimating the climate change impacts, PAGE09 includes values for GDP and Population for the base year detailed by the 8 world regions in the model. The GDP and population growth rates are used to build regional GDP and GDP per capita projections which will then be affected by climate change via user-definable emissions projections and adaptation policies. The user can define mitigation and adaptation policies which increase the tolerable level and/or the barrier at which climate change costs are incurred. These policies, which are defined at the global level, have costs associated to them.

The user-definable projected changes in GHG emissions vs. the base year are used to drive physical impacts in the model (temperature and sea level rise changes). These physical impacts are then translated into economic terms – monetary units in United States Dollars (USD) – via damage functions. Damage functions provide a measure of how climate change translates into societal costs (Nordhaus, 1991). PAGE09 includes four impact sectors: sea level rise, economic, non-economic and discontinuities. The economic impact sector represents all those which are directly included in GDP whereas the non-economic impact sector includes those segments which are not directly included in GDP (e.g.: human health, ecosystem services) (Hope and Schaefer, 2015). Discontinuities are those large-scale abrupt and/or irreversible events such as the melting of the Greenland icesheet (American Meteorological Society, 2022) which could have catastrophic impacts on the climate, ecosystem and society (Lenton et al., 2019).

Sea level rise impacts before adaptation are calculated as a polynomial function of physical sea level rise. Both economic and non-economic impacts before adaptation are calculated as a polynomial function of the regional temperatures. Discontinuities can only be triggered if temperature exceeds a certain temperature rise above pre-industrial values. If so, beyond this threshold, the probability of a discontinuity increases as temperature rises.

The focus of this chapter is incorporating a new impact sector based on the findings from Burke et al. (2015). As these are related to the economic impact sector, for ease of reference, a set of the equations which are used to estimate the impacts for the economic sector in PAGE09 are included in this section; this is how they are described by the original developer of the PAGE model (Hope, 2011).

The impacts are expressed as a percent loss of GDP in terms of consumption, which results from decreasing the GDP by a savings rate which remains constant for all regions and analysis time periods (Hope, 2011):

$$CONS_{i.r} = GDP_{i.r} * (1 - SAVE/100)$$

[Mill. USD] [4.1]

i=1-10, r=1-8,

$$GDP\_PER\_CAP_{i.r} = GDP_{i.r}/POP_{i.r}$$

[Mill. USD/ Mill.] [4.2]

i=1-10, r=1-8,

$$CONS\_PER\_CAP_{i.r} = GDP\_PER\_CAP_{i.r} * (1 - \frac{SAVE}{100})$$

[Mill. USD/ Mill.] [4.3]

i=1-10, r=1-8

where $CONS_{i.r}$, $POP_{i.r}$ and $GDP_{i.r}$ are the consumption, population and GDP values for the analysis time period i and region r respectively which are used to estimate the GDP per capita and consumption per capita values using equations [4.2] and [4.3] respectively. $SAVE$ is the savings rate which remains constant for all regions and analysis time periods. GDP and population are projected using base year – 2008 – values for each region and exogenous – user-definable – growth rates.

The model calculates the abatement costs – $\boldsymbol{tct\_per\_cap_{i.r}}$ – and adaptation costs – $\boldsymbol{act\_per\_cap_{i.r}}$ – which result from the user-definable abatement and adaptation policies[27]. The consumption per capita in equation 4.3 is then subtracted by abatement and adaptation costs:

$$cons\_per\_cap\_after\_costs_{i.r} = CONS\_PER\_CAP_{i.r} - (tct\_per\_cap_{i.r} + act\_per\_cap_{i.r})$$

[Mill. USD/ Mill.] [4.4]

i=1-10, r=1-8

The resulting $\boldsymbol{gdp\_per\_cap\_after\_costs_{i.r}}$ are used to calculate impacts:

$$gdp\_per\_cap\_after\_costs_{i.r} = cons\_per\_cap\_after\_costs_{i.r}/(1 - SAVE/100)$$

[Mill. USD/ Mill.] [4.5]

i=1-10, r=1-8

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[27] *Hope (2011) includes detail for the equations and rationale for the calculation of the abatement and adaptation costs. As the calculation of these costs was not modified when developing PAGE22 the equations are not included in this thesis. They are mentioned here for future reference.*

The user-definable adaptation policies can increase the tolerable level of physical impacts beyond which costs are incurred (expressed in metres for the sea level impact sector and in degree Celsius for the economic and non-economic impact sectors) – equation [4.6] – and reduce the impacts in each region (expressed in percentual terms for the sea level, economic and non-economic impact sectors) – equation [4.7]. The index *1* is used to denote the economic impact sector. Similar equations are used for the sea level and non-economic impact sectors.

$$atl_{i.1,r} = if(Y_i - pstart\_a_{1,r} < 0, 0, if(((Y_i - pstart\_a_{1,r})/pyears\_a_{1,r})) < 1, ((Y_i - pstart\_a_{1,r})/pyears\_a_{1,r}) * plateau\_a_{1,r}, plateau\_a_{1,r}))$$

[°C] [4.6]

i=1-10, r=1-8

$$imp_{i.1,r} = if(Y_i - istart\_a_{1,r} < 0{,}0, if(((Y_i - istart\_a_{1,r})/iyears\_a_{1,r}) < 1, ((Y_i - istart\_a_{1,r})/iyears\_a_{1,r}) * impred\_a_{1,r}, impred\_a_{1,r}))$$

[%] [4.7]

i=1-10, r=1-8

where $atl_{i.1,r}$ is the tolerable temperature beyond which economic impacts occur for each region, Y_i are the time analysis period, $pstart\_a_{1,r}$ is the start year of the user-definable adaptation policy for the economic sector for each region, $pyears\_a_{1,r}$ is how long that adaptation policy will take to come into force, $plateau\_a_{1,r}$ is the increase in the tolerable temperature in each region via the adaptation policy, $imp_{i.1,r}$ is the reduction in impacts for each region after the tolerable temperature level has been surpassed through the second adaptation policy, $istart\_a_{1,r}$ is the start date for the second adaptation policy, $iyears\_a_{1,r}$ is the number of years the second adaptation policy takes to come into full effect and $impred\_a_{1,r}$ is the reduction in impacts expressed as a percentage. In equation 4.6 and 4.7 the suffix "_a" is used to denote the first user-definable adaptation policy. One run of the model replicates the analysis for a second user-definable policy "_b".

The temperature increase used to estimate the economic impacts is the difference between the temperature increase which results from the emissions projections without any adaptation – rtl_i – and the tolerable temperature increase – $atl_{i.1,r}$ – which can be higher than zero if adaptation is bought:

$$i_{i.1,r} = if((rtl_i - atl_{i.1,r}) < 0{,}0, rtl_i - atl_{i.1,r}) \qquad [°C] \qquad [4.8]$$

i=1-10, r=1-8

The impact at reference GDP per capita is:

$$iref_{i.1,r} = WINCF_r * ((W_1 + IBEN_1) * TCAL) * (i_{i.1,r}/TCAL)^\wedge POW_1 - i_{i.1,r} * IBEN_1)$$

[%] [4.9]

i=1-10, r=1-8

where $WINCF_r$ is the regional weighting which adjusts the vulnerability of each region to temperature and sea level rise compared to the focus region – EU – based on Anthoff et al. (2006), $TCAL$ is the calibration temperature with a triangular distribution of 2.5, 3 and 3.5 for the minimum, mode and maximum values, W_1 are the economic impacts – expressed as a %GDP –

at the calibration temperature, $IBEN_1$ are the economic initial benefits from low temperature rises (Tol, 2002; Stern, 2007) and POW_1 is the exponent of the economic impact function which is an uncertain input with a triangular distribution with minimum, mode and maximum values of 1.5, 2 and 3 respectively in line with Ackerman et al. (2009).

The impact at actual GDP per capita, without saturation, is

$$igdp_{i.1,r} = iref_{i.1,r} * (rgdp\_s\_per\_cap_{i,r} / GDP\_PER\_CAP\_FOCUS_0)^\wedge IPOW_1$$

[%] [4.10]

i=1-10, r=1-8,

where $rgdp\_s\_per\_cap_{i,r}$ is the remaining consumption after sea level rise impacts, $GDP\_PER\_CAP\_FOCUS_0$ is the initial GDP in the focus region and $IPOW_1$ adjusts the economic impact function exponent based on income.

The impact at saturation, including adaptation, is

$$isat_{i.1,r} = if(igdp_{i.1,r} < ISATG, igdp_{i.1,r}, ISATG + ((100 - SAVE) - ISATG) * ((igdp_{i.1,r} - ISATG)/(((100 - SAVE) - ISATG) + (igdp_{i.1,r} - ISATG)))) * (1 - imp_{i.1,r}/100 * if(i_{i.1,r} < impmax_{1,r}, 1, impmax_{1,r}/i_{i.1,r}))$$

[%] [4.11]

i=1-10, r=1-8,

where $ISATG$ ensures impacts never surpass 100% of consumption (Weitzman, 2009) and $impmax_{1,r}$ is the maximum temperature increase for which adaptation can be bought (assuming it would be ineffective above this value).

The resulting impact and remaining consumption per capita are calculated as the following:

$$isat\_per\_cap_{i.1,r} = (isat_{i.1,r}/100) * rgdp\_s\_per\_cap_{i,r}$$ [Mill. USD] [4.12]

i=1-10, r=1-8,

$$rcons\_per\_cap_{i.1,r} = rgdp\_s\_per\_cap_{i,r} - isat\_per\_cap_{i.1,r}$$ [Mill. USD] [4.13]

i=1-10, r=1-8,

In PAGE09 GDP is projected using exogenous GDP growth rates and the impacts from any sector (economic, non-economic, sea level and discontinuities) on a given year do not carry over to the next year. This is an important distinction that is relevant to the results from Burke et al. (2015) which persist over time.

The total effect of climate change in the model is equal to the sum of the impacts (sea level, economic, non-economic and discontinuities), the adaptation and abatement costs. These impacts are then equity-weighted discounted and then aggregated. The equity weighting is based on the approach by Anthoff et al. (2009) which uses the elasticity of the marginal utility of consumption (EMUC). In the default version of PAGE09, the EMUC is defined as a triangular distribution with a minimum, mode and maximum value of 0.5, 1, 2 (HM Treasury, 2003; Evans, 2005). Given that the EMUC is greater than zero, the impacts are greater/ lower than the focus region depending on whether their GDP in the base year is lower/greater than in the EU (Hope, 2011). The pure time preference rate is used for discounting and is defined as a triangular distribution with minimum, mode and maximum values of 0.1, 1 and 2 respectively based on Stern (2007) and Nordhaus (2007) for the lower and higher end values.

The total climate change effect is capped at the statistical value of civilisation – CIV_VALUE – (Hope, 2011). The net present value of this total is calculated for each user-defined policy in the model as well as the difference between them. There is an additional functionality around the preventative and adaptative costs so that the user can choose whether to equity weight the costs depending on whether the richer or poorer regions are expected to pay for them.

4.3. Modelling the persistent effect of temperature on economic impacts

One of the key developments in PAGE22 is the incorporation of a fifth element to the impacts: the persistent effect from temperature on economic production. As described in section 4.1, the rationale for this development is based on Burke et al. (2015)'s econometric analysis of 166 countries over 1960–2010, which demonstrated that temperature changes have persistent effects on GDP irrespective of each country's wealth (i.e., the non-linear effects from temperature on economic production carry on into the future, unlike the other impact sectors in PAGE22).

Following Burke et al. (2015), GDP per capita for region *r* at time *i* is given by

$$GDP\_PER\_CAP_{i,r} = GDP\_PER\_CAP_{i-1,r} \times \left(1 + \eta_{i,r} + \delta_{i,r}\right) \qquad [4.14],$$

where $\eta_{i,r}$ is the GDP growth rate without climate change, and $\delta_{i,r}$ is the projected effect of warming on growth in that year. This last term is in turn given by

$$\delta_{i,r} = h\left(T^{+}_{i,r}\right) - h(\overline{T_r}) \qquad [4.15],$$

where $\overline{T_r}$ is the average temperature for the base period (1980-2010) for region *r*, $T^{+}_{i,r}$ is the projected temperature in region *r* in year *i* (with $i_0 = 2010$). The h function in equation 4.14 is based on figure 4.1, which uses GDP-weighted temperatures. It was added in PAGE22 with its uncertainty using the vertical lines and global distribution of GDP on Burke et al. (2015) to work out the reference temperature values for each of PAGE regions.

Unlike the other impact sectors in PAGE09, the persistent effects carry over to the next year. As such, they are expected to be much larger than the existing economic impacts in PAGE09, which can be described as instantaneous. Like in PAGE09, in PAGE22 the impact functions include a saturation parameter so that impacts do not exceed 100% GDP.

4.3.1. Benchmark vs. Burke et al. (2015)

A comparison versus the results from Burke et al. (2015) is necessary to ensure that PAGE22 emulates the study properly before PAGE22 can be used for assessing climate change impacts under a range of scenarios. In the comparison against the results from Burke et al. (2015) in this section, PAGE22 is run with only the new persistent effects impact sector on. The other impact sectors – sea level, economic, non-economic, discontinuities – as well as the permafrost thawing emulator are switched off to ensure comparability in results.

Figure 4.2 presents a comparison of the projections of the persistent effect of temperature on GDP up to 2100 between PAGE22 and Burke et al. (2015) under the SSP5-RCP8.5 scenario. One of the key results from the latter is the projected loss of 23% of income by 2100 under the SSP5-RCP8.5 scenario which is aligned with results from PAGE22 with a mean value of 34% loss (10%-52% at the 95% confidence interval). The uncertainty at the 90% confidence interval in their results at the global level has a much larger spread than that in PAGE22. There are several reasons for this: Burke et al. (2015)'s analysis is done at the country level whereas in PAGE22 the world is divided into eight regions. In addition, PAGE22 is a fully integrated assessment model with a simplified climate model within in which physical climate variables are projected for future time analysis periods whereas Burke et al. (2015) assume there is a linear projection to country-level temperature increases up to 2100. These kinds of issues are within the realms of IAM parametrisation given the aim to emulate the results of studies in a simplified way. Figure 4.2 includes a regional analysis for those regions in PAGE22 which could be compared to the regional split in Burke et al. (2015)'s figure 4b. The results are aligned for all the regions in figure 4.2 considering the different approaches around regional split and temperature projections. Following Burke et al. (2015), the persistent effects are capped at 30 °C which is why results from India and Southeast Asia, Africa and Middle East and Latin America are conservative as their temperature projections surpass the 30 °C threshold by 2075/2100.

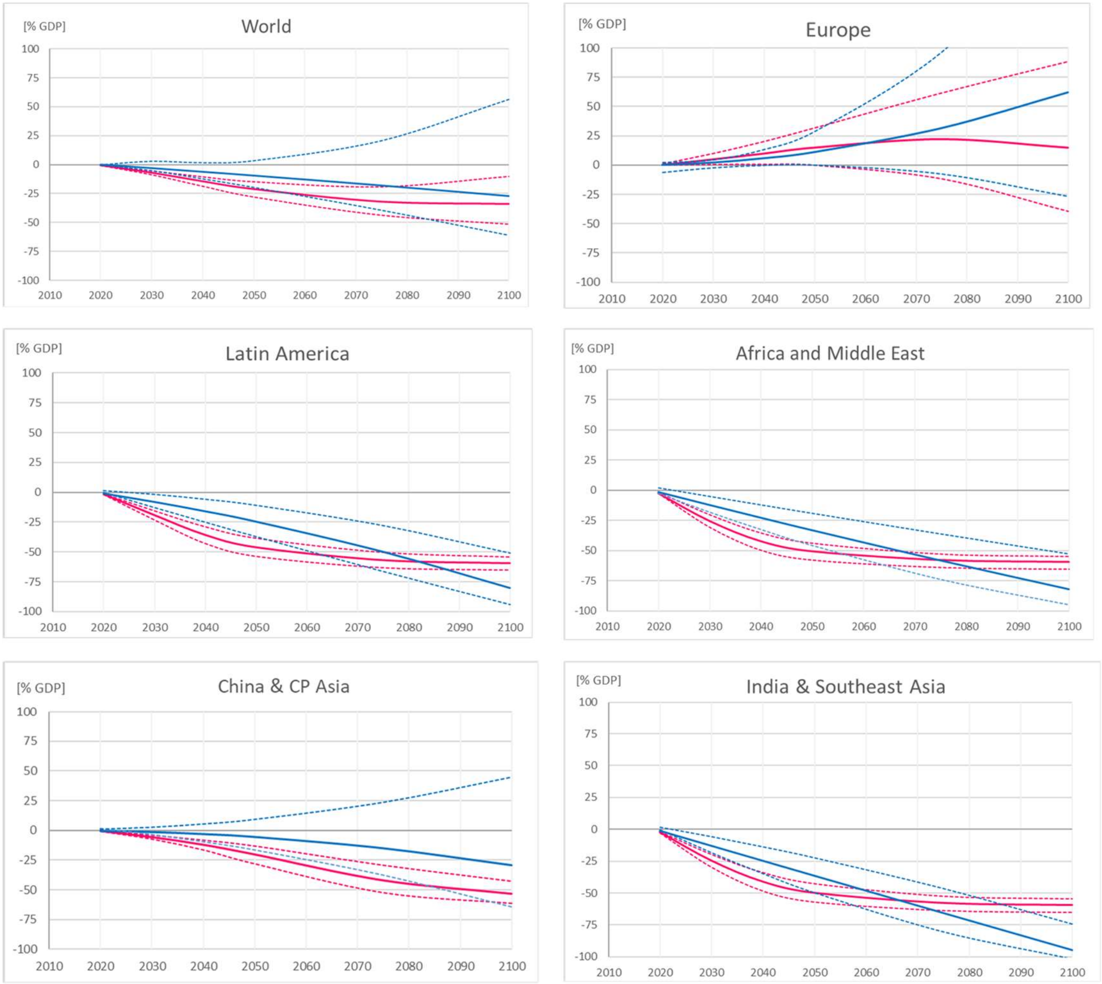

Figure 4.2. Regional projections of the persistent effect of temperature on GDP over 2020-2200 for the SSP5-RCP8.5 scenario. Regions include: (top left) World, (top right) Europe, (middle left) Latin America, (middle right) Africa and Middle East, (bottom left) China and Central Pacific Asia, (bottom right) India and Southeast Asia. Each panel shows the PAGE22v1.4 (pink) and Burke et al. (2015) (blue) projections, with the mean change indicated with solid lines, 95% confidence interval with dashed lines. PAGE22v1.4 results from 10,000 simulations.

As it can be seen in figure 4.2, the mean persistent effects in Europe are projected to be positive reaching a mean value of 15% in 2100 spanning across a loss of 40% to a gain of 88% in the 95% confidence interval. In line with Burke et al. (2015), the negative impacts appear from 2050 onwards. For Latin America, India and Southeast Asia and Africa and Middle East the projected results are negative at the 95% confidence interval with mean values reaching around 60% by 2100. These results depend on several factors. Asides from the physical climate representation in PAGE22 which is different than that in Burke et al. (2015), the regional temperatures used both to calibrate the reference period – 1980-2010 – in equation [4.15] and at the base year have great incidence in the results. These temperatures are GDP-weighted as the analysis in Burke et al. (2015). The base year temperatures for Latin America, India and Southeast Asia and Africa and Middle East are beyond 20 °C which, following figure 4.1, is expected to result in negative impacts. Europe and the Former Soviet Union and rest of Europe's base year temperatures are below the 13°C optimum in figure 4.1 and, as such, results are expected to encompass a positive range. The Former Soviet Union and rest of Europe region is not included in figure 4.2 as there is no analogous region to compare against in Burke et al. (2015).

Burke et al. (2015) aggregate their projections at the country-level to construct a damage function which measures how global changes in temperature affect global economic output. They use this function to project changes in global output under different temperature changes in 2100 and compare their results to those from the damage functions from three IAMs: PAGE, DICE and FUND. In their analysis, FUND 3.8 has the lowest impacts up to 2100, followed by PAGE09 and DICE2010 with a maximum projection of only a few GDP points. Unlike the damage functions in these IAMs, the damage function in Burke et al. (2015) is empirically derived.

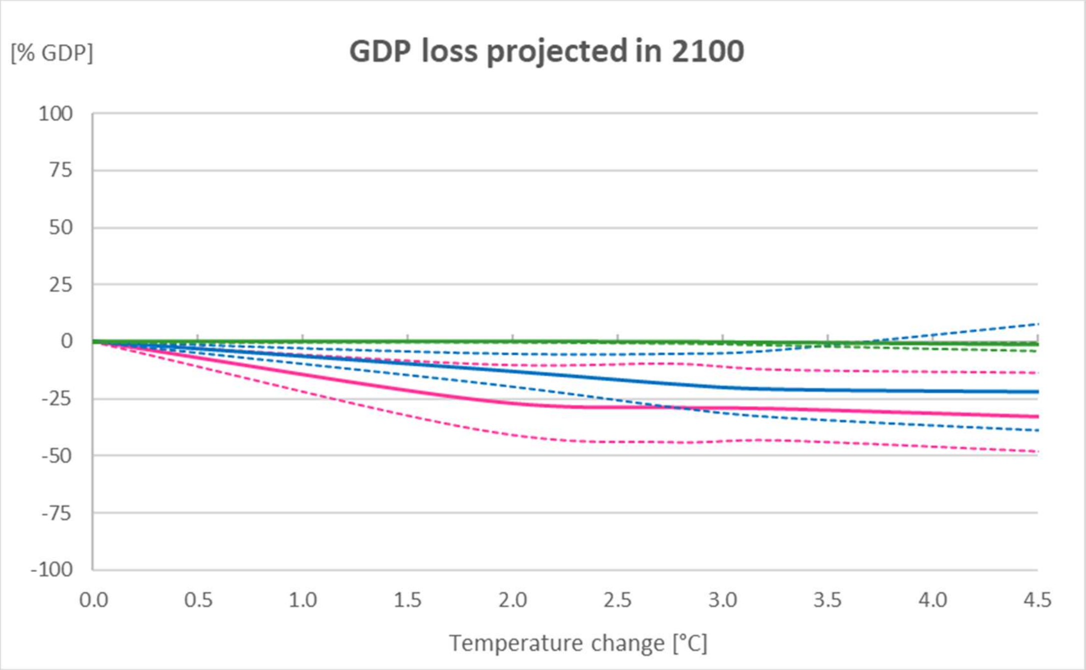

Figure 4.3. Projections of economic losses in 2100 under SSP5-RCP8.5 scenario for different levels of temperature changes vs. pre-industrial. PAGE22v1.4 (pink), PAGE09 (green) and Burke et al. (2015) (blue) projections, with the mean change indicated with solid lines and 90% confidence interval with dashed lines. PAGE09 and PAGE22v1.4 results from 10,000 simulations.

Figure 4.3 recreates this analysis using PAGE09 with only the economic impact sector switched on to compare against PAGE22 with only the persistent effects impact sector on. Like Burke et al. (2015), and as expected, the results from PAGE22 are much larger than those from PAGE09 given that the effects of temperature on economic production in one time analysis period affect the starting GDP in the following one. In PAGE22, a temperature increase of 2°C vs. pre-industrial in 2100 projects a mean GDP loss of 25% rising to 29% and 32% mean losses for temperature increases of 3°C and 4°C. In contrast, under all these temperature increases PAGE09 projects a mean GDP loss in 2100 of under 1%. PAGE09 results are aligned with those from other simplified IAMs DICE2010 and FUND3.8 as shown in Burke et al. (2015)'s fig. 5d.

The projections in PAGE22 are in line with those from Burke et al. (2015). The differences are due to the same reasons as explained earlier in this section, mainly the different level of regional aggregation as well as different approached to temperature projections. Burke et al. (2018) extend the analysis to include other SSPX-RCPY scenarios and project a decrease of GDP of 15-20%, 22-30% and 24-36% in 2100 for temperature increases vs. pre-industrial of 2°C, 3°C and 4°C. These values are aligned with the projections from PAGE22 which estimate a mean loss of 25%, 29% and 32% of GDP in 2100 for 2, 3 and 4 °C temperature increases vs. pre-industrial. For SSP5-RCP8.5 in particular, the mean temperature increase vs. pre-industrial in 2100 is 4.9°C and the projected mean global GDP loss is 34% GDP (14-50%, 90% confidence interval).

4.4. Results and discussion

This section consists of five main analyses around total global impact projections up to 2300: the first is a benchmark of PAGE22 without the persistent economic effects from Burke et al. (2015) and with the permafrost emulator switched off vs. PAGE09 up to 2200, the second is a benchmark of PAGE22 with and without the persistent economic effects (permafrost emulator switched off in both model configurations) up to 2300, the third is an analysis of PAGE22 with the persistent economic effects and the permafrost emulator switched off under the SSPX-RCPY socioeconomic scenarios, the fourth is an analysis of the contribution to impacts from permafrost thawing in the Arctic and the fifth is an analysis around the social cost of carbon dioxide estimates.

4.4.1. Baseline comparison of PAGE22 vs. PAGE09

This section compares the global total impacts projections for 2020- 2200 between PAGE09 vs. PAGE22. PAGE22 is run with the permafrost thawing emulator switched off and without incorporating the persistent economic effects from Burke et al. (2015). It is run with this configuration to progressively understand how all the parameter modifications and new developments from PAGE09 to create PAGE22 affect impact projections. The period of analysis was chosen as it represents the overlap between both models (PAGE09 projects physical and economic impacts from 2009 to 2200 and PAGE22 from 2020 to 2300).

Figure 4.4 presents the results for the four SSPX-RCPY scenarios. These scenarios were chosen for this analysis, as opposed to the SSPX-Y used in AR6, as none of the results from PAGE09 in the literature have used the most recent scenarios to date. PAGE09 includes potential benefits from small temperature increases vs. pre-industrial following Tol (2002) and Stern (2007) (Hope, 2011). In figure 4.4, this flexibility about PAGE09 results in projected global positive impacts (benefits which are represented as negative values in figure 4.4) from climate change closer to the 2.5% confidence interval limit in all SSPX-RCPY scenarios up to 2040. PAGE22 maintains this flexibility for small benefits from climate change as in PAGE09. In PAGE22 the benefits at the 2.5% confidence interval are projected for all scenarios except SSP5-RCP8.5 and only in 2030.

Figure 4.4. Projected global impacts per year over 2020- 2200 for (top left) SSP1-RCP2.6, (top right) SSP2-RCP4.5, (bottom left) SSP3-RCP6.0, and (bottom right) SSP5-RCP8.5. Each panel shows the PAGE09 (green) and PAGE22v1.0 (pink) projections, with the mean change indicated with solid lines and 95% confidence interval with dashed lines. PAGE09 and PAGE22v1.0 results from 10,000 simulations.

As seen in figure 4.4, the mean annual impacts in PAGE22 are larger than those in PAGE09 for all analysis time periods irrespective of the SSPX-RCPY scenario. In all scenarios and analysis time periods except for SSP5-RCP8.5 in 2150 the 97.5% confidence interval values are larger in PAGE22 than in PAGE09. Table 4.1 offers some insight on how the mean global annual impacts in 2200 increase from PAGE09 to PAGE22. The first effect listed is the cumulative inflation adjustment to convert monetary units in PAGE09´s base year (USD 2008) into PAGE22's (USD 2019). This totals 19%, irrespective of the scenario under analysis. The new base and parameters effect over global impacts in 2200 differ considerably depending on the scenario: from -1% in SSP5-RCP8.5 to 42%, 110% and 140% in SSP2-RCP4.5, SSP1-RCP2.6 and SSP3- RCP6.0 respectively (all % estimates based on PAGE09 2200 impacts expressed in 2019 dollars).

Table 4.1. Global impacts in 2200: from PAGE09 to PAGE22v1.0. Analysis of the difference in projected global annual impacts in 2200 [USD Trill./yr between PAGE09 and PAGE22 under the SSPX-RCPY scenarios. The "2008-2019 USD inflation" represents the inflationary adjustment from PAGE09 which uses USD2008 in its base year to PAGE22v1.0 which uses USD2019 in its base year. The "New base year and parameters" column corresponds to all the other developments made to PAGE09 to develop PAGE22v1.0.

Scenario	PAGE09 v1.7 [$Trill./yr]	2008-2019 USD inflation	New base year and parameters	PAGE22 [$Trill./yr]
SSP1-RCP2.6	0.3	0.1	0.5	0.9
SSP2-RCP4.5	4.6	0.9	2.3	7.8
SSP3-RCP6.0	21.0	3.9	27.3	52.2
SSP5-RCP8.5	45.1	8.5	(0.8)	52.8

From table 4.1, it is not clear which are the reasons for the different percentual magnitudes of the new base year and parameter changes under the SSPX-RCPY scenarios. To explore this further, the graphs on figure 4.5 show which five variables have the greater influence on the yearly global impacts in 2200. It represents how changes to these variables in percentual terms (x-axis) would affect the global impacts in 2200 (y-axis). In both models, three recurring variables are the elasticity of the marginal utility of consumption (EMUC) – in PAGE22 it is SSP3-RCP6.0 ranked 6th, the transient climate response (TCR) and the feedback response time (FRT). The other variables included in the graph are IND which is the slope of the indirect sulphates forcing term, RAND_DIS is the random parameter which calculates whether a discontinuity is triggered in each simulation, W_2 is the impact at the calibration temperature for the non-economic impact function, POW_1 and POW_2 are the exponents of the economic and non-economic impact functions with temperature respectively.

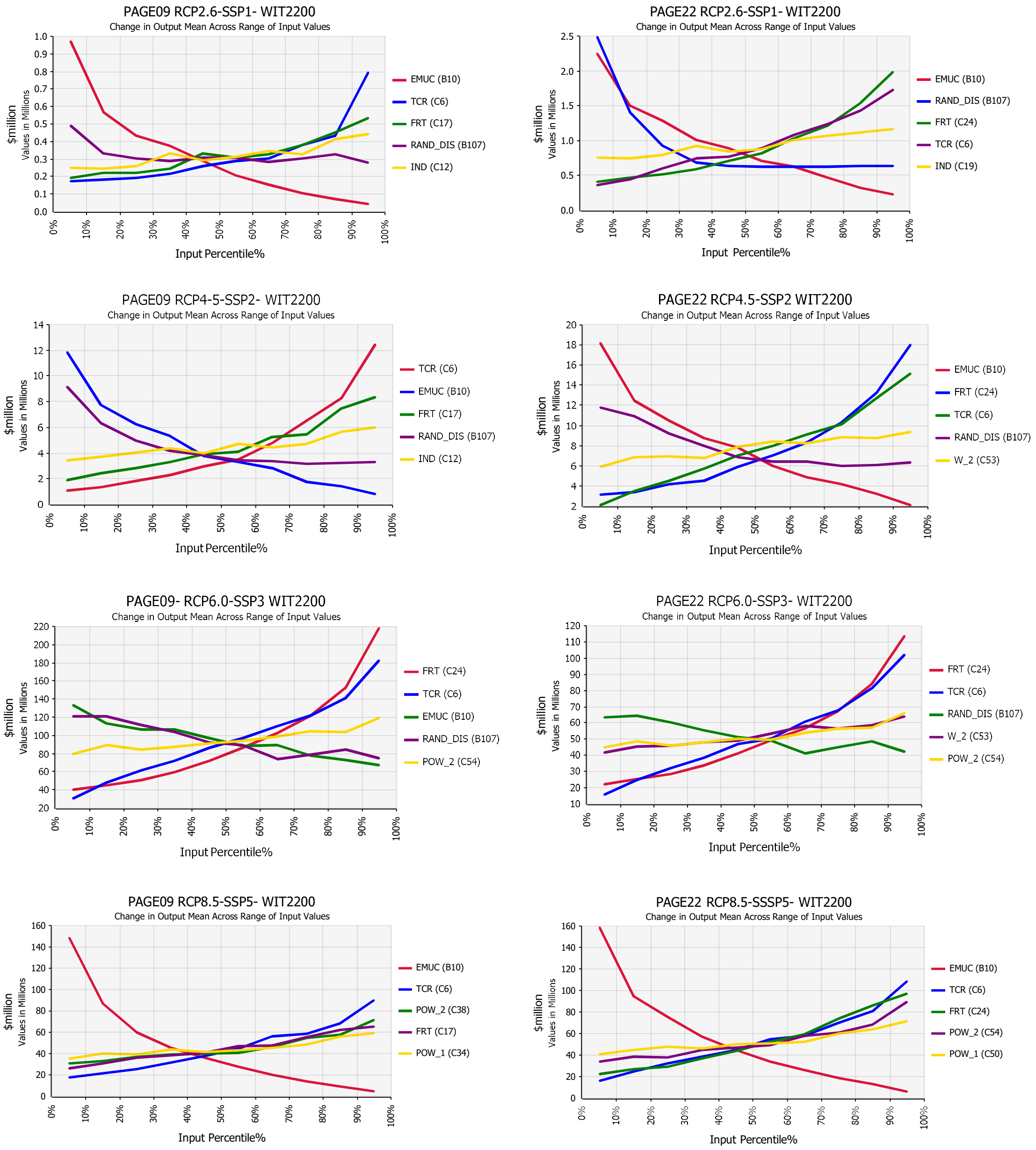

Figure 4.5. Main variables affecting global impacts projections in 2200 in PAGE09 and PAGE22v1.0 for the SSPX-RCPY scenarios (different panel for each scenario). Each coloured line represents a single variable (see legend) showing the resulting change in 2200 global impacts projections (y-axis) for a change in the given variable (x-axis). See the main text for discussion and definition of the different variables. PAGE09 and PAGE22v1.0 results from 10,000 simulations.

4.4.2. PAGE22: quantifying the persistent effects of economic impacts

This section builds on section 4.4.1. by analysing how the projected economic impacts in PAGE22 change when incorporating the persistent economic effects of Burke et al. (2015). For the sake of comparability, it focusses on the same analysis period – 2020-2200 – and scenarios – SSPX-RCPY – than the previous section.

As seen in figure 4.6, the projected results from PAGE22 with the persistent effects are much larger than those with PAGE22 without them for all the 5-95% confidence interval in all scenarios. In addition, except for 2020, the 5% confidence interval curve in PAGE22 with the persistent effects is greater than the 95% confidence interval curve in PAGE22 without the persistent effects.

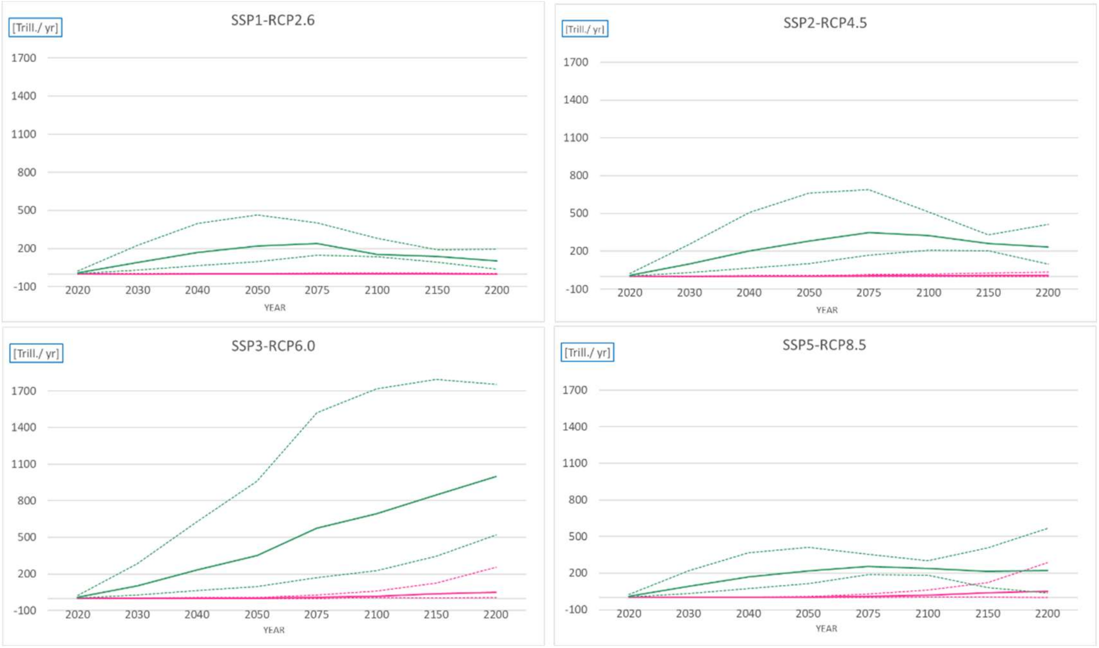

Figure 4.6. Projections of global impacts per year over 2020-2200 for (top left) SSP1-RCP2.6, (top right) SSP2-RCP4.5, (bottom left) SSP3-RCP6.0, and (bottom right) SSP5-RCP8.5. Each panel shows the PAGE22v1.2 (green) and PAGE22v1.0 (pink), with the mean change indicated with solid lines and 90% confidence interval with dashed lines. PAGE22v1.0, 1.2 results from 10,000 simulations.

In PAGE22 without the persistent effects, as shown in table 4.1, the lowest mean values in 2200 were in SSP1-RCP2.6, followed by SSP2-RCP4.5, SSP3-RCP6.0 and SSP5-RCP8.5 following the same logic as those in PAGE09. These results were consistent with projected temperature increases in 2200: the smallest mean values corresponded to the scenario with the lowest mean projected temperature increase –SSP1-RCP2.6 – and the largest impacts to the scenario with the largest projected temperature increase – SSP5-RCP8.5.

This correlation between temperature and economic impacts does not stand in the global impact projections from PAGE22 with the persistent effects from Burke et al (2015). In the latter, the mean projected impacts in 2200 total 104 Trill. USD in SSP1-RCP2.6, 235 Trill. USD in SSP2-RCP4.5, 1,000 Trill. USD in SSP3-RCP6.0 and 224 Trill. USD in SSP5-RCP8.5. In SSP3-RCP6.0, the 95% confidence interval in 2200 surpasses 1,700 Trill., almost seven times its value in PAGE22 without the persistent effects. There are two main reasons for these results. First, as temperature increases, the probability of triggering a discontinuity in a simulation increases as well. In both SSP3-RCP6.0 and SSP5-RCP8.5 discontinuities are triggered from 2100 onwards whereas in SSP1-RCP2.6 and SSP2-RCP4.5 they are not. Second, the most important effect is due to the GDP per capita projections from the different SSPs.

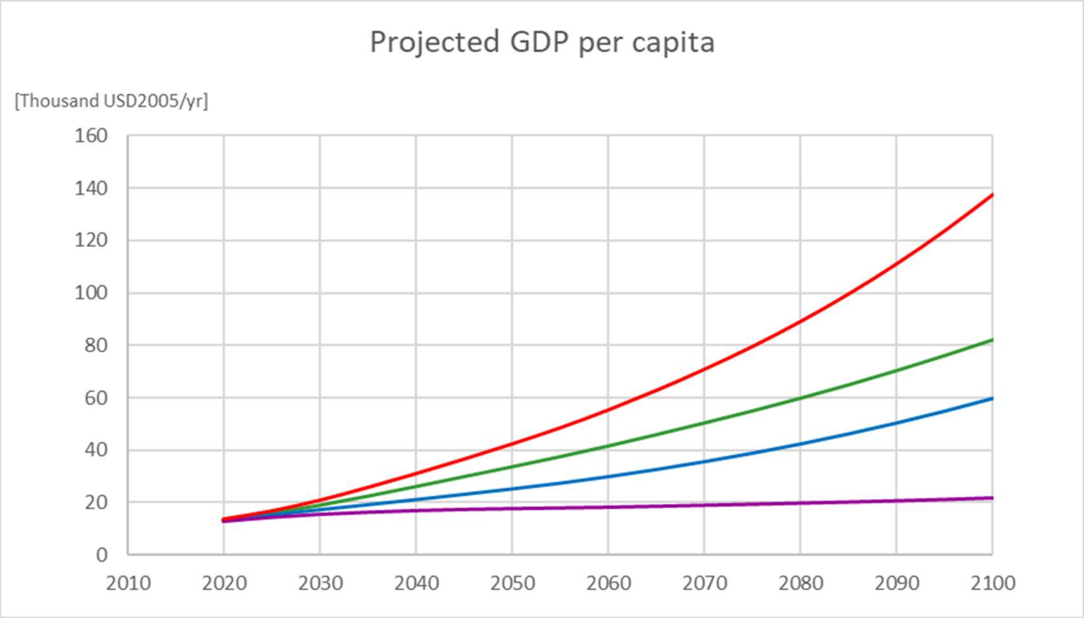

Figure 4.7. Projected GDP per capita from 2010 to 2100 for SSP1 (green line), SSP2 (blue line), SSP3 (purple line) and SSP5 (red line) scenarios. Source: SSP database.

As seen in figure 4.7, the projected GDP per capita[28] varies considerably between the four SSP scenarios included in this analysis. The projected GDP

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[28] GDP per capita growth rates are based on GDP projections from OECD using Purchasing Power Parities (PPP) to ensure comparability between countries (Dellink et al., 2017).

per capita in 2100 represents 6 times the projected value in 2020 in SSP1, 4.5 times in SSP2, 1.7 times in SSP3 and 10.2 times in SSP5. As a result, projected GDP per capita values in 2100 for SSP5 range from 1.7, 2.3 and 6.3 times those projected for SSP1, SSP2 and SSP3 respectively. When incorporating the temperature projections, even though SSP5-RCP8.5- projects higher temperature increases than SSP3-RCP6.0, the latter projects a much poorer – though less hot – world. As a consequence, even though the unweighted impacts of the persistent effects from Burke et al. (2015) as a % of GDP will be lower in SSP3-RCP6.0 than in SSP5-RCP8.5, when including the EMUC weighting, impacts in lower GDP scenarios increase greatly.

4.4.3. PAGE22: the global total impacts from climate change under the SSPX-Y scenarios

This section includes an analysis of the global projected impacts from PAGE22 including the persistent effects from Burke et al. (2015) with the permafrost carbon emulator switched off for the SSPX-Y scenarios. The analysis period is 2020-2300. As explained in section 3.3.2, the SSPX-Y scenarios – which inform the IPCC AR6 – were developed from the SSPs pathways by different IAM modelling teams, and their projected GHGs emissions were also used for CMIP6 (Rogelj et al., 2018; Gidden et al., 2019; Tebaldi et al., 2021).

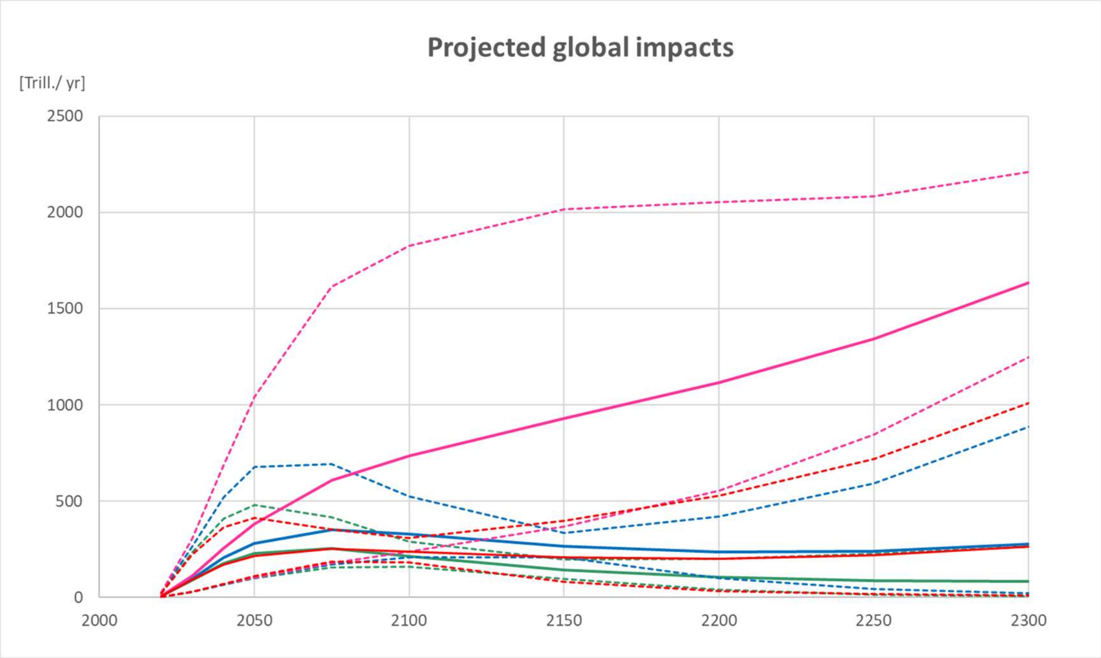


Figure 4.8. Projected global impacts per year from 2020 to 2300 for SS1-26 (green), SSP2-45 (blue), SSP3-70 (pink) and SSP5-85 (purple). PAGE22v1.2 with the persistent economic impacts from Burke et al. (2015) with the mean change indicated with solid lines and 90% confidence interval with dashed lines. PAGE22v1.2 results from 10,000 simulations.

As shown in figure 4.8, the mean projections for SSP3-70 are much larger than for the rest of the scenarios, representing approximately 6 times the mean 2300 projected impacts in SSP5-85 and SSP2-45 and almost 20 times the mean value in SSP1-26. The second scenario with higher projected mean global impacts is SSP2-45, with mean projected values greater than those in SSP5-85 in all analysis time periods with increases ranging between 4 to 28%. Unlike the mean projected curves, the 95% confidence interval curve in SSP5-85 is higher than in SSP2-45 from 2150 onwards.

As shown in figure 4.7, the projections in GDP per capita vary greatly between the SSP scenarios. Like in section 4.4.2., the greater impacts are expected in the scenario with the lowest GDP per capita growth and the inverse relationship between projected GDP per capita growth and projected impacts remains despite SSPX-Y scenarios have different GHGs emissions than in the SSPX-RCPY scenarios.

4.4.4. The global economic impacts from permafrost thawing in the Arctic

This section includes an analysis of the global projected impacts from PAGE22 including the persistent effects from Burke et al. (2015) with the permafrost carbon emulator switched on for the SSPX-Y scenarios. The analysis period is 2020-2300. This section and section 4.4.3. include projections up to 2300 to incorporate the potential long-term impacts from permafrost thawing in the Arctic (Schneider von deimling et al., 2012; Schaefer et al., 2014) following similar impact studies such as Yumashev et al., (2019).

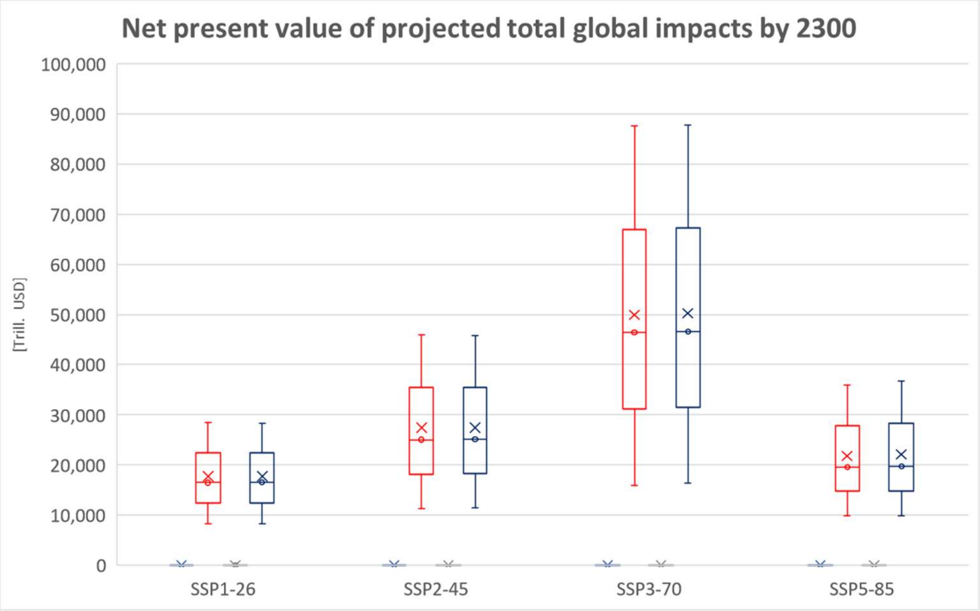


Figure 4.9. Net present value of total global impacts from climate change under SSPY-X scenarios. Results from PAGE22v1.3 (blue) and PAGE22v.12 (red). Crosses represent mean values and error bars 90% confidence interval values. PAGE22v1.2,v1.3 results from 10,000 simulations.

In line with the global projections for SSPX-Y scenarios in figure 4.8, the net present value of projected total global impacts is the largest in SSP3-70 reaching a mean value of over 46,400 trillion [15,900-87,500, 90% confidence interval] and 46,600 trillion [16,400-87,800, 90% confidence interval] with and without including the permafrost carbon feedback. The mean results in SSP3-70 are approximately 1.9, 2.4 and 2.8 times those in SSP2-45, SSP5-85 and SSP1-26 respectively, both for projections with or without the permafrost carbon feedback.

The permafrost carbon feedback in the Arctic increases the mean net present value of impacts by 50, 90, 160 and 200 Trill. USD in SSP1-26, SSP2-45, SSP5-85 and SSP3-70 respectively. These results are towards the higher range of similar studies. Hope and Schaefer (2015) used PAGE09 to estimate that permafrost thawing would contribute 43 Trill. USD to the net present value of climate change impacts in 2015-2200 under the A1B scenario. Unlike the impacts from PAGE22 which only include the permafrost thawing from the top three meters of permafrost carbon stock in the Arctic region, Hope and Schaefer (2015) study includes the global stock which has a mean value of 1,700 PgC, 70% higher than the permafrost stock in PAGE22.

Yumashev et al. (2019) estimate that the permafrost carbon feedback would contribute by 13, 21, 30, 82 and 104 Trill. USD to the net present value of impacts in 2015-2300 under a zero emissions, 1.5 °C target, 2 °C target, NDCs and business as usual scenarios respectively. The 1.5 °C target and 2 °C target scenarios correspond to worlds in which there is a 50% of staying below 1.5°C and 2°C respectively by 2100. The NDCs scenario is projected based on the climate pledges made by governments – nationally determined contributions. Unlike PAGE22, they incorporate Burke et al. (2015) under the assumption that the effects of temperature on economic production do not carry on into the next year. As expected, this compounding effect in PAGE22 results in much larger effects under different projections of a warmer world by 2300. If PAGE22 is set to incorporate Burke et al. (2015) as a level effect, the net present value of impacts under SSP5-RCP8.5 totals 5,100 Trill. USD [1,900-12,940, 90% confidence interval]. These results are more in line with those for the business-as-usual scenario in Yumashev et al. (2019) – 2,200 Trill. USD – which includes a positive effect – decrease in negative impacts – from incorporating the surface albedo feedback.

4.4.5. Social cost of carbon dioxide

This section includes an analysis of the first social cost of carbon dioxide estimates from PAGE22 under the SSPX-RCPY scenarios. These scenarios were chosen over the SSPX-Y for the SCCO2 calculation to compare with other estimates in the literature. Each estimate results from 100,000 simulations. Table 4.2 shows the different estimates for 2020, 2030 and 2050. It includes estimates for each scenario and time period of four different PAGE22 configurations: PAGE22 default with the permafrost carbon feedback emulator and the persistent effects switched off, PAGE22 default with the PCF switched on, PAGE22 default with the persistent effects switched on and PAGE22ALL with both the PCF emulator and persistent effects switched on. The aim of this progressive analysis is to understand the contributions from PCF and the persistent effects to results.

Table 4.2. Social cost of carbon dioxide [USD 2019/tn] for the SSPX-RCPY scenarios. Mean values and 90% confidence interval in brackets. 100,000 simulations of PAGE22-SCCO2. Column "PAGE22 default" corresponds to PAGE-SCCO2v1.0, "+PCF" to PAGE22-SCCO2v.1., "+PERSISTENT EFFECTS" to PAGE22-SCCO2v.1.2 and "PAGE22 ALL" to PAGE22-SCCO2v1.3.

Scenario	Calculation year	PAGE22 default	+ PCF	+ PERSISTENT EFFECTS	PAGE22 ALL
SSP1-RCP2.6	2020	87 [10, 222]	95 [10, 251]	776 [296, 1655]	779 [298, 1655]
	2030	110 [12, 273]	116 [12, 299]	907 [340, 1966]	909 [341, 1976]
	2050	126 [11,305]	135 [12,340]	723 [274,1441]	724 [276,1453]
SSP2-RCP4.5	2020	197 [23,621]	209 [24,670]	856 [126,2027]	866 [0,2035]
	2030	240 [29,741]	256 [30,818]	975 [0,2332]	986 [0, 2357]
	2050	312 [36,937]	332 [38,1037]	782 [29,1789]	810 [0,1914]
SSP3-RCP6.0	2020	465 [43,1565]	504 [44, 1741]	611 [0, 1934]	620 [0, 1986]
	2030	576 [53, 1924]	615 [54, 2105]	708 [0, 2294]	717 [0, 2347]
	2050	743 [69,2400]	788 [71, 2643]	614 [0, 2041]	632 [0, 2125]
SSP5-RCP8.5	2020	241 [32,761]	249 [33,800]	732 [282,1491]	737 [281,1501]
	2030	312 [44,978]	321 [45,1005]	884 [339,1827]	888 [336,1845]
	2050	471 [69, 1453]	481 [68,1491]	877 [297,2039]	884 [296,2074]

According to Table 4.2, the SCCO2 results from PAGE22 default in SSP1-26 are the lowest followed by SSP2-45 for each calculation year; yet the results from SSP3-60 are the highest despite temperature projections are much lower than SSP5-RCP8.5. This points to GDP projections playing a larger influence than temperature increases as discussed in section 4.4.2. When estimating the SCCO2 for the SSP3-RCP8.5 scenario, the SCCO2 results in: 744 [71,2473], 935 [88,3115] and 1261 [122,4162] USD/tn in 2020, 2030 and 2050 respectively. For all PAGE22 default results, in each scenario the results in 2020 are the lowest and the results in 2050 are the highest.

Recent SCCO2 estimates based on expert elicitation reached a mean value of around 300 USD/tn with lower mean estimates of 174 USD/tn for economists and 316 USD/tn for climate scientists (Pindyck, 2019). The latter does not include persistent effects of climate change on the economy and the mean results are in line with the results from PAGE22 default for all scenarios but SSP3-RCP6.0. Kikstra et al. (2021) estimate the mean SCCO2 in 2020 under SSP2-45 for PAGE09 and PAGE-ICE (including only the parameter updates to be consistent with AR5) at 158 and 217 USD/tn respectively (values in 2015 USD) which would be equal to 170 and 234 in USD 2019/tn (same unit as in table 4.2). According to table 4.2, using PAGE22, the mean SCCO2 in 2020 for SSP2-45 is 209 [26,633] USD/tn (mean and 90% confidence interval) which sits comfortably between both estimates in Kikstra et al. (2021); mean value 23% higher than PAGE09 and 11% lower than PAGE-ICE.

Adding the permafrost carbon feedback to the default version of PAGE22 increases the mean social cost of carbon dioxide by 2-3%, 6-7%, 5-9% and 6-8% in SSP5-RCP8.5, SSP2-RCP4.5, SSP1-26 and SSP3-RCP6.0 scenarios respectively. These results are in line with Kikstra et al. (2021) which estimate that the permafrost carbon feedback in PAGE-ICE increases SCCO2 estimates by 7% under the SSP2-45 scenario and within range of Kessler (2017) which estimates the PCF increases the SCCO2 by 10-20% using DICE.

Regardless of the scenario, in both PAGE22 default + persistent effects and PAGE2ALL, the SCCO2 is lowest in 2020 and highest in 2030. Incorporating the persistent effects to the PAGE22 default version increases results considerably in all scenarios (except for SSP3-RCP6.0 in 2050) and calculation year to almost 6 to 9 times those in PAGE22 default for SSP1-26. This was expected given the findings in section 4.4.2. These is in line with Moore and Diaz (2015) which found that incorporating growth effects – using Dell et al. (2012) – in DICE (Nordhaus, 2013) increases the social cost of carbon in 2015 to almost seven times (from 33 to 220 USD 2005/tn, 43 and 288 USD 2019/tn respectively). The results in their analysis fall within SSP1-RCP2.6 and SSP2-RCP4.5 temperature ranges. The estimate of 43 USD 2019/tn SCCO2 is below the mean value in PAGE22 of 87 USD2019/tn under SSP1-RCP2.6 but falls withing the confidence interval in both SSP1-RCP2.6 and SSP2-RCP4.5. SCCO2 estimates from PAGE09 have been higher than DICE estimates in previous calculations for the US Government (see IAWG, 2016, table A2). There are several reasons why, including PAGE using probability distribution for most of its parameters whilst DICE uses point estimates and PAGE incorporating discontinuities whilst DICE does not. In addition, Moore and Diaz (2015) base their growth effects on Dell, Jones & Olken (2012) which, as stated in section 4.1, only assume growth effects in poorer regions whilst Burke et al. (2015) assumes persistent effects on economic growth regardless of a country's wealth.

Recent approaches to estimate the social cost of carbon dioxide using a stochastic version of DICE incorporating different risk states, estimate that moving away from risk aversion increases SCCO2 estimates by more than 2.5 times to up to 987 US$/tn in 2050 (Crost & Traeger, 2014). Hansel et al. (2020) updates to DICE (including a revision on damage estimates) result in a doubling of SCCO2 over baseline version. Ricke et al. (2018) estimate the SCCO2 at country level for different SSPX-RCPY scenarios under a range of persistent damages configurations based on Dell et al. (2012) and Burke et al. (2015). Their global median estimates in 2020 range from approximately 100-800 USD/tn in SSP2-45, 100-1,100 USD/tn in SSP3-RCP6.0, 100-1,500 USD/tn in SSP3-RCP8.5 and 100- 900 USD/tn for SSP5-RCP8.5, aligned with estimates from table 4.2.

There are two unusual things about the results from this model configurations: that several of the lower boundaries of results are zero and that the results in SSP3-60 in 2050 with persistent effect are lower than without them. The latter is related to the former. The SCCO2 results in zero for 35% of simulations in SSP3-RCP6.0, 1% in SSP5-RCP8.5, 5% in SSP2-RCP4.5 none in SSP1-RCP2.6 and 30% in SPP3-RCP8.5. The graphs in figure 4.10 can help clarify both points.

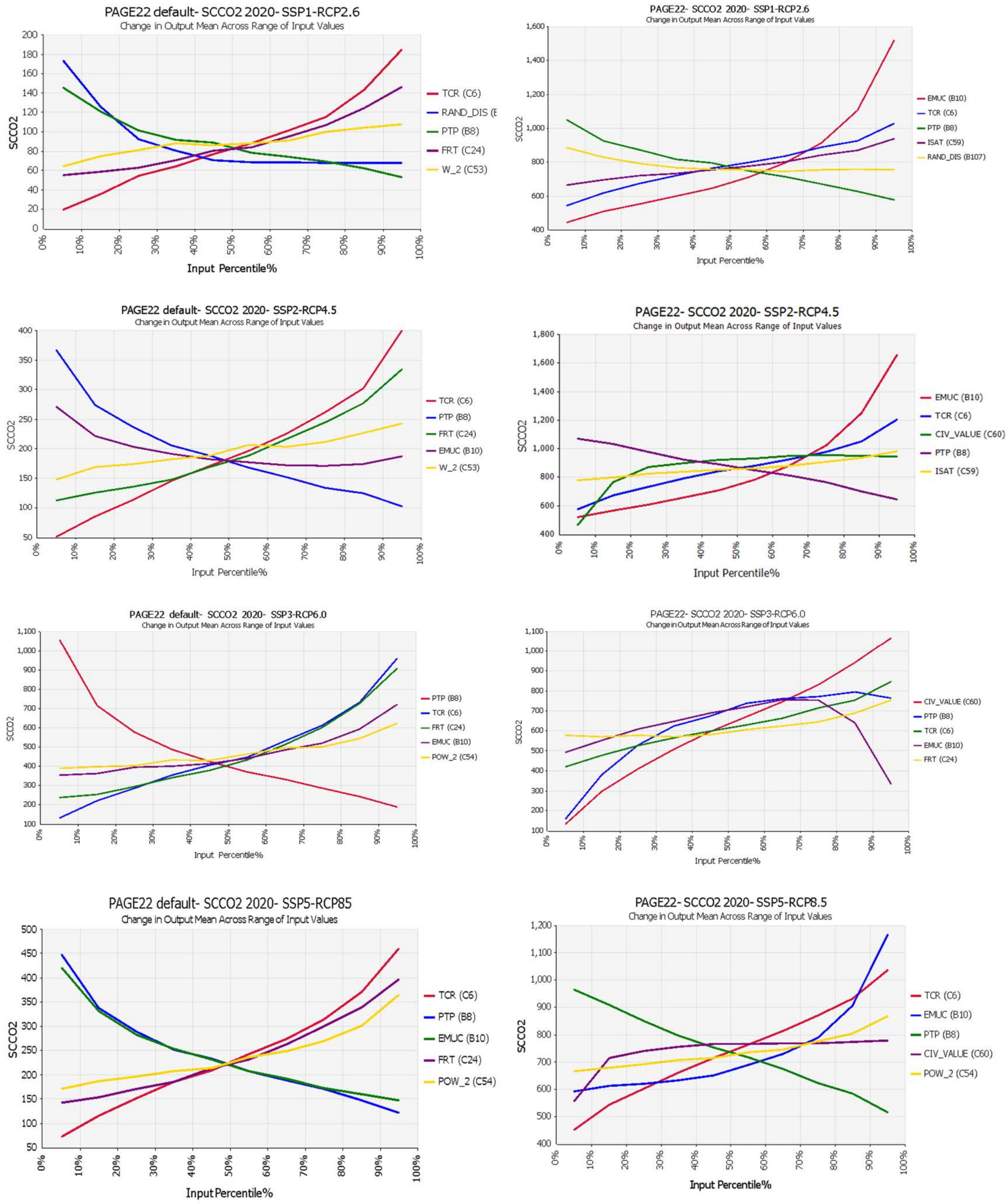


Figure 4.10. Main variables affecting the social cost of carbon dioxide in 2020 in PAGE22v1.0 and 1.3 for the SSPX-RCPY scenarios ((different panel for each scenario). Each coloured line represents a single variable (see legend) showing the resulting change in 2200 global mean temperature (y-axis) for a change in the given variable (x-axis). See the main text for discussion and definition of the different variables. PAGE22v.1.0 and PAGE22v.1.3 results from 100,000 simulations.

Figure 4.10 show which five variables have the greater influence on the social cost of carbon dioxide in 2020 for the PAGE22 default version and PAGE22 with both the permafrost carbon feedback and persistent effects switched on. Each curve represents how changes to these variables in percentual terms (x-axis) would affect the social cost of carbon dioxide (y-axis). There are three recurrent variables in each graph (except for PAGE22 default in SSP1-RCP2.6): the transient climate response (TCR), the elasticity of the marginal utility of consumption (EMUC) and the pure time preference rate (PTP). The latter two were expected given that they are the parameters used for equity weighting and discounting respectively. The other variables vary depending on the model version. In the SCCO2 estimates with PAGE22 default, the feedback response time (FRT) is on the top four variables for all scenarios and the fifth variable is related to the estimates of the non-economic impact sector (W_2 and POW_2). All these variables are in the top 8 variables for SCCO2 estimates in 2010 using PAGE09 (Hope, 2013).

In the SCCO2 estimates using PAGE22ALL with both the permafrost carbon emulator and persistent effects, the statistical value of civilisation – CIV_VALUE – is one of the four top variables in all scenarios but SSP1-RCP2.6. It is used to limit the total effect – sum of climate change impacts, preventative and adaptation costs – from each policy. This is not surprising given the magnitude of projected impacts from incorporating the persistent effects of Burke et al. (2015).

Table 4.3. Social cost of carbon dioxide [USD 2019/tn] for the SSPX-RCPY scenarios with default and high statistical value of civilisation. Mean values and 90% confidence interval in

brackets. 100,000 simulations of PAGE22. Column "PAGE22 ALL" corresponds to PAGE22-SCCO2v1.3 and "PAGE22ALL high CIV_VALUE" to PAGE22-SCCO2v1.4.

Scenario	SCCO2	PAGE22 ALL	PAGE22ALL high CIV_VALUE
SSP1-RCP2.6	**2020**	**779 [298, 1655]**	**791 [309,1690]**
	2030	**909 [341, 1976]**	**923 [354,2001]**
	2050	**724 [276,1453]**	**736 [286,1465]**
SSP2-RCP4.5	**2020**	**866 [0,2035]**	**949 [315,2197]**
	2030	**986 [0, 2357]**	**1082 [352,2543]**
	2050	**810 [0,1914]**	**886 [281,2060]**
SSP3-RCP6.0	**2020**	**620 [0, 1986]**	**1693 [326,4883]**
	2030	**717 [0, 2347]**	**1982 [358,5880]**
	2050	**632 [0, 2125]**	**1831 [259,5554]**
SSP5-RCP8.5	**2020**	**737 [281,1501]**	**778 [331,1582]**
	2030	**888 [336,1845]**	**938 [397,1938]**
	2050	**884 [296,2074]**	**937 [346,2195]**
SSP3-RCP8.5	**2020**	**535 [0,1876]**	**2241 [354,6866]**
	2030	**628 [0,2248]**	**2685 [396,8463]**
	2050	**632 [0,2442]**	**3007 [314, 10062]**

Table 4.3. shows a comparison of how SCCO2 estimates vary in PAGE22ALL when using the default CIV_VALUE as in table 4.2. which has a mean value of 67,000 USD trill. (13,000, 63,000 and 130,000 USD trill. for the min, mode and max of the triangular distribution parameters respectively) based on Weitzman (2009), and a higher CIV_VALUE which results from multiplying the parameters in the default version by 1,000,000,000,000. The latter was chosen to prevent from getting a value of zero for the SCCO2 regardless of the scenario so that the SCCO2 estimates are not capped by the CIV_VALUE in any given run. As shown in table 4.3, the SCCO2 estimates with the high CIV_VALUE have a negligible effect (2%) on results in SSP1-RCP2.6 but increase the mean values by 6%, 9-10%, 170-190% and 320-380% in SSP5-RCP8.5, SSP2-RCP4.5, SSP3-RCP6.0 and SSP3-RCP8.5 respectively. In addition, in the SSP3 scenarios the upper

boundary of the 90% CI increases by around 2.5 times in SSP3-RCP6.0 to around 4 times in SSP3-RCP8.5.

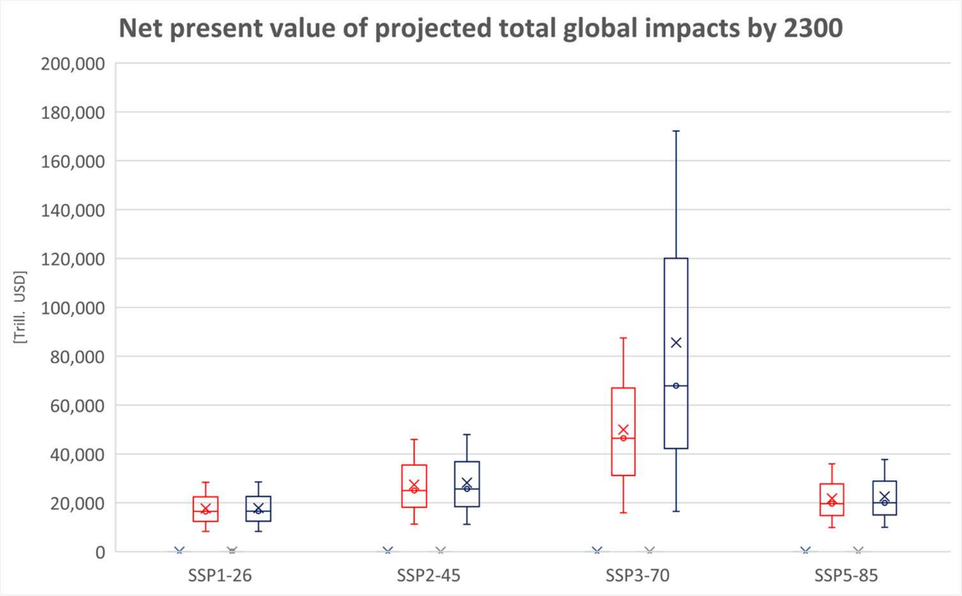


Figure 4.11. *Net present value of total global impacts from climate change under SSPY-X scenarios. Results from PAGE22v1.5 and v.1.3 with higher (blue) and lower (red) statistical value of civilisation value respectively. Crosses represent mean values and error bars 90% confidence interval values. PAGE22 results from 10,000 simulations.*

The statistical value of civilisation – CIV_VALUE – affects the SCCO2 calculation by affecting the estimates of the total impacts in PAGE22. The latter was used to analyse the global economic impacts from permafrost thawing in section 4.4.4. Following on the insight from the SCCO2 calculation, figure 4.11. compares the net present value (NPV) of projected global impacts by 2300 using the default and higher CIV_VALUE. In both models, PAGE22 includes the permafrost carbon feedback and persistent effects and the mean NPV increases by 1-2% in SSP1-26, SSP2-45 and SSP5-85 but by almost 50% in SSP3-70. For the latter, the upper boundary of the 90% confidence interval almost doubles: from 87,820 USD trill. to 172,200 USD trill. In the model configuration with the higher CIV_VALUE, the permafrost carbon feedback increases the NPV by 90, 100, 130 and 900 USD trillion in SSP1-26, SSP2-45, SSP5-85 and SSP3-60 respectively.

4.5. Limitations

This chapter introduced the first estimates of the global economic impacts from PAGE22 with five analyses:

1. a comparison of PAGE22 against PAGE09, without including the permafrost carbon feedback nor the persistent economic effects from Burke et a. (2015);
2. the impact of including the persistent effects of Burke et al. (2015) in PAGE22;
3. the impact of additionally including the permafrost carbon feedback;
4. an analysis of the global economic impacts from permafrost thawing in the Arctic region, designed to quantify how the different developments made to PAGE09 to develop PAGE22 contributed to results; and
5. the first estimates of the social cost of carbon dioxide from PAGE22 and an analysis of the contribution to results from the PCF and the persistent effects.

One of the biggest limitations of projecting climate change economic impacts into the future is not having enough historical period to validate against. Unlike climate models, which can exploit observations to validate their representation of physical processes, projecting economic impacts from climate change does not have an analogous record to compare against.

Burke et al. (2015)'s study sparked the new model development on the impact sectors in PAGE22. Despite their analysis points to much larger economic impacts from climate change than previous studies (e.g. Dell et al., 2012), there are at least two reasons why these could be an underestimate. First, one of the assumptions of using Burke et al. (2015) is presuming that the response function between temperature and economic production will remain unchanged in the period under analysis. Given the uncertainty about the future and that some of the scenarios included temperature increases considerably higher than the temperature changes in Burke et al. (2015)'s 1960-2010 analysis period, it could be argued that results in these scenarios are conservative. Following Burke et al. (2015), in PAGE22 the persistent economic effects are capped at 30 °C, which may result in underestimating losses in regions which are projected to warm beyond this level, including Latin America, the Middle East and Africa and India and Southeast Asia. Second, Burke et al. (2015) only includes temperature-driven effects on the economy. As such, non-market impacts and other climate change impacts, such as sea level rise and tropical cyclones, are excluded in their analysis. PAGE22 includes sea level rise impacts and the non-market impacts in the sea level and non-economic impact sectors respectively. However, the potential increase in extreme weather events is not factored into the model as the parametrisation has been done with studies based on past events.

Incorporating the explicit representation of permafrost thawing has a larger effect on economic impacts than the inflation adjustment under all scenarios followed by the new base year and parameters. By large, incorporating the persistent effects has the biggest impacts on results. The latter was expected given that, unlike in PAGE09, the persistent effects in one year are carried onto the next analysis period, as shown in equation 4.14. Another expected feature was a greater uncertainty in results, in particular positive ones. This is consistent with Burke et al. (2015)'s global damages projections in 2100 for SSP5-RCP8.5 which projected positive effects in Europe and a 95% confidence interval which encompassed both positive and negative effects for North America, Central and East Asia and the World. It should be noted that there is a potential overlap in PAGE22 by including both an economic impact sector and the persistent effects impact sector. This is by design, to enable the user to turn each of them on/off depending on the scenario analysis of interest. The alternative would have been to eliminate the economic impact sector and replace it with the persistent effects impact sector. In terms of results, as shown in figure 4.3, the magnitude of the persistent effects impacts overtakes the economic impacts.

Arguably, more stringent adaptation and mitigation policies would prevent reaching the projected impacts from PAGE22 with the persistent effects from Burke et al. (2015). However, the objective of research question 3 was to investigate how incorporating the persistent effects of temperature on economic production affect climate change economic impact projections precisely because the projections from Burke et al. (2015) – 23% of global GDP loss by 2100 under a business-as-usual scenario – are considered an improvement over impact studies to date. Hence, if Burke et al. (2015) based their analysis on what has happened between 1960 and 2010 it is a valid exercise to wonder what the impacts of extending their results into the future would mean.

The results from PAGE22 reflect much larger impacts than those from similar IAMs to date, – PAGE09 and PAGE-ICE included – in line with some of the criticisms on the literature to the latter (Keen et al., 2020; Keen, 2021). In addition, these are calculated with a discount rate which places a smaller effect to future impacts than present ones. As a result, depending on the discount rate used, the projected impacts could be smaller or much larger.

4.6. Summary and conclusion

Chapter 3 introduced PAGE22, concentrating on the new developments made to the physical impacts to develop it from PAGE09. This chapter presented the rationale for incorporating the persistent effects from temperature on economic production for Burke et al. (2015). Section 4.1 explained the rationale behind Burke et al. (2015) and how incorporating it into PAGE22 would address some of the criticisms to the damage functions in PAGE09 and other similar IAMs. Section 4.2 introduced the economic modelling in PAGE09 to depict the existing impact modelling architecture. Section 4.3 focussed on how to develop a new impact sector in PAGE22 and included a benchmark analysis of results from PAGE22 vs. those in Burke et al. (2015). The latter is needed to validate PAGE22 before exploring the impacts through a range of scenarios.

Section 4.4 presented an analysis of results starting from a benchmark of PAGE09 vs. PAGE22 for 2020-2200 without the persistent effects and with the permafrost carbon emulator switched off. Then, it compared the results from PAGE22 with and without the persistent effects for the SSPX-RCPY scenarios for 2020-2200 followed by an analysis of impacts from PAGE22 with the persistent effects for the SSPX-Y scenarios up to 2300 – all model configurations with the permafrost carbon emulator switched off. It included an analysis of the impacts from permafrost thawing in the Arctic for the SSPX-Y scenarios up to 2300, addressing research question 4. It followed by estimates from the SCCO2 under the SSPX-RCPY scenarios.

The focus on permafrost thawing impacts in the Arctic resulted from the framework introduced in Chapter 2 for assessing the potential economic impacts stemming from Arctic change. Asides from negative local impacts (Hovelsrud et al., 2011) (as depicted in box ii in figure 2.1), permafrost thawing in the Arctic can result in large indirect global impacts on the economy posing threats to large economic regions outside the Arctic (box iii in figure 2.1). Given that the permafrost carbon feedback is largely underrepresented in CMIP6, the projected economic global impacts estimated using the former as input do not include this feedback.

PAGE22 can be used to inform policymakers on a range of climate change impacts. By incorporating the persistent effects from Burke et al. (2015) and including a permafrost carbon emulator it addresses some of the criticisms mentioned in section 4.1. Despite these new developments and as discussed in section 4.5, the results presented on this chapter point to these estimates being conservative.

Chapter 5 – Summary and Conclusions

This thesis is focussed on the potential global economic impacts from climate change in the Arctic. Chapter 1 presented the four research questions (RQ) this thesis set out to investigate. This Chapter is structured around these research questions explaining how they were addressed in the previous chapters and highlighting the research contributions from this thesis. It concludes with a section about future research.

RQ1: How can climate change in the Arctic region translate into local and global economic impacts?

Chapter 1 introduced the concept of Arctic amplification, which denotes how the Arctic is changing faster than the global average. The latter is a result of a rate of increase in regional temperatures which was double the global average (IPCC, 2013; Overland et al., 2015). Chapter 2 introduced a framework built to understand how physical changes in the Arctic such as melting of glaciers and the Greenland icesheet, permafrost thawing and a decline in sea ice (Stroeve et al., 2012a; Van den Broeke et al., 2016; Chadburn et al., 2017) can translate into positive and negative economic impacts both in the region and beyond (Alvarez et al., 2020).

The framework includes four transmission channels that connect physical changes in the Arctic with impacts. First, there are economic opportunities such as agriculture, commercial shipping, oil & gas extraction, mining and tourism which could potentially unlock multi-billion-dollar annual revenues (ACIA, 2005; Gautier et al., 2009; Dyck and Sumalia, 2010; Hovelsrud and

Smit, 2010; Hovelsrud et al., 2011; Emerson and Lahn, 2012; Bekkers et al., 2016; Lam et al., 2016). Second, there are direct regional impacts on local communities, ecosystems, and climate (ACIA, 2005; Hovelsrud et al. 2011; Wassmann et al., 2011; AMAP, 2015). Third, there are indirect economic impacts outside the Arctic region that result from Arctic change (Euskirchen et al., 2013; Hope and Schaefer, 2015; González-Eguino et al., 2016, 2017; Yumashev et al., 2017a). These indirect impacts include how the melting of the Greenland ice sheet can contribute to global sea level rise (Chylek et al., 2009; Tedesco et al., 2011; Francis and Vavrus, 2012) and how permafrost thawing on land (Schuur et al., 2009, 2015; Schaefer et al., 2011) and subsea (Romanovskii et al., 2005; Shakhova et al., 2010, 2014, 2017; Nicolsky et al., 2012) can increase global temperature through carbon dioxide and methane emissions, amongst others. Fourth, economic opportunities, direct regional impacts and indirect global impacts can translate into secondary impacts through knock-on effects on the economy.

Chapter 2 also presented an analysis of the existing quantitative methods and models required for quantitative assessments of the four impacts (benefits and costs) presented in the framework. It also highlighted that a transdisciplinary approach combining climate, economics and policy is required to quantify the economic impacts from Arctic change. Integrated assessment models are presented as the tool for assessing the indirect global impacts from Arctic change. The interest in using integrated assessment models to quantify the global economic impacts from Arctic change spurred RQ2, 3 and 4.

In summary, this thesis brings new insight to RQ1 by introducing a new framework which explains how Arctic climate change can translate into regional and global economic impacts.

RQ2: How can the Arctic permafrost carbon feedback affect the temperature projections up to 2300?

Chapter 3 introduced the concept of permafrost carbon feedback which describes the process of how climate warming results in an increase in permafrost thawing which, via the release of carbon dioxide and methane, further reinforces temperature rise. The permafrost carbon stock in the northern circumpolar permafrost region is almost double the total carbon in the atmosphere (Schuur et al., 2018). Yet, the permafrost carbon feedback is not included in most ESMs in CMIP6 (Canadell et al., 2021). As a result, climate impact studies based on CMIP6 may underestimate the magnitude of the impacts they are trying to quantify (Yumashev et al., 2019).

To address this gap, Chapter 3 presented PAGE22, an integrated assessment model developed to estimate the potential economic impacts from the permafrost carbon feedback. PAGE22 is based on its predecessor (PAGE09, Hope, 2011) and includes several changes to its climate parameters, economic parameters and analysis time periods. The default model version makes projections up to 2300 but, like the parameters in the model, the analysis time periods are user definable. In addition, three structural changes were made to develop PAGE22 from PAGE09. First, it includes a permafrost carbon feedback emulator (based on Burke et al., 2017) which can estimate the carbon dioxide and methane emissions from permafrost thawing. Second, a new forecasting temperature variable was added to the model based on Holt's method with damped linear trend for irregular time series (Cipra, 2006; Hanzák, 2014). This structural improvement was needed to work with the permafrost carbon feedback emulator, avoiding the lag of using the existing variable which measures temperature rise as input. As a result, PAGE22 does not use the temperature rise in 2100 to estimate the permafrost carbon emissions in 2150 but a forecasted temperature variable which is closer to the temperature rise in 2150 as input. Third, PAGE22 includes a new impact sector, which quantifies the persistent effect of temperature on economic production based on Burke et al. (2015). This is discussed further under RQ3, below.

Section 3.3.3. focussed on quantifying the projected cumulative permafrost carbon loss in 2100, 2200 and 2300. It consisted of three analyses: projections of the permafrost emissions under the SSPX-RCPY scenarios and a comparison to Burke et al. (2017), a comparison against the literature and an analysis of the contribution of permafrost thawing to temperature projections. In response to RQ2, including the feedback from permafrost carbon emissions increases the mean temperature values in 2300 by 20% (0.28 °C), 10% (0.38 °C), 4% (0.17 °C) and 3% (0.34 °C) in SSP1-RCP2.6, SSP2-RCP4.5, SSP3-RCP6.0 and SSP5-RCP8.5 respectively. These values are rather large considering the current policy discussions around limiting global temperature increases vs. pre-industrial to 1.5°C and 2°C, a 0.5°C temperature difference between them. These projections are conservative for three main reasons. First, and most importantly, the parametrisation of the permafrost carbon stock in PAGE22 is based on the top 3 meters of permafrost carbon which has a mean value of 1,000 GtC vs. 1,672 PgC of permafrost carbon in the northern circumpolar region. Second, the permafrost carbon feedback in PAGE22 is capped at 10.5 °C above pre-industrial, following Burke et al. (2017), and this temperature increase is surpassed in SSP5-RCP8.5 after 2100. Third, the permafrost carbon emulator models gradual permafrost thawing and not abrupt thawing

(Turetsky et al., 2019; 2020) given the lack of impact studies needed to incorporate it onto PAGE22.

In summary, this thesis brings new insight to RQ2 by providing new estimates on the permafrost carbon feedback potential contributions to temperature projections by 2300. In addition, PAGE22 can be used to expand on this analysis for different scenarios and time periods.

RQ3: How does incorporating the persistent effects of temperature on economic production affect climate change economic impact projections?

Chapter 4 introduced the rationale for incorporating the persistent effects of temperature on economic production (after Burke et al., 2015) to PAGE22. It explained how this new development addressed three recurrent criticisms to IAMs damage estimates: 1) that they use outdated impact studies (Burke et al., 2016; Diaz and Moore, 2017), 2) that simplified IAMs are calibrated interdependently (Rose et al., 2014) and 3) that high temperatures only result in implausible damages (Dietz and Stern, 2014). Given simplified IAMs are used to inform climate change policy metrics like the social cost of carbon dioxide (SCCO2) (IAWG, 2010, 2013), these three issues can result in an underestimation of policy metrics.

One of the takeaways of the Burke et al. (2015) study is that there is a non-linear relationship between local temperature and the change in GDP per capita, peaking at 13 °C. As a result, they project a loss of 23% of output by 2100 under the SSP5-RCP8.5 scenario which are much larger than previous estimates from IAMs in the literature. As expected, the projected climate change impacts in PAGE22 with the persistent effects are much larger than those without including this effect. As seen in figure 4.6, in the 2020-2200 analysis period the 5% confidence interval curve in PAGE22 with the persistent effects is greater than the 95% confidence interval curve in PAGE22 without the persistent effects for all SSPX-RCPY scenarios except for 2020.

In PAGE22 without the persistent economic effects the mean projected impacts in 2200 reach 1 Trill. USD in SSP1- RCP2.6, 8 Trill. USD in SSP2-RCP4.5, 52 Trill. USD in SSP3- RCP6.0 and 53 Trill. USD in SSP5- RCP8.5 respectively. There is a correlation between temperature increases and economic impacts with SSP1-RCP2.6 and SSP5-RCP8.5 resulting in the lowest and highest temperature and total impacts projections respectively. This dynamic changes when incorporating the persistent effects from Burke et al. (2015) into the analysis with the mean projected impacts in 2200 totalling 104 Trill. USD in SSP1- RCP2.6, 224 Trill. USD in SSP5- RCP8.5, 235 Trill. USD in SSP2-RCP4.5 and 1,000 Trill. USD in SSP3- RCP6.0 respectively. The GDP per capita growth – which is included as an exogenous variable in the model – plays a key role on impacts with an inverse relationship between projected GDP per capita growth and projected impacts (figure 4.7). As shown in figure 4.8, this same logic applies for the global economic impact projections for the SSPX-Y scenarios up to 2300.

In addition, incorporating the persistent effects to the PAGE22 default version increases the social cost of carbon dioxide considerably up to 9 times its value without them under the SSPX-RCPY scenarios.

In summary, this thesis brings new insight to RQ3 by providing new estimates on the climate change impacts and social cost of carbon dioxide under a range of scenarios. In addition, both model versions of PAGE22 can be used expand on economic impact and SCCO2 estimates for a range of different scenarios and time periods.

RQ4: What are the potential economic impacts from the Arctic permafrost carbon feedback?

Chapter 4 also included an analysis of the total economic effect of the permafrost carbon feedback under the SSPX-Y scenarios up to 2300. As shown in figure 4.9, the permafrost carbon feedback in the Arctic increases the mean net present value of impacts by 50, 90, 160 and 200 Trill. USD in SSP1-26, SSP2-45, SSP5-85 and SSP3-70 respectively. These results are towards the higher range of similar studies and the differences between them are addressed in section 4.4.4.

In addition, the permafrost carbon feedback contributes to an increase of the social cost of carbon dioxide estimates by 2-3%, 6-7%, 5-9% and 6-8% in SSP5-RCP8.5, SSP2-RCP4.5, SSP1-26 and SSP3-RCP6.0 scenarios respectively.

In summary, this thesis brings new insight to RQ4 by contributing to the literature with new estimates of the effect of the permafrost carbon feedback on both the global economic impacts and social cost of carbon dioxide.

The main contributions from this thesis are three: the framework presented in Chapter 2, the default version of PAGE22 presented in Chapter 3 and 4 and the SCCO2 version of PAGE22 which was specifically developed to estimate the SCCO2 in section 4.4.5.. As explained in section 2.4, a transdisciplinary approach is required to translate the physical impacts from climate change in the Arctic into economic terms. Developing PAGE22 entailed such an effort with Chapter 3 explaining the changes to the climate module and Chapter 4 on the economic module. Different methodologies and models are needed to perform quantitative assessments of the four categories of impacts in figure 2.1. Through the development of PAGE22, this thesis contributes to new estimate of the indirect impacts from permafrost thawing in the Arctic region.

Future research

Even though PAGE22 was developed to estimate the global economic implications from permafrost thawing, it can be used for many other analyses. The functionality of the model enables the user to switch on/off as well as modify the parameters and scenarios used in the model which presents infinite options. This section includes some ideas for future research which follow from this thesis.

The framework in Chapter 2 does not account for the climate feedbacks from oil& gas extraction in the Arctic which is in contradiction with the Paris Agreement (Warren, viva voce Jimena Alvarez, 5th April 2023). Some context on this could be provided by a range of commitments towards net zero amongst the eight Arctic countries. Finland, Iceland and Sweden are committed to achieve net zero by 2035, 2040 and 2045 respectively; Denmark, Canada and the United States by 2050 whilst Russia by 2060 and Norway has no commitment (Net Zero tracker, 2023). PAGE22 could be used to estimate the costs of different emission scenarios given varying policy commitments.

The global impacts from permafrost thawing could be explored in more detail using PAGE22. New analyses could focus on estimating how the impacts of the permafrost carbon feedback change when considering different parameters such as carbon stocks, incorporating N2O emissions and enabling abrupt thawing mechanisms to interact with gradual ones. These would fall in the indirect impacts category of the framework introduced in Chapter 2 (box iii in figure 2.1). Some of these analyses entail simple modifications to the model – e.g.: changing the permafrost carbon stock – whilst other are more complex such as investigating the abrupt mechanisms building up on latest research.

A further area of study would be to revise the sea level rise and discontinuities impact sector in PAGE22. Sea level rise modelling in PAGE22 includes physical and economic impacts. An example of modifications to the former would be to split the sea level rise impact sector into the different components: thermal expansion, glaciers, Greenland ice sheet, Antarctic ice sheet and land water storage. In doing so, the discontinuities sector would need to exclude the icesheets. Another area of further study would be to revise the discontinuities sector and perform analysis around the different tipping points (Lenton, 2019).

Another area that could be further investigated is around the SCCO2 estimates given some challenges identified in the literature (Stern and Stiglitz, 2021; Wagner et al., 2021). Some of the analysis that follow through from this thesis include estimating the SCCO2 for all the SSPX-Y scenarios with and without the permafrost carbon feedback emulator and with and without the persistent effects from Burke et al. (2015); modifying the PTP and EMUC parametrisation to see how the results change with different discount rates; extending the SCCO2 calculation further than 2050. In addition, a regional analysis of SCCO2 estimates from PAGE22 given the unequal distribution between regions and countries (Tol, 2019; Ricke et al., 2018; Kikstra et al., 2021) would contribute to expanding the literature.

Finally, estimating how climate change impacts and the SCCO2 varies under different adaptation policies would complement the results in this thesis which were calculated with no adaptation changes from PAGE09. This would entail not only a decrease in damages already included in the model but also investigating how the persistent effects of temperature on economic production could change for different adaptation levels (Kikstra et al., 2021).

One of the main reasons for developing an integrated assessment model as part of this thesis is the ultimate aim that its results can be used by policymakers to estimate the potential huge damages from climate change to press towards more stringent climate policy. The objective of working with economic impacts stems on the appeal these may have to actors involved in the climate change crisis who may not be interested in the unfairness around it towards poorer countries or future generations but on how it may be costly not to be a part of the climate change solution.

Tackling the twin crises of climate change and loss of biodiversity (Seddon et al., 2020) requires a transdisciplinary effort spanning through the public and private sectors. Translating physical risk into socioeconomic impacts can be helpful to engage with a wide range of stakeholders. Economic indicators such as impacts expressed as % of GDP can be useful to engage with stakeholders who may otherwise not care about how climate change can be disruptive to millions of peoples' lives, reinforce inequalities and increase poverty but are yet needed as part of the conversation to contribute to being a solution and not a part of the problem.

In addition, and perhaps more importantly, the societal impacts -which cannot be measured in economic terms and hence are not included in PAGE22- are potentially very large and may even pose a threat to the way of living in some communities in the Northern Hemisphere (e.g., indigenous communities in the Arctic region as included in box ii of figure 2.1). For example, asides from the release of pollutants and heavy metals (Hock et al., 2019), permafrost thawing can remobilize toxins and pathogens (Larsen et al., 2021). Other societal impacts include relocation, impacts on food chain, potential zoonotic diseases (Parkinson et al., 2014) and impacts from pollutants (Hock et al., 2019), pathogens and toxins as well as the effect on well-being from the threats posed to ecosystems and infrastructure on which communities depend on. This stands for regions outside of the Arctic, in particular for those regions which do not have the means to adapt. All these limitations point to the results from PAGE22 presented in this thesis being conservative.

Appendix A

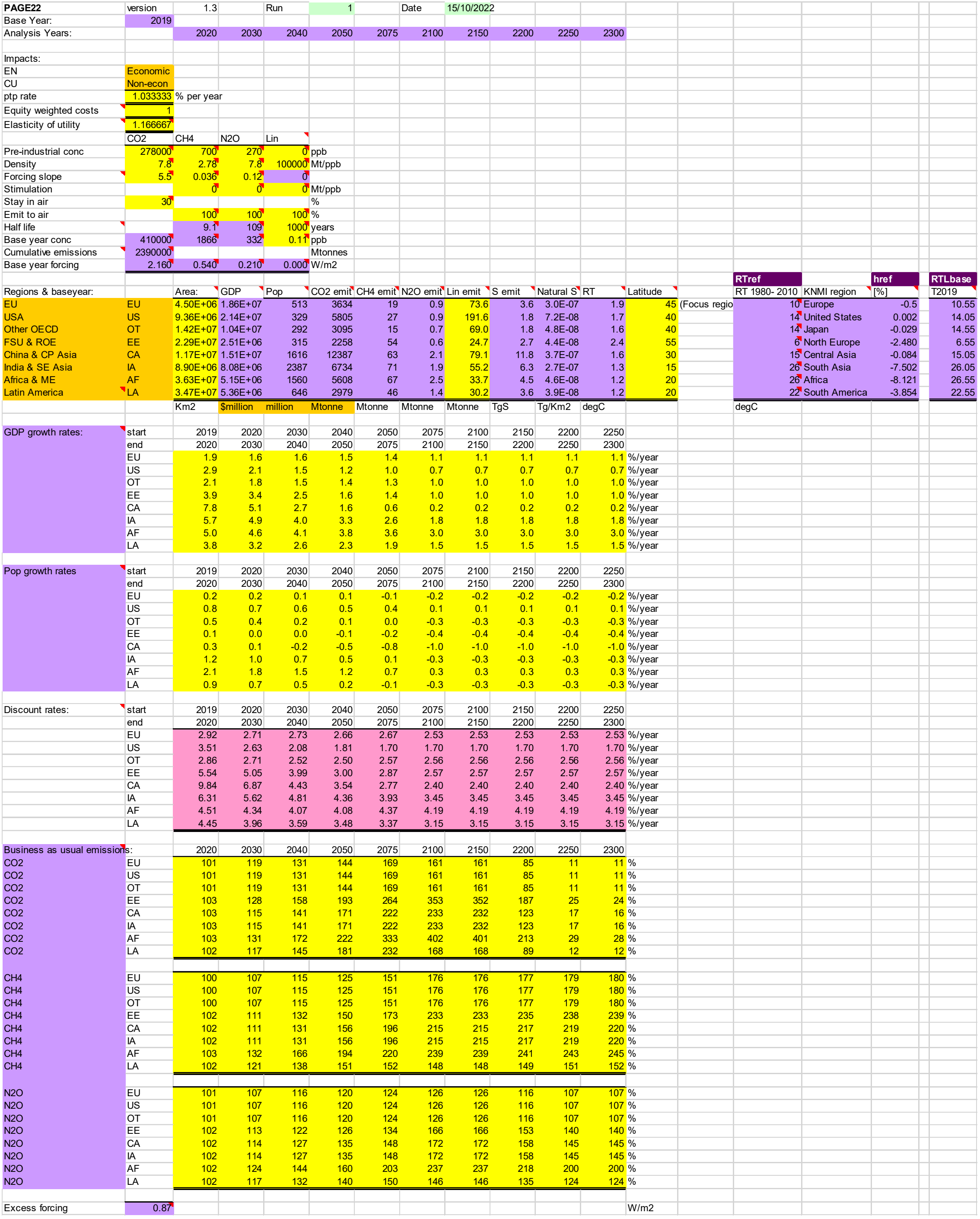
This Appendix includes screen shots of the worksheets (names in bold below) in the PAGE22 model which include inputs for calculations.

The Base data sheet includes several climate and economic parameters for the base year of calculation (2019) including GDP, Population and GHG emissions. It also includes the GDP and Population growth rates from 2019 to 2300.

The Library data sheet contains most of the climate and other parameters in the model. The min, mode and max values are used as inputs for the triangular distributions of each parameter.

The Policy A and Policy B sheets are used to specify the mitigation and adaptation policies in the model. The top of the screen shot of each Policy sheet shows the CO2, CH4, N2O and sulphates projections up to 2300 (measured vs. 2019, the base year) for each region and the excess forcing projected at the global level. The bottom of the screen shots includes the adaptation policies.

BASE DATA



PAGE22	version	1.3		Run	1		Date	15/10/2022			
Base Year:	2019										
Analysis Years:		2020	2030	2040	2050	2075	2100	2150	2200	2250	2300
Impacts:											
EN	Economic										
CU	Non-econ										
ptp rate	1.033333	% per year									
Equity weighted costs	1										
Elasticity of utility	1.166667										

	CO2	CH4	N2O	Lin	
Pre-industrial conc	278000	700	270	0	ppb
Density	7.8	2.78	7.8	100000	Mt/ppb
Forcing slope	5.5	0.036	0.12	0	
Stimulation		0	0	0	Mt/ppb
Stay in air	30				%
Emit to air		100	100	100	%
Half life		9.1	109	1000	years
Base year conc	410000	1866	332	0.11	ppb
Cumulative emissions	2390000				Mtonnes
Base year forcing	2.160	0.540	0.210	0.000	W/m2

														RTref		href	RTLbase
Regions & baseyear:		Area:	GDP	Pop	CO2 emit	CH4 emit	N2O emit	Lin emit	S emit	Natural S	RT	Latitude		RT 1980- 2010	KNMI region	[%]	T2019
EU	EU	4.50E+06	1.86E+07	513	3634	19	0.9	73.6	3.6	3.0E-07	1.9	45	(Focus regio	10	Europe	-0.5	10.55
USA	US	9.36E+06	2.14E+07	329	5805	27	0.9	191.6	1.8	7.2E-08	1.7	40		14	United States	0.002	14.05
Other OECD	OT	1.42E+07	1.04E+07	292	3095	15	0.7	69.0	1.8	4.8E-08	1.6	40		14	Japan	-0.029	14.55
FSU & ROE	EE	2.29E+07	2.51E+06	315	2258	54	0.6	24.7	2.7	4.4E-08	2.4	55		6	North Europe	-2.480	6.55
China & CP Asia	CA	1.17E+07	1.51E+07	1616	12387	63	2.1	79.1	11.8	3.7E-07	1.6	30		15	Central Asia	-0.084	15.05
India & SE Asia	IA	8.90E+06	8.08E+06	2387	6734	71	1.9	55.2	6.3	2.7E-07	1.3	15		26	South Asia	-7.502	26.05
Africa & ME	AF	3.63E+07	5.15E+06	1560	5608	67	2.5	33.7	4.5	4.6E-08	1.2	20		26	Africa	-8.121	26.55
Latin America	LA	3.47E+07	5.36E+06	646	2979	46	1.4	30.2	3.6	3.9E-08	1.2	20		22	South America	-3.854	22.55
		Km2	$million	million	Mtonne	Mtonne	Mtonne	Mtonne	TgS	Tg/Km2	degC			degC			

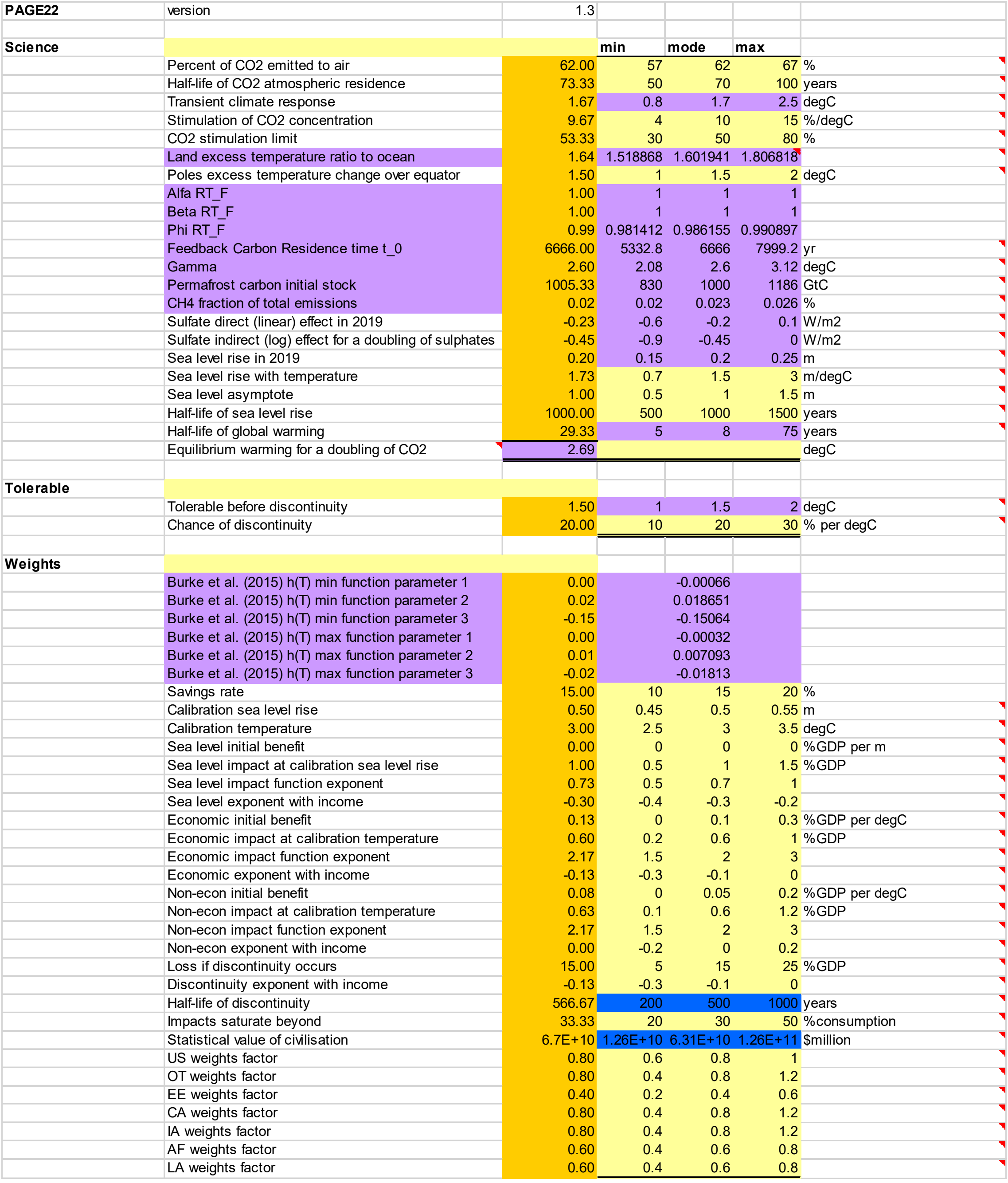
GDP growth rates:	start	2019	2020	2030	2040	2050	2075	2100	2150	2200	2250	
	end	2020	2030	2040	2050	2075	2100	2150	2200	2250	2300	
	EU	1.9	1.6	1.6	1.5	1.4	1.1	1.1	1.1	1.1	1.1	%/year
	US	2.9	2.1	1.5	1.2	1.0	0.7	0.7	0.7	0.7	0.7	%/year
	OT	2.1	1.8	1.5	1.4	1.3	1.0	1.0	1.0	1.0	1.0	%/year
	EE	3.9	3.4	2.5	1.6	1.4	1.0	1.0	1.0	1.0	1.0	%/year
	CA	7.8	5.1	2.7	1.6	0.6	0.2	0.2	0.2	0.2	0.2	%/year
	IA	5.7	4.9	4.0	3.3	2.6	1.8	1.8	1.8	1.8	1.8	%/year
	AF	5.0	4.6	4.1	3.8	3.6	3.0	3.0	3.0	3.0	3.0	%/year
	LA	3.8	3.2	2.6	2.3	1.9	1.5	1.5	1.5	1.5	1.5	%/year

Pop growth rates	start	2019	2020	2030	2040	2050	2075	2100	2150	2200	2250	
	end	2020	2030	2040	2050	2075	2100	2150	2200	2250	2300	
	EU	0.2	0.2	0.1	0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	%/year
	US	0.8	0.7	0.6	0.5	0.4	0.1	0.1	0.1	0.1	0.1	%/year
	OT	0.5	0.4	0.2	0.1	0.0	-0.3	-0.3	-0.3	-0.3	-0.3	%/year
	EE	0.1	0.0	0.0	-0.1	-0.2	-0.4	-0.4	-0.4	-0.4	-0.4	%/year
	CA	0.3	0.1	-0.2	-0.5	-0.8	-1.0	-1.0	-1.0	-1.0	-1.0	%/year
	IA	1.2	1.0	0.7	0.5	0.1	-0.3	-0.3	-0.3	-0.3	-0.3	%/year
	AF	2.1	1.8	1.5	1.2	0.7	0.3	0.3	0.3	0.3	0.3	%/year
	LA	0.9	0.7	0.5	0.2	-0.1	-0.3	-0.3	-0.3	-0.3	-0.3	%/year

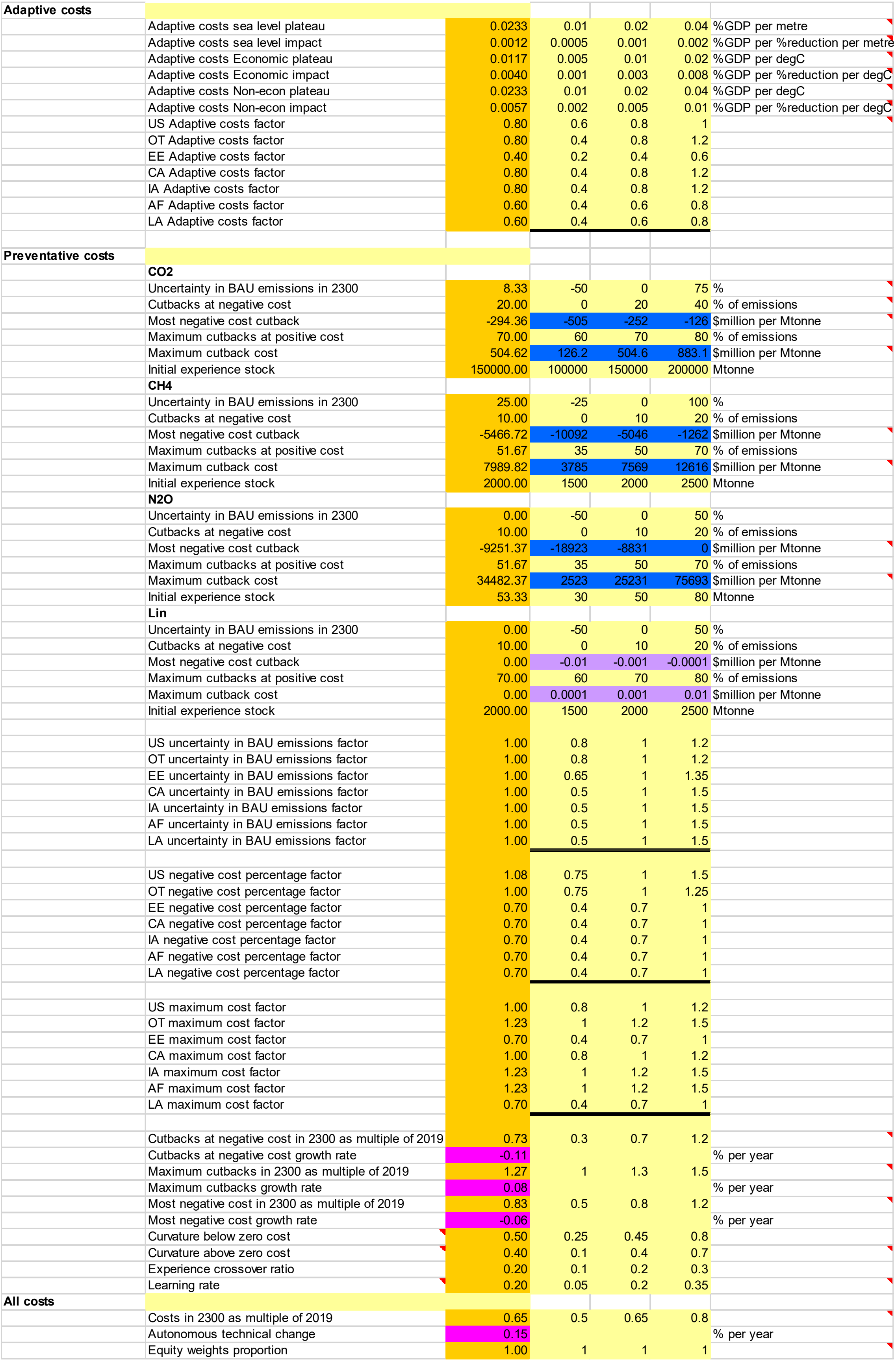
Discount rates:	start	2019	2020	2030	2040	2050	2075	2100	2150	2200	2250	
	end	2020	2030	2040	2050	2075	2100	2150	2200	2250	2300	
	EU	2.92	2.71	2.73	2.66	2.67	2.53	2.53	2.53	2.53	2.53	%/year
	US	3.51	2.63	2.08	1.81	1.70	1.70	1.70	1.70	1.70	1.70	%/year
	OT	2.86	2.71	2.52	2.50	2.57	2.56	2.56	2.56	2.56	2.56	%/year
	EE	5.54	5.05	3.99	3.00	2.87	2.57	2.57	2.57	2.57	2.57	%/year
	CA	9.84	6.87	4.43	3.54	2.77	2.40	2.40	2.40	2.40	2.40	%/year
	IA	6.31	5.62	4.81	4.36	3.93	3.45	3.45	3.45	3.45	3.45	%/year
	AF	4.51	4.34	4.07	4.08	4.37	4.19	4.19	4.19	4.19	4.19	%/year
	LA	4.45	3.96	3.59	3.48	3.37	3.15	3.15	3.15	3.15	3.15	%/year

Business as usual emissions:		2020	2030	2040	2050	2075	2100	2150	2200	2250	2300	
CO2	EU	101	119	131	144	169	161	161	85	11	11	%
CO2	US	101	119	131	144	169	161	161	85	11	11	%
CO2	OT	101	119	131	144	169	161	161	85	11	11	%
CO2	EE	103	128	158	193	264	353	352	187	25	24	%
CO2	CA	103	115	141	171	222	233	232	123	17	16	%
CO2	IA	103	115	141	171	222	233	232	123	17	16	%
CO2	AF	103	131	172	222	333	402	401	213	29	28	%
CO2	LA	102	117	145	181	232	168	168	89	12	12	%
CH4	EU	100	107	115	125	151	176	176	177	179	180	%
CH4	US	100	107	115	125	151	176	176	177	179	180	%
CH4	OT	100	107	115	125	151	176	176	177	179	180	%
CH4	EE	102	111	132	150	173	233	233	235	238	239	%
CH4	CA	102	111	131	156	196	215	215	217	219	220	%
CH4	IA	102	111	131	156	196	215	215	217	219	220	%
CH4	AF	103	132	166	194	220	239	239	241	243	245	%
CH4	LA	102	121	138	151	152	148	148	149	151	152	%
N2O	EU	101	107	116	120	124	126	126	116	107	107	%
N2O	US	101	107	116	120	124	126	126	116	107	107	%
N2O	OT	101	107	116	120	124	126	126	116	107	107	%
N2O	EE	102	113	122	126	134	166	166	153	140	140	%
N2O	CA	102	114	127	135	148	172	172	158	145	145	%
N2O	IA	102	114	127	135	148	172	172	158	145	145	%
N2O	AF	102	124	144	160	203	237	237	218	200	200	%
N2O	LA	102	117	132	140	150	146	146	135	124	124	%
Excess forcing	0.87											W/m2

LIBRARY DATA



PAGE22	version	1.3				
Science			**min**	**mode**	**max**	
	Percent of CO2 emitted to air	62.00	57	62	67	%
	Half-life of CO2 atmospheric residence	73.33	50	70	100	years
	Transient climate response	1.67	0.8	1.7	2.5	degC
	Stimulation of CO2 concentration	9.67	4	10	15	%/degC
	CO2 stimulation limit	53.33	30	50	80	%
	Land excess temperature ratio to ocean	1.64	1.518868	1.601941	1.806818	
	Poles excess temperature change over equator	1.50	1	1.5	2	degC
	Alfa RT_F	1.00	1	1	1	
	Beta RT_F	1.00	1	1	1	
	Phi RT_F	0.99	0.981412	0.986155	0.990897	
	Feedback Carbon Residence time t_0	6666.00	5332.8	6666	7999.2	yr
	Gamma	2.60	2.08	2.6	3.12	degC
	Permafrost carbon initial stock	1005.33	830	1000	1186	GtC
	CH4 fraction of total emissions	0.02	0.02	0.023	0.026	%
	Sulfate direct (linear) effect in 2019	-0.23	-0.6	-0.2	0.1	W/m2
	Sulfate indirect (log) effect for a doubling of sulphates	-0.45	-0.9	-0.45	0	W/m2
	Sea level rise in 2019	0.20	0.15	0.2	0.25	m
	Sea level rise with temperature	1.73	0.7	1.5	3	m/degC
	Sea level asymptote	1.00	0.5	1	1.5	m
	Half-life of sea level rise	1000.00	500	1000	1500	years
	Half-life of global warming	29.33	5	8	75	years
	Equilibrium warming for a doubling of CO2	2.69				degC
Tolerable						
	Tolerable before discontinuity	1.50	1	1.5	2	degC
	Chance of discontinuity	20.00	10	20	30	% per degC
Weights						
	Burke et al. (2015) h(T) min function parameter 1	0.00		-0.00066		
	Burke et al. (2015) h(T) min function parameter 2	0.02		0.018651		
	Burke et al. (2015) h(T) min function parameter 3	-0.15		-0.15064		
	Burke et al. (2015) h(T) max function parameter 1	0.00		-0.00032		
	Burke et al. (2015) h(T) max function parameter 2	0.01		0.007093		
	Burke et al. (2015) h(T) max function parameter 3	-0.02		-0.01813		
	Savings rate	15.00	10	15	20	%
	Calibration sea level rise	0.50	0.45	0.5	0.55	m
	Calibration temperature	3.00	2.5	3	3.5	degC
	Sea level initial benefit	0.00	0	0	0	%GDP per m
	Sea level impact at calibration sea level rise	1.00	0.5	1	1.5	%GDP
	Sea level impact function exponent	0.73	0.5	0.7	1	
	Sea level exponent with income	-0.30	-0.4	-0.3	-0.2	
	Economic initial benefit	0.13	0	0.1	0.3	%GDP per degC
	Economic impact at calibration temperature	0.60	0.2	0.6	1	%GDP
	Economic impact function exponent	2.17	1.5	2	3	
	Economic exponent with income	-0.13	-0.3	-0.1	0	
	Non-econ initial benefit	0.08	0	0.05	0.2	%GDP per degC
	Non-econ impact at calibration temperature	0.63	0.1	0.6	1.2	%GDP
	Non-econ impact function exponent	2.17	1.5	2	3	
	Non-econ exponent with income	0.00	-0.2	0	0.2	
	Loss if discontinuity occurs	15.00	5	15	25	%GDP
	Discontinuity exponent with income	-0.13	-0.3	-0.1	0	
	Half-life of discontinuity	566.67	200	500	1000	years
	Impacts saturate beyond	33.33	20	30	50	%consumption
	Statistical value of civilisation	6.7E+10	1.26E+10	6.31E+10	1.26E+11	$million
	US weights factor	0.80	0.6	0.8	1	
	OT weights factor	0.80	0.4	0.8	1.2	
	EE weights factor	0.40	0.2	0.4	0.6	
	CA weights factor	0.80	0.4	0.8	1.2	
	IA weights factor	0.80	0.4	0.8	1.2	
	AF weights factor	0.60	0.4	0.6	0.8	
	LA weights factor	0.60	0.4	0.6	0.8	



Adaptive costs						
	Adaptive costs sea level plateau	0.0233	0.01	0.02	0.04	%GDP per metre
	Adaptive costs sea level impact	0.0012	0.0005	0.001	0.002	%GDP per %reduction per metre
	Adaptive costs Economic plateau	0.0117	0.005	0.01	0.02	%GDP per degC
	Adaptive costs Economic impact	0.0040	0.001	0.003	0.008	%GDP per %reduction per degC
	Adaptive costs Non-econ plateau	0.0233	0.01	0.02	0.04	%GDP per degC
	Adaptive costs Non-econ impact	0.0057	0.002	0.005	0.01	%GDP per %reduction per degC
	US Adaptive costs factor	0.80	0.6	0.8	1	
	OT Adaptive costs factor	0.80	0.4	0.8	1.2	
	EE Adaptive costs factor	0.40	0.2	0.4	0.6	
	CA Adaptive costs factor	0.80	0.4	0.8	1.2	
	IA Adaptive costs factor	0.80	0.4	0.8	1.2	
	AF Adaptive costs factor	0.60	0.4	0.6	0.8	
	LA Adaptive costs factor	0.60	0.4	0.6	0.8	
Preventative costs						
	CO2					
	Uncertainty in BAU emissions in 2300	8.33	-50	0	75	%
	Cutbacks at negative cost	20.00	0	20	40	% of emissions
	Most negative cost cutback	-294.36	-505	-252	-126	$million per Mtonne
	Maximum cutbacks at positive cost	70.00	60	70	80	% of emissions
	Maximum cutback cost	504.62	126.2	504.6	883.1	$million per Mtonne
	Initial experience stock	150000.00	100000	150000	200000	Mtonne
	CH4					
	Uncertainty in BAU emissions in 2300	25.00	-25	0	100	%
	Cutbacks at negative cost	10.00	0	10	20	% of emissions
	Most negative cost cutback	-5466.72	-10092	-5046	-1262	$million per Mtonne
	Maximum cutbacks at positive cost	51.67	35	50	70	% of emissions
	Maximum cutback cost	7989.82	3785	7569	12616	$million per Mtonne
	Initial experience stock	2000.00	1500	2000	2500	Mtonne
	N2O					
	Uncertainty in BAU emissions in 2300	0.00	-50	0	50	%
	Cutbacks at negative cost	10.00	0	10	20	% of emissions
	Most negative cost cutback	-9251.37	-18923	-8831	0	$million per Mtonne
	Maximum cutbacks at positive cost	51.67	35	50	70	% of emissions
	Maximum cutback cost	34482.37	2523	25231	75693	$million per Mtonne
	Initial experience stock	53.33	30	50	80	Mtonne
	Lin					
	Uncertainty in BAU emissions in 2300	0.00	-50	0	50	%
	Cutbacks at negative cost	10.00	0	10	20	% of emissions
	Most negative cost cutback	0.00	-0.01	-0.001	-0.0001	$million per Mtonne
	Maximum cutbacks at positive cost	70.00	60	70	80	% of emissions
	Maximum cutback cost	0.00	0.0001	0.001	0.01	$million per Mtonne
	Initial experience stock	2000.00	1500	2000	2500	Mtonne
	US uncertainty in BAU emissions factor	1.00	0.8	1	1.2	
	OT uncertainty in BAU emissions factor	1.00	0.8	1	1.2	
	EE uncertainty in BAU emissions factor	1.00	0.65	1	1.35	
	CA uncertainty in BAU emissions factor	1.00	0.5	1	1.5	
	IA uncertainty in BAU emissions factor	1.00	0.5	1	1.5	
	AF uncertainty in BAU emissions factor	1.00	0.5	1	1.5	
	LA uncertainty in BAU emissions factor	1.00	0.5	1	1.5	
	US negative cost percentage factor	1.08	0.75	1	1.5	
	OT negative cost percentage factor	1.00	0.75	1	1.25	
	EE negative cost percentage factor	0.70	0.4	0.7	1	
	CA negative cost percentage factor	0.70	0.4	0.7	1	
	IA negative cost percentage factor	0.70	0.4	0.7	1	
	AF negative cost percentage factor	0.70	0.4	0.7	1	
	LA negative cost percentage factor	0.70	0.4	0.7	1	
	US maximum cost factor	1.00	0.8	1	1.2	
	OT maximum cost factor	1.23	1	1.2	1.5	
	EE maximum cost factor	0.70	0.4	0.7	1	
	CA maximum cost factor	1.00	0.8	1	1.2	
	IA maximum cost factor	1.23	1	1.2	1.5	
	AF maximum cost factor	1.23	1	1.2	1.5	
	LA maximum cost factor	0.70	0.4	0.7	1	
	Cutbacks at negative cost in 2300 as multiple of 2019	0.73	0.3	0.7	1.2	
	Cutbacks at negative cost growth rate	-0.11				% per year
	Maximum cutbacks in 2300 as multiple of 2019	1.27	1	1.3	1.5	
	Maximum cutbacks growth rate	0.08				% per year
	Most negative cost in 2300 as multiple of 2019	0.83	0.5	0.8	1.2	
	Most negative cost growth rate	-0.06				% per year
	Curvature below zero cost	0.50	0.25	0.45	0.8	
	Curvature above zero cost	0.40	0.1	0.4	0.7	
	Experience crossover ratio	0.20	0.1	0.2	0.3	
	Learning rate	0.20	0.05	0.2	0.35	
All costs						
	Costs in 2300 as multiple of 2019	0.65	0.5	0.65	0.8	
	Autonomous technical change	0.15				% per year
	Equity weights proportion	1.00	1	1	1	

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PAGE22	version	1.3									
Prevention	**RCP 4.5**										
	2020	**2030**	**2040**	**2050**	**2075**	**2100**	**2150**	**2200**	**2250**	**2300**	
EU CO2 emissions	100	100	93	81	40	29	11	8	6	5	%
US CO2 emissions	100	100	93	81	40	29	11	8	6	5	%
OT CO2 emissions	100	100	93	81	40	29	11	8	6	5	%
EE CO2 emissions	100	99	90	78	34	26	10	7	5	5	%
CA CO2 emissions	102	122	134	138	60	45	16	12	9	8	%
IA CO2 emissions	102	122	134	138	60	45	16	12	9	8	%
AF CO2 emissions	101	116	126	131	76	63	23	17	13	11	%
LA CO2 emissions	98	95	101	108	81	78	28	20	16	14	%
EU CH4 emissions	100	99	96	92	79	68	68	68	68	68	%
US CH4 emissions	100	99	96	92	79	68	68	68	68	68	%
OT CH4 emissions	100	99	96	92	79	68	68	68	68	68	%
EE CH4 emissions	101	96	94	96	42	47	47	48	48	48	%
CA CH4 emissions	100	103	103	101	91	81	81	81	81	81	%
IA CH4 emissions	100	103	103	101	91	81	81	81	81	81	%
AF CH4 emissions	101	108	113	118	112	112	112	113	113	113	%
LA CH4 emissions	100	106	107	104	106	93	93	94	94	94	%
EU N2O emissions	99	103	105	105	100	99	86	86	86	86	%
US N2O emissions	99	103	105	105	100	99	86	86	86	86	%
OT N2O emissions	99	103	105	105	100	99	86	86	86	86	%
EE N2O emissions	99	96	91	85	78	75	65	65	65	65	%
CA N2O emissions	101	106	106	103	97	94	81	81	81	81	%
IA N2O emissions	101	106	106	103	97	94	81	81	81	81	%
AF N2O emissions	101	108	113	118	116	116	100	100	100	100	%
LA N2O emissions	100	102	102	100	99	98	85	85	85	85	%
EU sulphates	96	76	58	41	29	26	26	26	26	26	%
US sulphates	96	76	58	41	29	26	26	26	26	26	%
OT sulphates	96	76	58	41	29	26	26	26	26	26	%
EE sulphates	98	80	60	39	18	13	13	13	13	13	%
CA sulphates	100	78	56	35	14	11	11	11	11	11	%
IA sulphates	100	78	56	35	14	11	11	11	11	11	%
AF sulphates	101	103	99	90	65	46	46	46	46	46	%
LA sulphates	99	90	79	66	38	32	32	32	32	32	%
Excess forcing	0.70	0.64	0.50	0.32	0.10	-0.08	0.19	0.39	0.54	0.63	W/m2
New adaptation											
	Plateau	Pstart	Pyears		Impred	Istart	Iyears	Impmax			
EU sea level	0.25	2000	20		50	2020	40	1			
US sea level	0.25	2000	20		50	2020	40	1			
OT sea level	0.25	2000	20		50	2020	40	1			
EE sea level	0.25	2000	20		50	2020	40	1			
CA sea level	0.20	2000	30		25	2020	40	1			
IA sea level	0.20	2000	30		25	2020	40	1			
AF sea level	0.20	2000	30		25	2020	40	1			
LA sea level	0.20	2000	30		25	2020	40	1			
	Plateau	Pstart	Pyears		Impred	Istart	Iyears	Impmax			
EU Economic	1.0	2000	20		30	2010	20	2			
US Economic	1.0	2000	20		30	2010	20	2			
OT Economic	1.0	2000	20		30	2010	20	2			
EE Economic	1.0	2000	20		30	2010	20	2			
CA Economic	1.0	2010	30		15	2010	30	2			
IA Economic	1.0	2010	30		15	2010	30	2			
AF Economic	1.0	2010	30		15	2010	30	2			
LA Economic	1.0	2010	30		15	2010	30	2			
	Plateau	Pstart	Pyears		Impred	Istart	Iyears	Impmax			
EU Non-econ	0	2000	100		15	2010	40	2			
US Non-econ	0	2000	100		15	2010	40	2			
OT Non-econ	0	2000	100		15	2010	40	2			
EE Non-econ	0	2000	100		15	2010	40	2			
CA Non-econ	0	2000	100		15	2010	40	2			
IA Non-econ	0	2000	100		15	2010	40	2			
AF Non-econ	0	2000	100		15	2010	40	2			
LA Non-econ	0	2000	100		15	2010	40	2			

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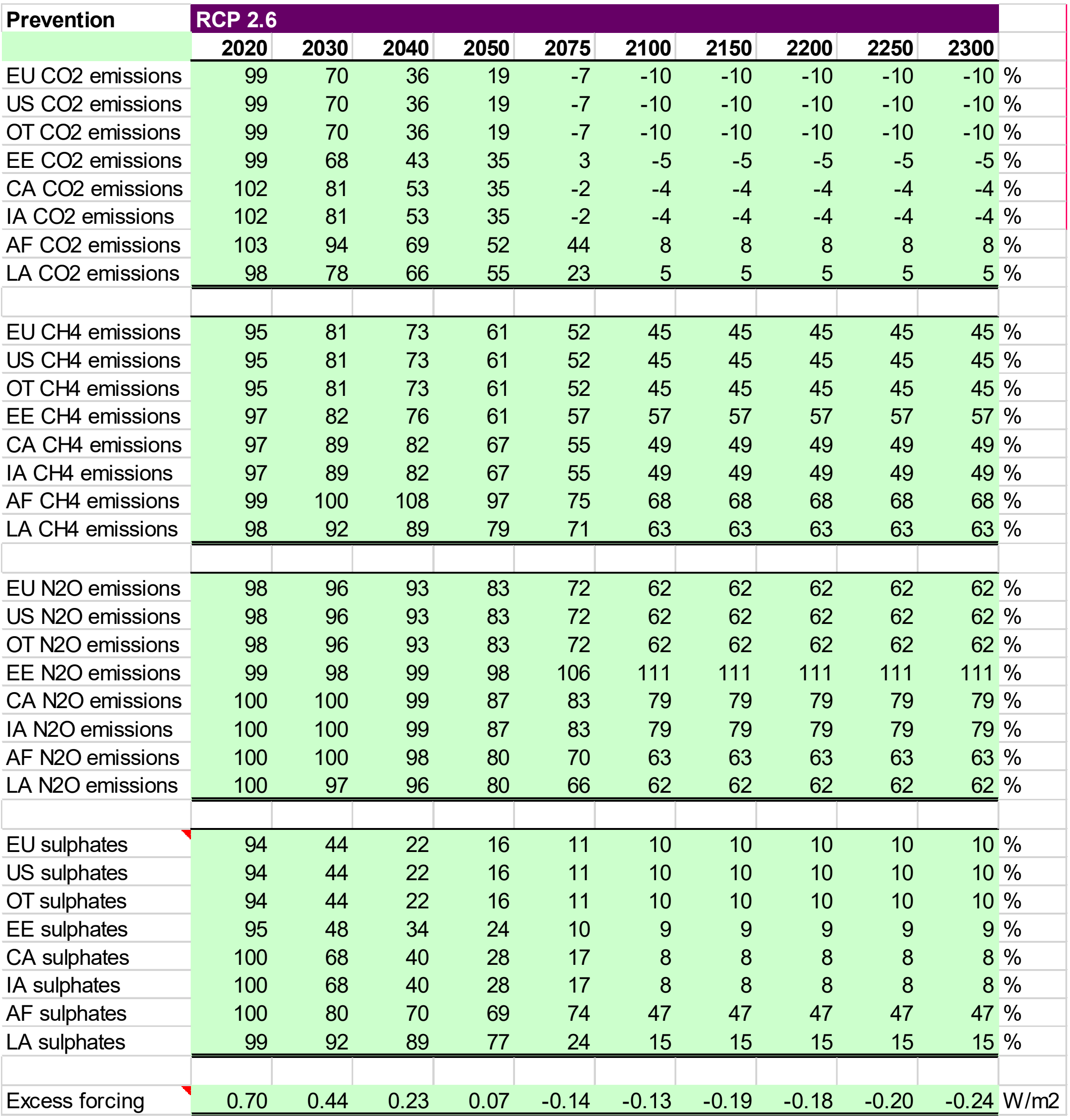
PAGE22	version	1.3									
Prevention	**RCP 8.5**										
	2020	**2030**	**2040**	**2050**	**2075**	**2100**	**2150**	**2200**	**2250**	**2300**	
EU CO2 emissions	101	119	131	144	169	161	161	85	11	11	%
US CO2 emissions	101	119	131	144	169	161	161	85	11	11	%
OT CO2 emissions	101	119	131	144	169	161	161	85	11	11	%
EE CO2 emissions	103	128	158	193	264	353	352	187	25	24	%
CA CO2 emissions	103	115	141	171	222	233	232	123	17	16	%
IA CO2 emissions	103	115	141	171	222	233	232	123	17	16	%
AF CO2 emissions	103	131	172	222	333	402	401	213	29	28	%
LA CO2 emissions	102	117	145	181	232	168	168	89	12	12	%
EU CH4 emissions	100	107	115	125	151	176	176	177	179	180	%
US CH4 emissions	100	107	115	125	151	176	176	177	179	180	%
OT CH4 emissions	100	107	115	125	151	176	176	177	179	180	%
EE CH4 emissions	102	111	132	150	173	233	233	235	238	239	%
CA CH4 emissions	102	111	131	156	196	215	215	217	219	220	%
IA CH4 emissions	102	111	131	156	196	215	215	217	219	220	%
AF CH4 emissions	103	132	166	194	220	239	239	241	243	245	%
LA CH4 emissions	102	121	138	151	152	148	148	149	151	152	%
EU N2O emissions	101	107	116	120	124	126	126	116	107	107	%
US N2O emissions	101	107	116	120	124	126	126	116	107	107	%
OT N2O emissions	101	107	116	120	124	126	126	116	107	107	%
EE N2O emissions	102	113	122	126	134	166	166	153	140	140	%
CA N2O emissions	102	114	127	135	148	172	172	158	145	145	%
IA N2O emissions	102	114	127	135	148	172	172	158	145	145	%
AF N2O emissions	102	124	144	160	203	237	237	218	200	200	%
LA N2O emissions	102	117	132	140	150	146	146	135	124	124	%
EU sulphates	97	84	56	34	16	8	8	8	8	8	%
US sulphates	97	84	56	34	16	8	8	8	8	8	%
OT sulphates	97	84	56	34	16	8	8	8	8	8	%
EE sulphates	98	87	67	52	33	24	24	24	24	24	%
CA sulphates	101	86	58	41	30	16	16	16	16	16	%
IA sulphates	101	86	58	41	30	16	16	16	16	16	%
AF sulphates	102	98	96	94	73	55	55	55	55	55	%
LA sulphates	99	98	93	82	65	40	40	40	40	40	%
Excess forcing	0.79	0.91	0.94	0.96	1.25	1.29	1.78	2.35	2.89	3.37	W/m2
New adaptation											
	Plateau	Pstart	Pyears		Impred	Istart	Iyears	Impmax			
EU sea level	0.25	2000	20		50	2020	40	1			
US sea level	0.25	2000	20		50	2020	40	1			
OT sea level	0.25	2000	20		50	2020	40	1			
EE sea level	0.25	2000	20		50	2020	40	1			
CA sea level	0.20	2000	30		25	2020	40	1			
IA sea level	0.20	2000	30		25	2020	40	1			
AF sea level	0.20	2000	30		25	2020	40	1			
LA sea level	0.20	2000	30		25	2020	40	1			
	Plateau	Pstart	Pyears		Impred	Istart	Iyears	Impmax			
EU Economic	1.0	2000	20		30	2010	20	2			
US Economic	1.0	2000	20		30	2010	20	2			
OT Economic	1.0	2000	20		30	2010	20	2			
EE Economic	1.0	2000	20		30	2010	20	2			
CA Economic	1.0	2010	30		15	2010	30	2			
IA Economic	1.0	2010	30		15	2010	30	2			
AF Economic	1.0	2010	30		15	2010	30	2			
LA Economic	1.0	2010	30		15	2010	30	2			
	Plateau	Pstart	Pyears		Impred	Istart	Iyears	Impmax			
EU Non-econ	0	2000	100		15	2010	40	2			
US Non-econ	0	2000	100		15	2010	40	2			
OT Non-econ	0	2000	100		15	2010	40	2			
EE Non-econ	0	2000	100		15	2010	40	2			
CA Non-econ	0	2000	100		15	2010	40	2			
IA Non-econ	0	2000	100		15	2010	40	2			
AF Non-econ	0	2000	100		15	2010	40	2			
LA Non-econ	0	2000	100		15	2010	40	2			

Appendix B

This Appendix includes screen shots of how the representative concentration pathways (RCPs) and extended concentration pathways (ECPs) are inputted in the Policy sheets in PAGE22. It also includes the GDP and Population growth rates for the Shared Socioeconomic Pathways.

B.1. RCPs and ECPs

Table B.0.1. RCP-ECP2.6 scenario input for PAGE22



Prevention	**RCP 2.6**										
	2020	**2030**	**2040**	**2050**	**2075**	**2100**	**2150**	**2200**	**2250**	**2300**	
EU CO2 emissions	99	70	36	19	-7	-10	-10	-10	-10	-10	%
US CO2 emissions	99	70	36	19	-7	-10	-10	-10	-10	-10	%
OT CO2 emissions	99	70	36	19	-7	-10	-10	-10	-10	-10	%
EE CO2 emissions	99	68	43	35	3	-5	-5	-5	-5	-5	%
CA CO2 emissions	102	81	53	35	-2	-4	-4	-4	-4	-4	%
IA CO2 emissions	102	81	53	35	-2	-4	-4	-4	-4	-4	%
AF CO2 emissions	103	94	69	52	44	8	8	8	8	8	%
LA CO2 emissions	98	78	66	55	23	5	5	5	5	5	%
EU CH4 emissions	95	81	73	61	52	45	45	45	45	45	%
US CH4 emissions	95	81	73	61	52	45	45	45	45	45	%
OT CH4 emissions	95	81	73	61	52	45	45	45	45	45	%
EE CH4 emissions	97	82	76	61	57	57	57	57	57	57	%
CA CH4 emissions	97	89	82	67	55	49	49	49	49	49	%
IA CH4 emissions	97	89	82	67	55	49	49	49	49	49	%
AF CH4 emissions	99	100	108	97	75	68	68	68	68	68	%
LA CH4 emissions	98	92	89	79	71	63	63	63	63	63	%
EU N2O emissions	98	96	93	83	72	62	62	62	62	62	%
US N2O emissions	98	96	93	83	72	62	62	62	62	62	%
OT N2O emissions	98	96	93	83	72	62	62	62	62	62	%
EE N2O emissions	99	98	99	98	106	111	111	111	111	111	%
CA N2O emissions	100	100	99	87	83	79	79	79	79	79	%
IA N2O emissions	100	100	99	87	83	79	79	79	79	79	%
AF N2O emissions	100	100	98	80	70	63	63	63	63	63	%
LA N2O emissions	100	97	96	80	66	62	62	62	62	62	%
EU sulphates	94	44	22	16	11	10	10	10	10	10	%
US sulphates	94	44	22	16	11	10	10	10	10	10	%
OT sulphates	94	44	22	16	11	10	10	10	10	10	%
EE sulphates	95	48	34	24	10	9	9	9	9	9	%
CA sulphates	100	68	40	28	17	8	8	8	8	8	%
IA sulphates	100	68	40	28	17	8	8	8	8	8	%
AF sulphates	100	80	70	69	74	47	47	47	47	47	%
LA sulphates	99	92	89	77	24	15	15	15	15	15	%
Excess forcing	0.70	0.44	0.23	0.07	-0.14	-0.13	-0.19	-0.18	-0.20	-0.24	W/m2

Table B.0.2. RCP-ECP4.5 scenario input for PAGE22

Prevention	**RCP 4.5**										
	2020	**2030**	**2040**	**2050**	**2075**	**2100**	**2150**	**2200**	**2250**	**2300**	
EU CO2 emissions	100	100	93	81	40	29	11	8	6	5	%
US CO2 emissions	100	100	93	81	40	29	11	8	6	5	%
OT CO2 emissions	100	100	93	81	40	29	11	8	6	5	%
EE CO2 emissions	100	99	90	78	34	26	10	7	5	5	%
CA CO2 emissions	102	122	134	138	60	45	16	12	9	8	%
IA CO2 emissions	102	122	134	138	60	45	16	12	9	8	%
AF CO2 emissions	101	116	126	131	76	63	23	17	13	11	%
LA CO2 emissions	98	95	101	108	81	78	28	20	16	14	%
EU CH4 emissions	100	99	96	92	79	68	68	68	68	68	%
US CH4 emissions	100	99	96	92	79	68	68	68	68	68	%
OT CH4 emissions	100	99	96	92	79	68	68	68	68	68	%
EE CH4 emissions	101	96	94	96	42	47	47	48	48	48	%
CA CH4 emissions	100	103	103	101	91	81	81	81	81	81	%
IA CH4 emissions	100	103	103	101	91	81	81	81	81	81	%
AF CH4 emissions	101	108	113	118	112	112	112	113	113	113	%
LA CH4 emissions	100	106	107	104	106	93	93	94	94	94	%
EU N2O emissions	99	103	105	105	100	99	86	86	86	86	%
US N2O emissions	99	103	105	105	100	99	86	86	86	86	%
OT N2O emissions	99	103	105	105	100	99	86	86	86	86	%
EE N2O emissions	99	96	91	85	78	75	65	65	65	65	%
CA N2O emissions	101	106	106	103	97	94	81	81	81	81	%
IA N2O emissions	101	106	106	103	97	94	81	81	81	81	%
AF N2O emissions	101	108	113	118	116	116	100	100	100	100	%
LA N2O emissions	100	102	102	100	99	98	85	85	85	85	%
EU sulphates	96	76	58	41	29	26	26	26	26	26	%
US sulphates	96	76	58	41	29	26	26	26	26	26	%
OT sulphates	96	76	58	41	29	26	26	26	26	26	%
EE sulphates	98	80	60	39	18	13	13	13	13	13	%
CA sulphates	100	78	56	35	14	11	11	11	11	11	%
IA sulphates	100	78	56	35	14	11	11	11	11	11	%
AF sulphates	101	103	99	90	65	46	46	46	46	46	%
LA sulphates	99	90	79	66	38	32	32	32	32	32	%
Excess forcing	0.70	0.64	0.50	0.32	0.10	-0.08	0.19	0.39	0.54	0.63	W/m2

Table B.0.3. RCP-ECP6.0 scenario input for PAGE22

Prevention	**RCP 6.0**										
	2020	**2030**	**2040**	**2050**	**2075**	**2100**	**2150**	**2200**	**2250**	**2300**	
EU CO2 emissions	100	93	92	93	87	55	14	7	5	5	%
US CO2 emissions	100	93	92	93	87	55	14	7	5	5	%
OT CO2 emissions	100	93	92	93	87	55	14	7	5	5	%
EE CO2 emissions	99	92	89	89	120	111	28	15	11	9	%
CA CO2 emissions	101	120	152	182	241	188	47	26	19	16	%
IA CO2 emissions	101	120	152	182	241	188	47	26	19	16	%
AF CO2 emissions	96	76	132	219	514	568	143	77	56	48	%
LA CO2 emissions	99	68	63	82	157	128	32	17	13	11	%
EU CH4 emissions	100	101	105	105	89	54	55	55	55	56	%
US CH4 emissions	100	101	105	105	89	54	55	55	55	56	%
OT CH4 emissions	100	101	105	105	89	54	55	55	55	56	%
EE CH4 emissions	99	91	88	82	70	48	49	49	49	50	%
CA CH4 emissions	100	107	113	118	118	91	92	92	93	93	%
IA CH4 emissions	100	107	113	118	118	91	92	92	93	93	%
AF CH4 emissions	100	112	127	140	148	98	99	100	100	101	%
LA CH4 emissions	99	99	100	102	111	73	73	74	74	74	%
EU N2O emissions	99	110	120	127	131	122	90	90	90	90	%
US N2O emissions	99	110	120	127	131	122	90	90	90	90	%
OT N2O emissions	99	110	120	127	131	122	90	90	90	90	%
EE N2O emissions	100	107	115	123	120	116	85	85	85	85	%
CA N2O emissions	100	110	119	126	141	136	100	100	100	100	%
IA N2O emissions	100	110	119	126	141	136	100	100	100	100	%
AF N2O emissions	99	118	137	158	213	249	183	183	183	183	%
LA N2O emissions	98	108	120	134	172	172	127	127	127	127	%
EU sulphates	97	74	56	42	13	5	5	5	5	5	%
US sulphates	97	74	56	42	13	5	5	5	5	5	%
OT sulphates	97	74	56	42	13	5	5	5	5	5	%
EE sulphates	97	81	49	36	15	11	11	11	11	11	%
CA sulphates	100	83	113	108	51	27	27	27	27	27	%
IA sulphates	100	83	113	108	51	27	27	27	27	27	%
AF sulphates	99	102	95	86	61	43	43	43	43	43	%
LA sulphates	100	86	83	78	47	35	35	35	35	35	%
Excess forcing	0.60	0.51	0.35	0.15	-0.29	-0.90	-0.95	-0.71	-0.42	-0.25	W/m2

Table B.0.4. RCP-ECP8.5 scenario input for PAGE22

Prevention	**RCP 8.5**										
	2020	**2030**	**2040**	**2050**	**2075**	**2100**	**2150**	**2200**	**2250**	**2300**	
EU CO2 emissions	101	119	131	144	169	161	161	85	11	11	%
US CO2 emissions	101	119	131	144	169	161	161	85	11	11	%
OT CO2 emissions	101	119	131	144	169	161	161	85	11	11	%
EE CO2 emissions	103	128	158	193	264	353	352	187	25	24	%
CA CO2 emissions	103	115	141	171	222	233	232	123	17	16	%
IA CO2 emissions	103	115	141	171	222	233	232	123	17	16	%
AF CO2 emissions	103	131	172	222	333	402	401	213	29	28	%
LA CO2 emissions	102	117	145	181	232	168	168	89	12	12	%
EU CH4 emissions	100	107	115	125	151	176	176	177	179	180	%
US CH4 emissions	100	107	115	125	151	176	176	177	179	180	%
OT CH4 emissions	100	107	115	125	151	176	176	177	179	180	%
EE CH4 emissions	102	111	132	150	173	233	233	235	238	239	%
CA CH4 emissions	102	111	131	156	196	215	215	217	219	220	%
IA CH4 emissions	102	111	131	156	196	215	215	217	219	220	%
AF CH4 emissions	103	132	166	194	220	239	239	241	243	245	%
LA CH4 emissions	102	121	138	151	152	148	148	149	151	152	%
EU N2O emissions	101	107	116	120	124	126	126	116	107	107	%
US N2O emissions	101	107	116	120	124	126	126	116	107	107	%
OT N2O emissions	101	107	116	120	124	126	126	116	107	107	%
EE N2O emissions	102	113	122	126	134	166	166	153	140	140	%
CA N2O emissions	102	114	127	135	148	172	172	158	145	145	%
IA N2O emissions	102	114	127	135	148	172	172	158	145	145	%
AF N2O emissions	102	124	144	160	203	237	237	218	200	200	%
LA N2O emissions	102	117	132	140	150	146	146	135	124	124	%
EU sulphates	97	84	56	34	16	8	8	8	8	8	%
US sulphates	97	84	56	34	16	8	8	8	8	8	%
OT sulphates	97	84	56	34	16	8	8	8	8	8	%
EE sulphates	98	87	67	52	33	24	24	24	24	24	%
CA sulphates	101	86	58	41	30	16	16	16	16	16	%
IA sulphates	101	86	58	41	30	16	16	16	16	16	%
AF sulphates	102	98	96	94	73	55	55	55	55	55	%
LA sulphates	99	98	93	82	65	40	40	40	40	40	%
Excess forcing	0.79	0.91	0.94	0.96	1.25	1.29	1.78	2.35	2.89	3.37	W/m2

B.2. SSPs

Table B.0.5. SSP Population growth rates up to 2300 in PAGE22

SSP1											
year	2019	2020	2030	2040	2050	2075	2100	2150	2200	2250	
	2020	2030	2040	2050	2075	2100	2150	2200	2250	2300	
EU	1.9%	1.9%	2.0%	1.7%	1.3%	0.9%	0.9%	0.9%	0.9%	0.9%	%/ year
US	3.0%	2.5%	2.0%	1.5%	1.2%	0.9%	0.9%	0.9%	0.9%	0.9%	%/ year
OT	2.1%	2.1%	2.1%	1.7%	1.3%	0.7%	0.7%	0.7%	0.7%	0.7%	%/ year
EE	4.0%	4.1%	3.3%	1.8%	0.9%	0.2%	0.2%	0.2%	0.2%	0.2%	%/ year
CA	8.1%	6.3%	3.9%	2.0%	0.3%	-0.6%	-0.6%	-0.6%	-0.6%	-0.6%	%/ year
IA	5.7%	5.7%	5.2%	4.1%	2.4%	1.0%	1.0%	1.0%	1.0%	1.0%	%/ year
AF	5.0%	5.2%	5.2%	4.6%	3.7%	2.3%	2.3%	2.3%	2.3%	2.3%	%/ year
LA	3.8%	3.7%	3.5%	2.8%	1.7%	0.7%	0.7%	0.7%	0.7%	0.7%	%/ year

SSP2											
year	2019	2020	2030	2040	2050	2075	2100	2150	2200	2250	
	2020	2030	2040	2050	2075	2100	2150	2200	2250	2300	
EU	1.9%	1.6%	1.6%	1.5%	1.4%	1.1%	1.1%	1.1%	1.1%	1.1%	%/ year
US	2.9%	2.1%	1.5%	1.2%	1.0%	0.7%	0.7%	0.7%	0.7%	0.7%	%/ year
OT	2.1%	1.8%	1.5%	1.4%	1.3%	1.0%	1.0%	1.0%	1.0%	1.0%	%/ year
EE	3.9%	3.4%	2.5%	1.6%	1.4%	1.0%	1.0%	1.0%	1.0%	1.0%	%/ year
CA	7.8%	5.1%	2.7%	1.6%	0.6%	0.2%	0.2%	0.2%	0.2%	0.2%	%/ year
IA	5.7%	4.9%	4.0%	3.3%	2.6%	1.8%	1.8%	1.8%	1.8%	1.8%	%/ year
AF	5.0%	4.6%	4.1%	3.8%	3.6%	3.0%	3.0%	3.0%	3.0%	3.0%	%/ year
LA	3.8%	3.2%	2.6%	2.3%	1.9%	1.5%	1.5%	1.5%	1.5%	1.5%	%/ year

SSP3											
year	2019	2020	2030	2040	2050	2075	2100	2150	2200	2250	
	2020	2030	2040	2050	2075	2100	2150	2200	2250	2300	
EU	1.6%	1.1%	0.7%	0.4%	0.2%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	%/ year
US	2.6%	1.6%	0.9%	0.5%	0.1%	-0.4%	-0.4%	-0.4%	-0.4%	-0.4%	%/ year
OT	1.9%	1.3%	0.8%	0.5%	0.3%	0.2%	0.2%	0.2%	0.2%	0.2%	%/ year
EE	3.9%	3.0%	1.9%	0.9%	0.9%	1.0%	1.0%	1.0%	1.0%	1.0%	%/ year
CA	7.7%	4.3%	1.6%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	%/ year
IA	5.7%	4.1%	2.6%	1.9%	1.5%	1.2%	1.2%	1.2%	1.2%	1.2%	%/ year
AF	5.0%	4.2%	3.3%	2.6%	2.4%	2.2%	2.2%	2.2%	2.2%	2.2%	%/ year
LA	3.9%	2.8%	1.9%	1.5%	1.2%	1.1%	1.1%	1.1%	1.1%	1.1%	%/ year

SSP4											
year	2019	2020	2030	2040	2050	2075	2100	2150	2200	2250	
	2020	2030	2040	2050	2075	2100	2150	2200	2250	2300	
EU	1.8%	1.8%	1.8%	1.4%	1.1%	0.7%	0.7%	0.7%	0.7%	0.7%	%/ year
US	2.9%	2.4%	1.9%	1.3%	1.0%	0.7%	0.7%	0.7%	0.7%	0.7%	%/ year
OT	2.0%	2.0%	1.8%	1.5%	1.1%	0.6%	0.6%	0.6%	0.6%	0.6%	%/ year
EE	3.8%	3.5%	2.7%	1.6%	1.0%	0.4%	0.4%	0.4%	0.4%	0.4%	%/ year
CA	7.8%	5.1%	2.7%	1.5%	0.2%	-0.5%	-0.5%	-0.5%	-0.5%	-0.5%	%/ year
IA	5.6%	4.6%	3.5%	2.6%	1.7%	0.8%	0.8%	0.8%	0.8%	0.8%	%/ year
AF	5.0%	4.4%	3.6%	2.8%	2.2%	1.8%	1.8%	1.8%	1.8%	1.8%	%/ year
LA	3.7%	3.0%	2.4%	2.0%	1.4%	0.9%	0.9%	0.9%	0.9%	0.9%	%/ year

SSP5											
year	2019	2020	2030	2040	2050	2075	2100	2150	2200	2250	
	2020	2030	2040	2050	2075	2100	2150	2200	2250	2300	
EU	2.2%	2.6%	2.8%	2.6%	2.4%	2.1%	2.1%	2.1%	2.1%	2.1%	%/ year
US	3.3%	3.2%	2.8%	2.4%	2.3%	2.1%	2.1%	2.1%	2.1%	2.1%	%/ year
OT	2.3%	2.9%	3.1%	2.7%	2.3%	1.8%	1.8%	1.8%	1.8%	1.8%	%/ year
EE	4.2%	5.0%	4.3%	2.5%	1.5%	0.8%	0.8%	0.8%	0.8%	0.8%	%/ year
CA	8.3%	7.4%	4.7%	2.5%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	%/ year
IA	5.8%	6.5%	6.1%	4.7%	3.0%	1.6%	1.6%	1.6%	1.6%	1.6%	%/ year
AF	5.2%	6.0%	6.3%	5.4%	4.2%	2.8%	2.8%	2.8%	2.8%	2.8%	%/ year
LA	3.8%	4.3%	4.3%	3.4%	2.2%	1.3%	1.3%	1.3%	1.3%	1.3%	%/ year

Table B.6. SSP GDP growth rates up to 2300 in PAGE22

SSP1											
year	2019	2020	2030	2040	2050	2075	2100	2150	2200	2250	
	2020	2030	2040	2050	2075	2100	2150	2200	2250	2300	
EU	0.3%	0.3%	0.2%	0.2%	0.0%	-0.4%	-0.4%	-0.4%	-0.4%	-0.4%	%/ year
US	0.8%	0.8%	0.7%	0.6%	0.4%	0.1%	0.1%	0.1%	0.1%	0.1%	%/ year
OT	0.5%	0.4%	0.2%	0.1%	-0.1%	-0.5%	-0.5%	-0.5%	-0.5%	-0.5%	%/ year
EE	0.0%	-0.1%	-0.2%	-0.3%	-0.5%	-0.9%	-0.9%	-0.9%	-0.9%	-0.9%	%/ year
CA	0.2%	0.0%	-0.3%	-0.6%	-1.0%	-1.4%	-1.4%	-1.4%	-1.4%	-1.4%	%/ year
IA	1.0%	0.7%	0.4%	0.1%	-0.3%	-0.8%	-0.8%	-0.8%	-0.8%	-0.8%	%/ year
AF	1.8%	1.5%	1.2%	0.8%	0.3%	-0.2%	-0.2%	-0.2%	-0.2%	-0.2%	%/ year
LA	0.7%	0.5%	0.2%	-0.1%	-0.4%	-0.9%	-0.9%	-0.9%	-0.9%	-0.9%	%/ year
SSP2											
year	2019	2020	2030	2040	2050	2075	2100	2150	2200	2250	
	2020	2030	2040	2050	2075	2100	2150	2200	2250	2300	
EU	0.2%	0.2%	0.1%	0.1%	-0.1%	-0.2%	-0.2%	-0.2%	-0.2%	-0.2%	%/ year
US	0.8%	0.7%	0.6%	0.5%	0.4%	0.1%	0.1%	0.1%	0.1%	0.1%	%/ year
OT	0.5%	0.4%	0.2%	0.1%	0.0%	-0.3%	-0.3%	-0.3%	-0.3%	-0.3%	%/ year
EE	0.1%	0.0%	0.0%	-0.1%	-0.2%	-0.4%	-0.4%	-0.4%	-0.4%	-0.4%	%/ year
CA	0.3%	0.1%	-0.2%	-0.5%	-0.8%	-1.0%	-1.0%	-1.0%	-1.0%	-1.0%	%/ year
IA	1.2%	1.0%	0.7%	0.5%	0.1%	-0.3%	-0.3%	-0.3%	-0.3%	-0.3%	%/ year
AF	2.1%	1.8%	1.5%	1.2%	0.7%	0.3%	0.3%	0.3%	0.3%	0.3%	%/ year
LA	0.9%	0.7%	0.5%	0.2%	-0.1%	-0.3%	-0.3%	-0.3%	-0.3%	-0.3%	%/ year
SSP3											
year	2019	2020	2030	2040	2050	2075	2100	2150	2200	2250	
	2020	2030	2040	2050	2075	2100	2150	2200	2250	2300	
EU	0.0%	-0.2%	-0.3%	-0.5%	-0.7%	-0.8%	-0.8%	-0.8%	-0.8%	-0.8%	%/ year
US	0.5%	0.3%	0.0%	-0.1%	-0.3%	-0.6%	-0.6%	-0.6%	-0.6%	-0.6%	%/ year
OT	0.4%	0.2%	0.0%	-0.1%	-0.2%	-0.2%	-0.2%	-0.2%	-0.2%	-0.2%	%/ year
EE	0.2%	0.1%	0.0%	0.1%	0.1%	0.2%	0.2%	0.2%	0.2%	0.2%	%/ year
CA	0.4%	0.2%	-0.1%	-0.4%	-0.5%	-0.3%	-0.3%	-0.3%	-0.3%	-0.3%	%/ year
IA	1.4%	1.3%	1.1%	0.9%	0.6%	0.5%	0.5%	0.5%	0.5%	0.5%	%/ year
AF	2.3%	2.2%	1.9%	1.7%	1.3%	0.9%	0.9%	0.9%	0.9%	0.9%	%/ year
LA	1.2%	1.1%	0.9%	0.7%	0.5%	0.4%	0.4%	0.4%	0.4%	0.4%	%/ year
SSP4											
year	2019	2020	2030	2040	2050	2075	2100	2150	2200	2250	
	2020	2030	2040	2050	2075	2100	2150	2200	2250	2300	
EU	0.2%	0.1%	0.0%	-0.1%	-0.4%	-0.6%	-0.6%	-0.6%	-0.6%	-0.6%	%/ year
US	0.7%	0.6%	0.4%	0.3%	0.1%	-0.3%	-0.3%	-0.3%	-0.3%	-0.3%	%/ year
OT	0.4%	0.3%	0.1%	-0.1%	-0.3%	-0.7%	-0.7%	-0.7%	-0.7%	-0.7%	%/ year
EE	0.0%	-0.2%	-0.3%	-0.4%	-0.6%	-0.9%	-0.9%	-0.9%	-0.9%	-0.9%	%/ year
CA	0.2%	-0.1%	-0.4%	-0.8%	-1.2%	-1.6%	-1.6%	-1.6%	-1.6%	-1.6%	%/ year
IA	1.1%	0.9%	0.6%	0.4%	0.0%	-0.4%	-0.4%	-0.4%	-0.4%	-0.4%	%/ year
AF	2.3%	2.1%	1.8%	1.6%	1.2%	0.8%	0.8%	0.8%	0.8%	0.8%	%/ year
LA	0.8%	0.6%	0.3%	0.0%	-0.3%	-0.6%	-0.6%	-0.6%	-0.6%	-0.6%	%/ year
SSP5											
year	2019	2020	2030	2040	2050	2075 º		2150	2200	2250	
	2020	2030	2040	2050	2075 º		2150	2200	2250	2300	
EU	0.5%	0.5%	0.5%	0.6%	0.5%	0.2%	0.2%	0.2%	0.2%	0.2%	%/ year
US	1.1%	1.2%	1.1%	1.0%	1.0%	0.7%	0.7%	0.7%	0.7%	0.7%	%/ year
OT	0.6%	0.6%	0.5%	0.5%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	%/ year
EE	0.0%	-0.1%	-0.1%	-0.2%	-0.5%	-0.9%	-0.9%	-0.9%	-0.9%	-0.9%	%/ year
CA	0.2%	0.0%	-0.3%	-0.6%	-1.0%	-1.5%	-1.5%	-1.5%	-1.5%	-1.5%	%/ year
IA	1.0%	0.7%	0.4%	0.1%	-0.3%	-0.8%	-0.8%	-0.8%	-0.8%	-0.8%	%/ year
AF	1.8%	1.5%	1.1%	0.8%	0.3%	-0.2%	-0.2%	-0.2%	-0.2%	-0.2%	%/ year
LA	0.7%	0.4%	0.1%	-0.2%	-0.5%	-0.9%	-0.9%	-0.9%	-0.9%	-0.9%	%/ year

Appendix C

This appendix includes the feedback response time fitting analysis based on the complete dataset sent by personal communication with Eleanor Burke (9th September 2020). The last two columns in Table C.1. below show that for both model specifications- JULES-deepResp and JULES-suppressResp- the R^2 value is higher when including the complete datasets as opposed to the delta temperatures being constrained to 0.2-5 °C.

Table C.0.1. Feedback response time fitting analysis based on Burke et al. (2017)

JULES-deepResp

Parameters	Table 1	Data file-0.2<dtemp<5	Data file-all data	Data file-0.2<dtemp<5	Data file-all data	Data file-0.2<dtemp<5	Data file-all data
Source	**Burke et al. (2017)**	**Excel**	**Excel**	**Solver- Excel**	**Solver- Excel**	**Matlab**	**Matlab**
FCRt0	6666	7131	6075	7950	7790	7926 (7790, 8062)	7790 (7664, 7916)
1/Γ						-0.5116 (-0.5242, -0.4989)	-0.4961 (-0.5077, -0.4844)
Γ (degC)	2.6	2.2	2.8	1.9	2.0	2.0	2.0
R2	0.92	0.8757	0.8896	0.84	0.88	0.8432	0.8773

JULES-suppressResp

Parameters	Table 1	Data file-0.2<dtemp<5	Data file-all data	Data file-0.2<dtemp<5	Data file-all data	Data file-0.2<dtemp<5	Data file-all data
Source	**Burke et al. (2017)**	**Excel**	**Excel**	**Solver- Excel**	**Solver- Excel**	**Matlab**	**Matlab**
FCRt0	10155	11030	9811	11207	10745	1.12e+04 (1.101e+04, 1.139e+04)	1.075e+04 (1.06e+04, 1.089e+04
1/Γ						-0.264 (-0.2751, -0.2529)	-0.2319 (-0.2397, -0.224)
Γ (degC)	4.9	3.8	5.2	3.8	4.3	3.8	4.3
R2	0.73	0.7235	0.8163	0.63	0.76	0.6286	0.7551

Appendix D

A range of methods were tested to analyse creating a new forecasting variable to improve the existing modelling approach and decrease the time lag in computation:

1. temperature variable from previous analysis period (current modelling in PAGE09)
2. linear forecast using existing temperature change variable in PAGE09
3. linear forecast +error (difference between projected and forecasted temperature changes in previous time analysis period)
4. Holt’s method with linear trend for irregular time series: exponential smoothing method with level and trend based on Wright (1986) (Hanzák, 2014)
5. Holt’s method with exponential trend for irregular time series: based on Cipra (2006) (Hanzák, 2014)
6. Holt’s method with damped linear trend for irregular time series: based on Cipra (2006) (Hanzák, 2014)

Methods 4 to 6 entailed using the Solver function in Excel to find the a, b and phi parameters which resulted in the minimum sum of squared errors.

Figure D.0.1. Error time series for different forecasting methods

Figure D.1. shows the error time series of each forecasted temperature method vs. method 1 for the four RCPs. As it can be seen in the table D.1., method 6 (Holt's method with damped linear trend for irregular time series) results in the smallest errors for all RCP scenarios followed by method 3 (linear forecast +error).

Table D.0.1. Error analysis for different forecasting methods

Method	PAGE09-RT_G (t-1)	Linear forecast	Linear forecast + error	Holt´s method-irregular	HM- irregular exp. Trend	HM- irregular damped Trend
RCP 2.6						
SSE	11.99	1.49	0.63	1.49	12.16	0.30
MSE	1.20	0.15	0.06	0.15	1.22	0.03
RMSE	1.10	0.39	0.25	0.39	1.10	0.17
RCP 4.5						
SSE	1.58	0.30	0.15	0.30	1.66	0.04
MSE	0.16	0.03	0.01	0.03	0.17	0.00
RMSE	0.40	0.17	0.12	0.17	0.41	0.07
RCP 6.0						
SSE	3.15	0.63	0.31	0.63	2.92	0.08
MSE	0.39	0.08	0.04	0.08	0.36	0.01
RMSE	0.63	0.28	0.20	0.28	0.60	0.10
RCP 8.5						
SSE	6.05	1.38	0.72	1.38	5.90	0.23
MSE	0.86	0.20	0.10	0.20	0.84	0.03
RMSE	0.93	0.44	0.32	0.44	0.92	0.18

The issue with implementing method 6 is that it would entail running solver for each run of each scenario, something rather impractical. An alternative would be to find a compromise set of a, b and phi parameters which work well with all the scenarios included in this analysis.

As a starting point of the analysis, the parameters (a, b and phi) were calculated using Solver whilst minimising the sum of squared errors between the projected and forecasted temperatures for the four RCPs using Holt's method with damped trend for irregular time series. For RCP 4.5 and RCP8.5 the a, b and phi parameters were 0.828, 1, 0.992 and 1,1, 0.986 respectively (all values are between zero and one given the constraint in Hanzák, 2014). The parameter spread between both scenarios is rather small. To analyse this further and come up with a set of parameters, the statistical analysis was extended using three new "methods" (methods 4-6 in the detail below):

1. Temperature variable from previous analysis period (current modelling in PAGE09)

2. linear forecast +error (difference between projected and forecasted temperatures in previous time analysis period)

3. Holt’s method with damped linear trend for irregular time series: using the parameters that minimise the sum of squared errors for each RCP scenario with Solver (Parameters1 for RCP 8.5 and Parameters2 for RCP 4.5)

4. Holt’s method with damped linear trend for irregular time series: using Parameters1 for both RCPs

5. Holt’s method with damped linear trend for irregular time series: using Parameters2 for both RCPs

6. Holt’s method with damped linear trend for irregular time series: using the average of Parameters1 and Parameters2 for each parameter for both RCPs

Figure D.0.2. Error time series for different forecasting methods (second round)

As it can be seen from table D.3, method 6 (Holt's method with damped linear trend for irregular time series using the average of Parameters 1 and 2) results only in slightly bigger errors than method 3 ("HM- irregular damped trend" which uses Solver).

Table D.2. Error analysis for different forecasting methods (second round)

	PAGE09-RT_G (t-1)	Linear forecast + error	HM- irregular damped Trend	HM- irr. damped Trend Par1	HM- irr. damped Trend Par2	HM- irr. damped Trend Avg Par
			RCP 2.6			
SSE	11.99	0.63	0.30	0.30	0.70	0.41
MSE	1.20	0.06	0.03	0.03	0.07	0.04
RMSE	1.10	0.25	0.17	0.17	0.26	0.20
			RCP 4.5			
SSE	1.58	0.15	0.04	0.08	0.04	0.05
MSE	0.16	0.01	0.00	0.01	0.00	0.01
RMSE	0.40	0.12	0.07	0.09	0.07	0.07
			RCP 6.0			
SSE	3.15	0.31	0.08	0.16	0.08	0.10
MSE	0.39	0.04	0.01	0.02	0.01	0.01
RMSE	0.63	0.20	0.10	0.14	0.10	0.11
			RCP 8.5			
SSE	6.05	0.72	0.23	0.40	0.23	0.27
MSE	0.86	0.10	0.03	0.06	0.03	0.04
RMSE	0.93	0.32	0.18	0.24	0.18	0.20

Following the results from table D.3, the forecasting variable was added to the model using triangular distributions for the “a”, “b” and “phi” parameters with the min, mode and max values resulting from the range values of the parameters calculated with solver as detailed in table D.4.

Table D.3. Forecasting variable final parametrisation

Parameters	min	mode	max
a	1.000	1.000	1.000
b	1.000	1.000	1.000
φ	0.981	0.986	0.991

Glossary

- @RISK: software used to run probabilistic simulations in the PAGE IAM
- ACCESS: transdisciplinary European Union funded project Arctic Climate Change, Economy and Society
- ACIA: Arctic Climate Impact Assessment
- AIR: airbone fraction, percentage of CO_2 emissions that gets into the atmosphere
- AMAP: Arctic Monitoring Assessment Programme
- Anaktuvuk: city in the Arctic region within Alaska, United States
- AR5: Intergovernmental Panel on Climate Change Fifth Assessment Report
- AR6: Intergovernmental Panel on Climate Change Sixth Assessment Report
- Arctic amplification: temperature increases in the Arctic region exceeding double the global average (IPCC, 2013; Overland et al., 2015).
- Atlantic Meridional Overturning Circulation (AMOC): "The main current system in the South and North Atlantic Oceans. AMOC transports warm upper-ocean water northwards and cold, deep water southwards, as part of the global ocean circulation system. Changes in the strength of AMOC can affect other components of the climate system." (IPCC, 2021b, page 2238).
- Bering Strait: strait separating Russia from the United States between the Arctic and Pacific Oceans

- CH_4 : methane, the top 2 GHG emitted through anthropogenic activities
- CIV_VALUE: variable name in PAGE to denote the statistical value of civilisation
- Climate carbon feedback (CCFF): feedback which represents the release of soil carbon and decreased absorption from the ocean as temperature increases in PAGE
- CMIP5: the fifth phase of the coupled model intercomparison project
- CMIP6: the sixth phase of the coupled model intercomparison project
- CO_2: carbon dioxide, the top 1 GHG emitted through anthropogenic activities
- density: a measure of mass over volume
- DICE: Dynamic Integrated model of Climate and the Economy, a simplified IAM
- Discontinuities: large scale catastrophic events like the melting of the Greenland ice sheet
- Discount rate: the parameter used to estimate the value of the future cashflows into the present
- Earth System model (ESM): model which includes representation of different processes within the Earth system
- Ecosystem services: the benefits ecosystems provide to humans
- Extended Concentration Pathways (ECPs): extension of RCPs beyond 2100
- Frozen carbon residence time: ratio of the remaining permafrost carbon stock to the loss rate at a given time (Burke et al., 2017)
- FUND: Climate Framework for Uncertainty, Negotiation and Distribution IAM

- Greenhouse gases (GHGs): gases in the atmosphere which absorb heat contributing to warm the atmosphere
- GDP: Gross domestic product
- Hydrofluorocarbons: a type of greenhouse gas
- ICE-ARC: Ice Climate Economics- Arctic Research on Change, transdisciplinary project funded by the European Union 7th Framework Programme
- IEBM: integrated ecosystem-based management management tool with a focus on the Arctic Ocean developed during ACCESS project
- IIASA: International Institute for Applied Systems Analysis
- Input-output model: quantitative model which represents the connections between different sectors of a national or regional economy
- Integrated assessment models (IAMs): are simplified representations of climate processes and the economy
- Interagency Working Group on the Social cost of Greenhouse Gases (IWG): group set by the US Government to incorporate the latest scientific information in the monetisation of greenhouse gases metrics used
- Intergenerational justice: refers to the responsibility of current generations towards future generations on the availability of natural resources (Meyer,2017)
- Intragenerational justice: refers to the developed countries' contribution to climate change through greenhouse gases emissions since the industrial revolution.
- IPCC: Intergovernmental Panel on Climate Change

- Jet stream: the polar jet stream acts as a boundary between cold air closer to the Arctic and warmer air in mid-latitudes (NOAA, 2021)
- JULES: Joint UK Land Environment Simulator, a land surface model
- LULUCF: land use, land use change and forestry
- Latin Hypercube sampling (LHS): an alternative to Monte Carlo simple random sampling technique which “improves the coverage of the range of parameters” (Hope, 2006, page 47)
- Linear gases: greenhouse gases with an atmospheric concentration so low that their radiative forcing has a linear behaviour with respect to their concentration in PAGE09
- N_2O: nitrous oxide: the top 3 GHG emitted through anthropogenic activities
- Nationally Determined Contributions: non-binding pledges made by countries to meet the Paris Agreement
- Net present value: present value of future cashflows estimated using a discount rate to adjust for the time value of money
- NSR: North Sea shipping route in the Arctic
- OECD: Organisation for Economic Cooperation and Development
- ORCHIDEE-MICT: a land surface model
- PAGE: Policy Analysis of the Greenhouse Effect IAM
- Paris Agreement: a legally binding commitment to limit the global temperature increase vs. pre-industrial “*well below 2 °C*”, preferably 1.5 °C, to limit climate change risks and impacts (UN, 2015
- Perfluorocarbons: a type of greenhouse gas
- Permafrost: perennially frozen ground
- Public good: “A good or bad that is both nonrival and nonexcludable is a public good or bad.” (Kolstad, 1997, page 95)

- Radiative forcing: net imbalance in energy at the top of the atmosphere, which can be affected by changes in solar output, volcanoes, and GHGs (IPCC, 2021)
- Representative Concentration Pathways (RCPs): radiative forcing pathways which constitute the starting point of a parallel scenario development process for informing AR5
- SiBCASA: a land surface model that simulates permafrost processes
- SO_2: sulphur dioxide, a precursor to atmospheric sulphates
- Social cost of carbon dioxide (SCCO2): the marginal increase in climate change impacts from the emissions of an extra tonne of carbon dioxide
- SSPs: Shared Socioeconomic Pathways, second step in the parallel scenario development process for informing AR5
- Stern Review: report led by economist Nick Stern, commissioned by UK Government, to estimate the climate change impacts on the global economy
- Sulphates: aerosol particles in the atmosphere which reflect radiation and have a cooling effect
- Sulphur hexafluoride: a type of greenhouse gas
- Surface-albedo feedback: feedback to temperature increase from the melting of sea ice and snow
- Teleconnection: "significant relationships or links between weather phenomena at widely separated locations on earth, which typically entail climate patterns that span thousands of miles" (NOAA, 2022)
- Tipping point: threshold after which a gradual change in a driver results in a non-linear effect over the system

- Transient climate response (TCR): the temperature increase from a doubling of CO2 concentration resulting from a 1% increase per year
- USD: United States Dollars
- WGI: Intergovernmental Panel on Climate Change working group I focusses on the physical impacts from climate change
- WGII: Intergovernmental Panel on Climate Change working group II focusses on Impacts, Adaptation and Vulnerability
- WGIII: Intergovernmental Panel on Climate Change working group III focusses on climate change mitigation

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