THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Comparing Climate Forcers on a Common Scale

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Division of Physical Resource Theory

Chalmers University of Technology

Göteborg, Sweden 2015

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Cover:

The recent warming of the globe with a scale to illustrate the process of comparing climate forcers. BC (Black Carbon) has on purpose been made fussy in the edges (or coated), as a reference to its large uncertainties. NASA image, based on data from the Goddard Institute for Space Studies. The map illustrates how much warmer surface temperatures were on average in the decade (2000-2009) compared to average temperatures recorded between 1951 and 1980 (a common reference period for climate studies). The strongest warming, shown in red, was in the Arctic. Very few areas saw cooler temperatures, shown in blue. Grey areas over parts of the Southern Ocean are places where temperatures were not recorded. The analysis, conducted by the Goddard Institute for Space Studies (GISS) in New York City, is based on temperatures recorded at meteorological (weather) stations around the world and satellite data over the oceans

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ABSTRACT

The climate is changing at a rapid pace. Through the United Nations Framework Convention on Climate Change (UNFCCC), the world has agreed to hold the on-going temperature increase below 2 °C. Climate change is caused by emissions of different atmospheric species (climate forcers). In order to meet the UNFCCC objective, major emission abatement measures are needed. To compare the climate effects of different measures, emissions of different climate forcers need to be compared on a common scale. Emission metrics are used for this purpose.

In **Paper I**, we develop and analyse two new emission metrics based on the Sea Level Rise (SLR) that emissions of a given climate forcer cause. One of them is the Global Sea level rise Potential (GSP). The metrics are compared with the commonly used Global Warming Potential (GWP) and Global Temperature change Potential (GTP) metrics. Climate forcers with different atmospheric lifetimes are evaluated using an upwelling-diffusion energy balance model. All climate forcers, including short-lived forcers, have long-term influences on SLR. If we only account for the thermosteric part of SLR, GSP values fall in between GWP and GTP values.

In **Paper II**, we compare two different approaches to including climate-carbon cycle feedbacks (CCF) for emission metrics. The IPCC AR5 approach to including CCF is based on Linear Feedback Analysis (LFA). The second approach is based on a coupled climate-carbon cycle model in which CCF is modelled by explicitly making the biosphere and ocean carbon reservoirs temperature dependent. We find that including CCF for non-CO_2 climate forcers through the Explicit CCF (ECCF) approach gives higher GWP and GTP values than using the LFA approach, for short time horizons. While the opposite is true for long time horizons. With the LFA approach, a fraction of the indirectly induced atmospheric CO_2, caused by an emission pulse of a non-CO_2 forcer, stays in the atmosphere basically forever, while with the ECCF approach it eventually returns back to the unperturbed levels when the direct warming is gone.

In **Paper III**, we develop and analyse a spatially explicit model of multiple independent villagers engaged in forest extraction. A spatial Non-Cooperative Equilibrium (NCE) of extraction patterns is analysed and compared to an equilibrium with coordinated villagers, for a range of spatial landscapes and model assumptions. Each villager chooses from where, and how much, to extract and whether to perform non-forest wage work part or full-time instead. We investigate the model assumptions, commonly adopted by earlier research, which include the use of a representative villager and only allowing the villager to extract from one location. We find a priori identical villagers to behave differently in equilibrium and show that forest extraction and degradation patterns depend on the model assumptions used.

Keywords: Metric; Sea Level Rise; Short-lived Climate Forcers; Greenhouse Gases; Energy Balance; Upwelling-Diffusion; Carbon Cycle; Spatial-temporal Optimization; Non-cooperative Nash Equilibrium; Resource Extraction

LIST OF PUBLICATIONS

I. Sterner Erik, Johansson Daniel JA, Azar Christian, "Emission metrics and sea level rise". Climatic Change 127:335–351. doi: 10.1007/s10584-014-1258-1
DJ posed the idea with contributions from ES. DJ suggested modelling approach, while ES implemented the model. ES and DJ analyzed results together. CA contributed to the result analysis and came up with the analytical findings. ES wrote the paper with contributions from DJ and CA.

II. Sterner Erik, Johansson Daniel JA, "The climate-carbon cycle feedback effect on emission metrics". To be submitted.
DJ posed the idea, ES refined it. DJ suggested modelling approach with input from ES, while ES implemented the model. ES analyzed results and wrote the paper with contributions from DJ.

III. Sterner Erik, Robinson Elizabeth JZ, Albers Heidi J, "Spatial-temporal modeling of non-cooperative resource extraction: An application to forest management". Work in progress.
EJZ posed the idea, ES refined it with contributions from HJA. ES made the model with contributions from EJZ and HJA. ES and EJZ analyzed results together. ES, EJZ and HJA wrote the paper together.

PREFACE

I knocked on the door to Christian Azar's office and heard "Come in". The time had come to start thinking about a thesis project for my master's degree in Complex Adaptive Systems, and I was running around visiting attractive research departments.

"Hello!" I said.

"Hi!" "Hello!" said Christian and the person he was chatting with, Daniel Johansson.

"Do you have a suggestion for a master's thesis project that could potentially be relevant for PhD work after the thesis?" I asked.

"Hm," said Christian. "Do you know what black carbon is?"

"No," I responded.

"Neither do we," said Christian, smiling. "It's particles that contribute to global warming. Maybe you could help us figure out its precise role in climate change?"

That practically settled it. I got a more formal project description and also an indication that there was going to be a call for applications to quite a few PhD positions at Physical Resource Theory (PRT) soon.

What this little story offers is a glimpse of the spirit of PRT: An enthusiastic, bold, curious, ambitious, but at the same time well-informed call to explore the potentials and dynamics of various parts or mechanisms within a system or the entire system itself, with a main focus on systems that are large-scale or have large-scale implications for humankind. In other words: just what I was looking for.

During my work toward my thesis, I started to develop and explore energy balance models of the climate system with a focus on Black Carbon (BC). In the spirit of PRT, I constructed a simple climate model that was nevertheless sufficiently sophisticated to deal with annual global temperature means and to answer important questions regarding the role of BC in mitigating climate change. Questions like: What is its possible impact on global mean temperature? At what time scales does it affect ocean heat uptake? How does its impact compare to that of the other climate forcers?

ACKNOWLEDGEMENTS

I would like to say infinitely many thanks to:

My supervisors. Daniel Johansson for his persistently ambitious, knowledgeable, demanding yet trusting and understanding attitude towards my studies. Christian Azar for his razor sharp, instantaneous, yet wisely formulated questions, posed to let you bring important realizations to light on your own.

The whole entity or phenomenon of PRT, which carries more wisdom and answers as well as laughter and crazy competitions than you would think possible. If I were to thank all of the people that I would like to thank at PRT, the list would be just about everyone who works here. However, I cannot restrain myself from giving some extra attention to my roomy, David Andersson.

Financial support from the Swedish Energy Agency and Carl Bennet AB is greatly acknowledged. Paulina Essunger is thanked for making my words come out nicely.

Finally, I would also like to especially thank my dear Elin, my brothers, my parents, and all of my close friends for their support and good times.

Erik Sterner

Göteborg, March, 2015

CONTENTS

Appended papers with supplementary materials

1 INTRODUCTION

Climate change is one of the greatest global challenges (Biermann and Boas 2010; Thomas et al. 2004; Vörösmarty et al. 2010). No other environmental issue has ever been addressed with the same international effort, engaging parties from all parts of human society. The scientific endeavour of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) involved more than 800 scientists, from over 80 countries, as lead authors or review editors alone, assessing a vast amount of scientific work and answering more than 140,000 review comments on the draft report (IPCC 2015).

The change is already happening. So far, the global mean surface temperature has risen by about 0.62 °C from the average in 1850-1879 to the average in 1984-2013 (Morice et al. 2012), and the land surface temperature has increased about 40% more than the global average (Jones et al. 2012; Morice et al. 2012). In the near term, it is very likely that large-scale changes in precipitation patterns will occur (Kirtman et al. 2013). With stringent emissions reductions, the "likely" range for Sea Level Rise (SLR) during the 21st century is about 0.3 – 0.6 m; with emissions at the upper end of projections, the "likely" range is about 0.5 – 1 m; for a given emissions scenario, the likelihood that SLR falls outside the associated "likely" range is up to one-third (Church et al. 2013).

Climate change is mainly caused by anthropogenic emissions of greenhouse gases and aerosols (here referred to as *climate forcers*), most notably by CO_2 (Myhre et al. 2013). However, CO_2 is not the only climate forcer (see Fig. 1) and hence not the only option for climate change mitigation. The effects of various forcers need to be compared in order to decide on mitigation options. In order for such comparisons to be possible, we need metrics that translate forcers into a common scale. For this purpose, the United Nations Framework Convention on Climate Change (UNFCCC) has chosen the emission metric Global Warming Potential (GWP) with a time horizon of 100 years (see Equation 2). However, the choice of metric and time horizon is not trivial because of the different lifetimes of the various forcers. There is in fact no unique way of comparing the climate effects of 1 kg of CO_2 emissions with 1 kg of CH_4 emissions. In this thesis, we develop and analyse different ways of comparing climate forcers.

The main contributions of this thesis are: the construction and evaluation of emission metrics based on SLR (Paper I) and the analysis of the effects of two different ways of including the Climate-Carbon cycle Feedback (CCF) in emission metrics (Paper II). In addition, in a paper rather separate from the world of climate change analysis, we have analysed the effects of using various modelling assumptions for the extraction and forest degradation patterns under different institutional settings for the use and management of forested areas in low-income countries (Paper III).

2 Climate Modelling for Emission metrics

Climate change

The two main properties needed to determine the climate change effect of emissions of a climate forcer are the forcer's effect on Earth's radiative balance and its atmospheric adjustment lifetime. Radiative Forcing (RF) is the "net change in the energy balance of the Earth system due to some imposed perturbation" or more exactly "the change in net irradiance at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, while holding surface and tropospheric temperatures and state variables such as water vapour and cloud cover fixed at the unperturbed values" (Myhre et al. 2013). RF serves as the basis for comparison of climate forcers in the GWPs (see Equation 2). Figure 1, from IPCC AR5 (8.18 in Myhre et al. 2013), presents the total effective radiative forcing[1] (ERF) over time, split into nine categories of anthropogenic sources and two natural sources of ERF. By studying Figure 1 it becomes clear that anthropogenic forcing (red line) of the climate system has accelerated since the 1950s.

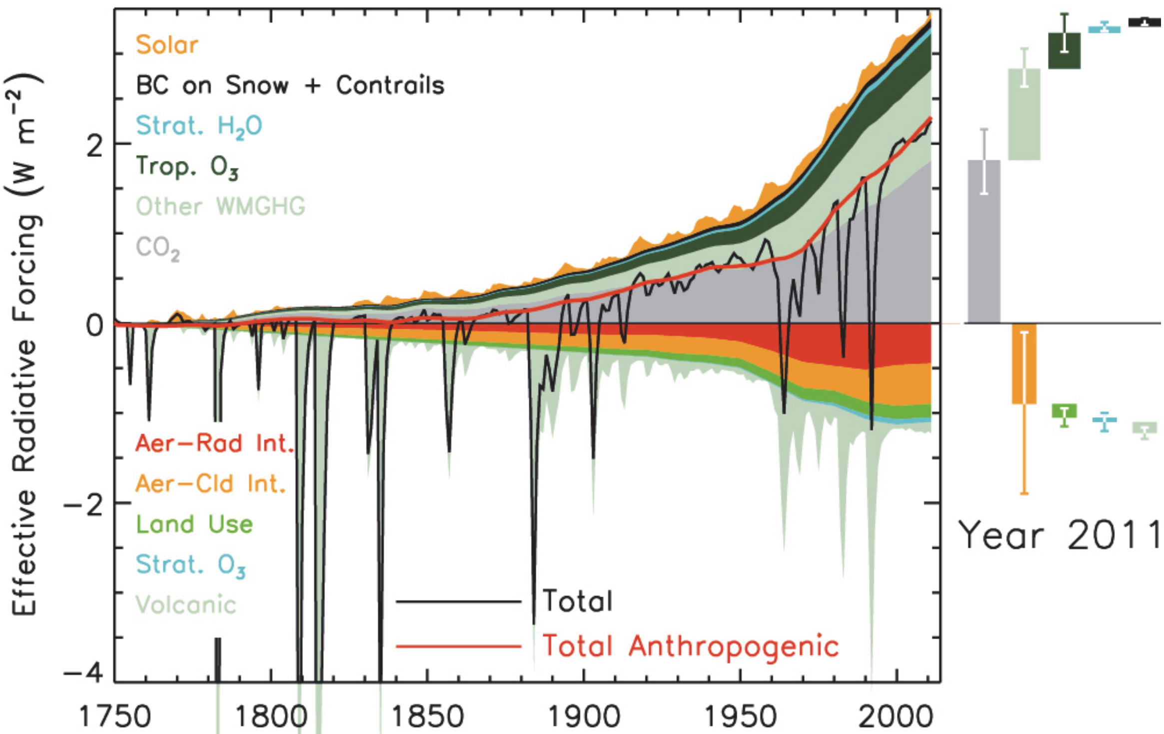

Figure 1. Time evolution of forcing for anthropogenic and natural forcing mechanisms. Bars with the present forcing and uncertainty ranges (5 to 95% confidence range) are given in the right part of the figure. For aerosols, the ERF due to Aerosol–Radiation Interaction (Aer-Rad Int.) and total aerosol ERF are shown. Aer-Cld Int. denotes the Aerosol-Cloud Interaction. The uncertainty ranges are for present (2011 versus 1750). The figure is from AR5 (Myhre et al. 2013). The caption has been abbreviated, see the original source for the full-length version.

[1] ERF is related to RF but allows for rapid adjustments in the atmosphere to take place after a radiative perturbation and thus better capture the potential for surface temperature changes.

To understand what Figure 1 means for the potential future temperature change, we note that the equilibrium temperature change is proportional to the climate sensitivity parameter λ (see Equation 1).

$$\Delta T = \lambda \cdot RF \qquad \text{(Eq. 1)}$$

λ is assessed to likely be in the range 0.4-1.2 °C/(W/m^2) (Stocker et al. 2013). Hence, for an increase in RF of 1 W/m^2 we should expect a global mean surface temperature increase of 0.4-1.2 °C equilibrium warming. Climate sensitivity is often described in terms of the global mean surface temperature change per doubling of CO_2. A doubling of the atmospheric CO_2 concentration leads to an RF increase of about 3.7 W/m^2 (Myhre et al. 1998). Hence, climate sensitivity is likely in the range 1.5-4.5 °C for a CO_2 doubling.

The main approach available for controlling concentrations of climate forcers is reducing emissions of these forcers. However, when analysing what effect the potential emission of a climate forcer at time *t* has on the climate, several questions arise. What time horizon and treatment of time are we interested in? What background scenario should be used? Which climate variable is most relevant? What geographical aspects of emissions and impacts should be taken into account? These questions are important mainly because of the differences in atmospheric lifetimes among forcers (see Fig. 2). These differences mean that choosing a method for comparing emissions of different climate forcers requires answering these questions, whether explicitly or implicitly. Figure 2 is an illustrative comparison of the removal, from the atmosphere, of instant emission pulses of CO_2 and CH_4 respectively. In Paper I we study their respective effect on temperature and SLR. The different effects on different time scales make it difficult to evaluate and compare the effectiveness of various climate mitigation measures involving emissions of different climate forcers.

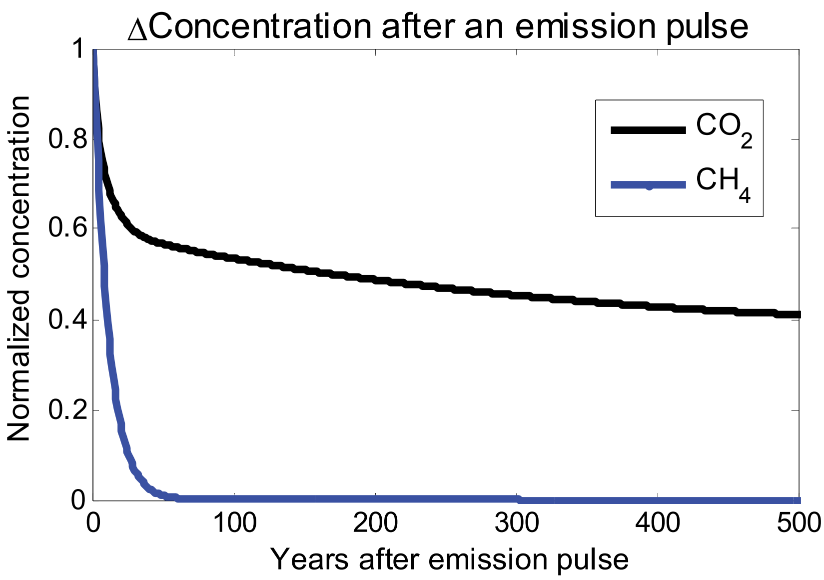

Figure 2. Illustration of the different atmospheric lifetimes of CO_2 and CH_4 emissions[2]. Normalized values for the change in the atmospheric concentration over time after equal-sized emission pulses of the two single most important greenhouse gases (Myhre et al. 2013).

The work presented in Papers I and II addresses the issue of putting emissions of the different climate forcers on a common scale, using a so-called emission metric. However, all emission metrics have their limitations; the equivalence given by one metric is only valid for the specific "climate variable" and the specific treatment of time that are assessed by the metric, see Fuglestvedt et al. (2003).

An emission metric must be based on a "climate variable". The relevant candidates are found within the following causal chain:

EMISSION CHANGE ⟶ CONCENTRATION CHANGE ⟶ RADIATIVE FORCING ⟶ TEMPERATURE CHANGE ⟶ CLIMATE IMPACTS

Radiative forcing is the first item in the cause and effect chain that offers a common scale for different climate forcers. Hence the basis for an emission metric has to be found at this position or further down the chain. While the relevance of a chosen climate variable with respect to the specific goal of an emissions reduction scheme is typically greater the further down the chain we go, so is the level of uncertainty.

Metrics

The Global Warming Potential (GWP) is the most commonly used metric, originating from work by Rodhe (1990), Lashof and Ahuja (1990), and Shine et al. (1990). GWP is defined as the time-integrated RF over a specific time horizon of an emission pulse of a forcer, divided by the time-integrated RF of an equal-sized (in terms of mass) emission pulse of CO_2 (Equation 2).

$$GWP_X = \frac{AGWP_X}{AGWP_{CO_2}} = \frac{\int_0^H RF_X(\tau)d\tau}{\int_0^H RF_{CO_2}(\tau)d\tau} \qquad \text{(Eq. 2)}$$

Here $AGWP_X(H)$ is the Absolute Global Warming Potential of forcer X at time horizon H, and $RF_X(\tau)$ is the radiative forcing of X at time τ.

The GWP has been criticized from various viewpoints (Wuebbles et al. 1995; O'Neill 2000; Manne & Richels 2001; Fuglestvedt et al. 2003), and its adoption by the UNFCCC has been questioned on the basis of it not being a good proxy for the actual temperature rise over longer

[2] Background scenario: Representative Concentration Pathway (RCP) 4.5 (Meinshausen et al. 2011).

time horizons (Smith and Wigley 2000). As a result, many alternative metrics have been suggested (Fisher et al. 1990; Shine et al. 2005; Tanaka et al. 2009; Gillett and Matthews 2010; Johansson, 2012). The most-discussed alternative is the Global Temperature change Potential (GTP) (Equation 3)., which is defined as the temperature response, after a certain time horizon, to an emission pulse of a forcer, divided by the corresponding temperature response to an equal-sized (in terms of mass) emission pulse of CO_2 (Shine et al. 2005).

$$GTP_X(H) = \frac{AGTP_X(H)}{AGTP_{CO_2}(H)} \qquad \text{(Eq. 3)}$$

Here $AGTP_X(H)$ is the Absolute Global Temperature change Potential of forcer X at time horizon H.

To capture the integrated temperature effect over time, the Integrated Global Temperature change Potential (IGTP) metric has been proposed (Peters et al. 2011; Azar & Johansson, 2012).

In Paper I, we introduce and evaluate two new metrics similar to GTP and IGTP but based on Sea Level Rise (SLR) instead of temperature. In Paper II, we investigate different approaches to taking into account the temperature feedback in the carbon cycle and what effect these have on the GWP and GTP values for a set of forcers.

Model

In both Papers I and II, an Upwelling-Diffusion Energy Balance Model (UD-EBM) is used to model the energy balance of the climate system. In order to estimate SLR due to thermal expansion of the ocean, we introduce a calculation of the density of the water in the model of Paper I (which is based on Johansson 2011; Azar and Johansson 2012). The UD-EBM of Paper II is expanded by being integrated with a carbon cycle model. The carbon cycle consists of two parts, an ocean UD-model analogous to the UD-EBM for the dissolution of carbon in the ocean and a box model for the terrestrial biosphere. Figure 3 shows a schematic picture of the models developed and applied in Papers I and II. Taking emissions of different climate forcers or the RF they cause as input, these types of models are designed and constructed to be able to reproduce the annual mean temperature, the ocean heat uptake, and the aggregated fluxes of carbon in the carbon cycle. Similar models have been developed and used in for example Shine et al. (2005) and Hoffert (1980).

Note that this type of model sets aside many aspects of climate change and parts of the climate system. The models focus on the globally-averaged flows and reservoirs of energy and carbon (see Fig. 3); only simpler gas cycle models are included for the other greenhouse gases.

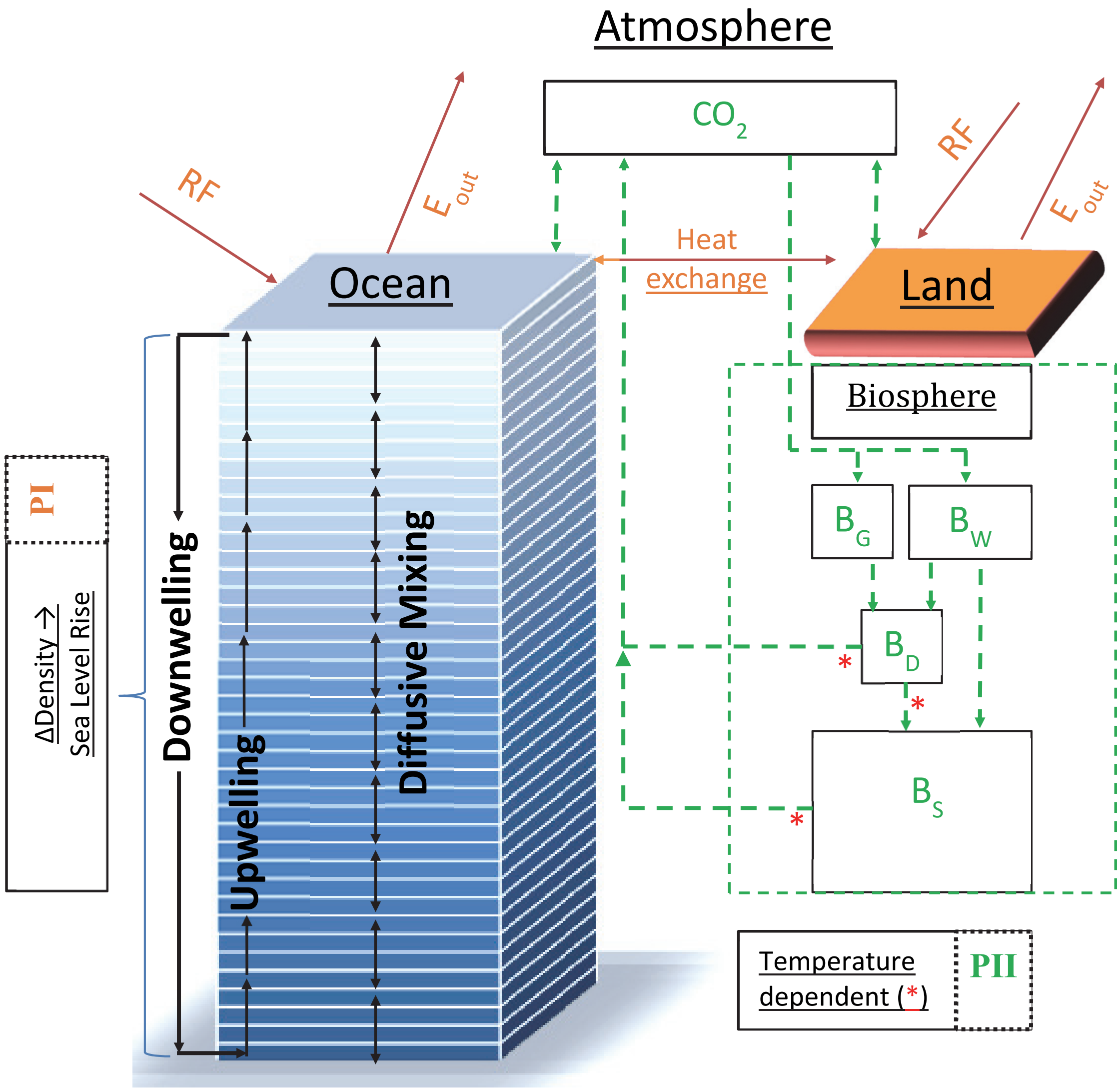

Figure 3. Schematic illustration of the main model features for Papers I and II. The energy balance is modelled with the flows of energy processes as illustrated (orange and black arrows). E_{out} denotes the energy that goes out to space through thermal radiation. Paper II also models the carbon cycle with its flows (dashed green and black arrows) and stocks. For Paper I, the particular focus was SLR, and for Paper II it was temperature dependence of decomposition and respiration, as noted in the boxes marked PI and PII. B_x are the four biosphere boxes (ground, wood, detritus and soil). The arrows marked RF represents the total RF, from all non-CO_2 forcers and from CO_2. Note that some parts of the models, such as the gas cycles for the other greenhouse gases and the aerosols, are left out for clarity.

Forcers

We have chosen to evaluate the metrics studied in Papers I and II with a set of climate forcers that covers the whole scale of atmospheric lifetimes, from the short-lived (BC) to the long-lived (SF_6). The BC particles are in the atmosphere for about a week, while the SF_6 gas molecules have a lifetime of about 3,200 years. Because of the short lifetime and unevenly distributed emissions of aerosols such as BC, along with climate changes that depend on for example the affected region's surface albedo[3], the appropriateness of an emission metric concept with a single global value has been questioned for these forcers, (Ramanathan and Carmichael 2008; Wang et al 2009). Shindell and Faluvegi (2009) examine the regional climate change effects and have shown that there is a strong dependence on the location of the emissions. We recognize that many aspects of the climate forcing from aerosols are highly uncertain, yet we include BC (with a global average value) in order to understand what climate change mitigation potential a generic climate forcer with a very short atmospheric life time could have. Other reasons to include BC in Paper I include Hu et al. (2013), which suggested that mitigation of Short Lived Climate Forcers (SLCFs) could achieve a reduction of the SLR projected for this century by 22-42%, and the recent policy interest in SLCFs (Anenberg et al. 2012; Shindell et al 2012), expressed in particular through the Climate and Clean Air Coalition[4].

The latest global inventory and report on BC by Bond et al. (2013) pins down some of the uncertainties about its climate impact. These uncertainty fall into several categories: anthropogenic emission quantity, direct, indirect, and semi-direct effects, lifetime in the atmosphere, lifetime on snow and ice, albedo effect and surface dimming. The direct effect is the easiest to understand. It is the effect caused by BC particles intercepting incoming solar radiation and absorbing it. The indirect and semi-direct effects stem from the impact of BC on clouds; these uncertainties are among the greatest when it comes to BC's overall radiative forcing.

A recent study (Hodnebrog et al. 2014) argues that the abundance of BC at different heights used in global aerosol models, together with the semi-direct effect, overestimates the current climate effect of BC. All in all, different studies come up with estimates of about 0.25-1.1 W/m^2 (Bond et al. 2013; Myhre el al 2013) for the aggregate RF of BC. However, the co-emission of mainly "organic carbon" (which is cooling) with all of its own uncertainties makes

[3] If emitted close to snow or ice-covered areas, BC causes a different pattern of climate changes than if emitted far away from these surfaces.

[4] CCAC has 46 partner states (as of January 2015). See http://www.ccacoalition.org/.

the mitigation potential lower (Andreae and Ramanathan 2013, Bond et al. 2013). In this thesis, we focus on the warming climate forcers.

The knowledge around the climate impact of CH_4 is well established. The confidence level in AR5 for the direct RF of CH_4 is considered to be very high, while the certainty around the indirect effects is lower because of radiative forcing and chemical interaction uncertainties (Myhre et al. 2013). The indirect effects of CH_4 are the effect on stratospheric water vapour and on tropospheric O_3. The stratospheric water vapour forcing is estimated to be about 15% of the direct CH_4 forcing (Hansen et al. 2005; Myhre et al. 2007). Tropospheric O_3 has several precursors and is assumed to cause an additional 50% of the RF due to CH_4 (Myhre et al. 2013).

The confidence level for N_2O and SF_6 forcing, along with the other well-mixed greenhouse gases (see Fig. 1 for their estimated aggregated effect), is also considered very high (Myhre et al. 2013).

2.1 PAPER I: EMISSION METRICS AND SEA LEVEL RISE

Background and aim

Depending on the scenario[5] used in IPCC AR5, SLR in the 21st century is projected to "likely" fall in the range 0.26 – 0.97 m (Church et al. 2013). Higher estimates also exist[6], and even for temperature stabilization scenarios, more than half of the rise is still to come after that (Schaeffer et al. 2012; Levermann et al. 2013). Global warming causes SLR through melting of glaciers, ice caps and ice sheets, calving of ice shelves and through thermal expansion of seawater. However, large uncertainties remain regarding the different mechanisms' past and future contributions to SLR (Church et al. 2013). In Paper I, we focus on the thermal expansion part of SLR, which is projected to be about 30-55% of the total SLR until 2100 (Church et al. 2013).

In the paper, we define and analyse two new emission metrics based on the effect of emission pulses of climate forcers on global mean sea level: the Global Sea level rise Potential (GSP) and Integrated Global Sea level rise Potential (IGSP). GSP compares the SLR from an emission of a climate forcer to that of an equal-sized (in mass) emission of CO_2, at a chosen point in time after the emission (see Equations 4-5). IGSP has the same structure but instead compares the integrated (or cumulative) SLR of the different forcers up to a chosen time

[5] The scenarios are the RCPs (Meinshausen et al. 2011).
[6] The estimates from Church et al. (2013) are from process-based models. Semi-empirical models with larger uncertainty suggest SLR 2100 could come close to two meters (Vermeer and Rahmstorf 2009).

horizon (see Equations 6-7). A central question in our work concerns the persistence of SLR from emissions of different forcers and how that persistence compares with their atmospheric lifetimes and their temperature responses.

Developing these new SLR metrics is in line with the recommendation to the scientific community given by the IPCC "Expert Meeting on the Science of Alternative Metrics" in 2009 to: "develop metrics for policy targets other than limits to temperature change, such as the rate of temperature change, the integral change, and cost-benefit analysis approaches, or other climate variables" (Plattner et al. 2009). SLR is one such climate variable that could have vital consequences for society and impacted ecosystems (Lenton 2011; Sriver et al. 2012; Church et al. 2013). It is the only climate impact that received a dedicated chapter in the Working Group I contribution to AR5 (Stocker et al. 2013) but has not previously been used as a basis for comparing climate forcers.

Method

We define GSP as follows:

$$GSP_X(t) = \frac{AGSP_X(t)}{AGSP_{CO_2}(t)}, \qquad \text{(Eq. 4)}$$

where $AGSP_X(t)$ is the (Absolute) Global mean Sea Level Rise Potential due to a unit pulse emission of a climate forcer X, and t is the time after the pulse emission. The contribution to the thermosteric part of SLR, $AGSP_{th,X}(t)$, which we primarily focus on, can be formalized as:

$$AGSP_{th,X}(t) = \int_0^B \Delta \mathrm{T}_X(t,z) \cdot \alpha\big(z, \Delta T_x(t,z) + T_0(z), s(z)\big) dz, \qquad \text{(Eq. 5)}$$

where z, ocean depth, is 0 at the sea surface and B at the seabed; ΔT_X is the change of the ocean mean temperature at time t after an emission pulse of climate forcer X in year 0, and at depth z. α is the thermal expansion coefficient at depth z; T_0 is the unperturbed temperature at different depths; and s is effective salinity.

The IGSP metric is the time-integrated SLR, up to time *t*, caused by a unit emission pulse of a forcer divided by the time-integrated SLR up to time *t* caused by an emission pulse of CO_2 of equal weight. Hence, the IGSP is defined as:

$$IGSP_X(t) = \frac{AIGSP_X(t)}{AIGSP_{CO_2}(t)}, \qquad \text{(Eq. 6)}$$

where AIGSP is the time-integrated AGSP:

$$AIGSP_X(t) = \int_0^t AGSP_X(\tau)d\tau, \quad \text{(Eq. 7)}$$

We model and assess these metrics using the simple climate model (UD-EBM), presented earlier, to estimate the thermosteric SLR (see Fig. 3). The thermosteric SLR is calculated using the polynomial approximation of the equation of state for the density of water by Gill (1982).

Main findings

All of the examined climate forcers have long-term influence on the thermosteric SLR on the century to millenia time scales (see Fig. 4). Consider the following. The SLR_{th} of a climate forcer like BC is about 12% of its peak value 200 years after the emission, with an atmospheric lifetime of about a week for BC. In other words, we show that even SLCFs have long-lived climate impacts. SLR lasts for a long time even for SLCFs because of the great thermal inertia of the deep oceans.

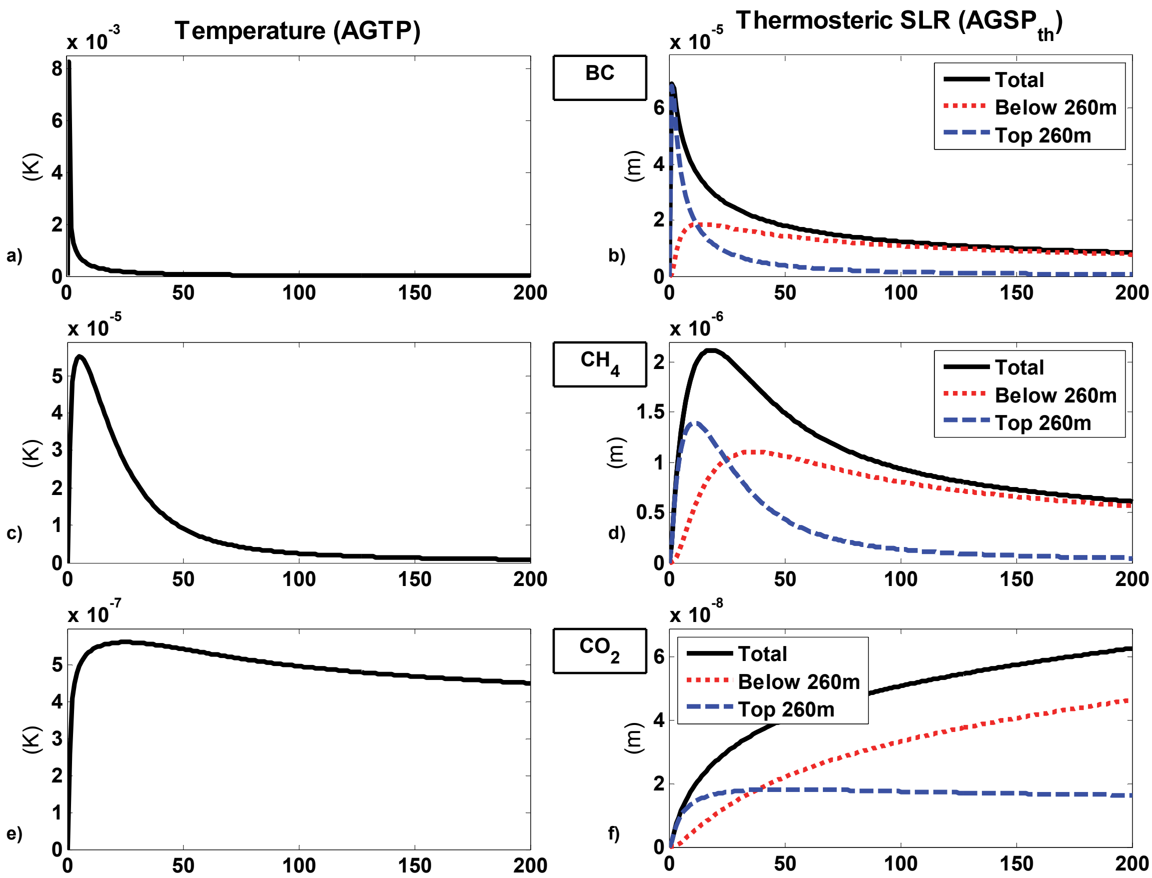

Figure 4. Annual global mean surface temperature changes (i.e. AGTP) and thermosteric SLR (AGSPth) following 1 Mt emission pulses of three of the forcers studied: a) & b) BC, c) & d) CH_4, e) & f) CO_2. The AGSPth figures on the right show the total rise as well as the contributions from the top 260 m and the deep ocean (below 260 m), respectively. Note the different orders of magnitude, for the different climate forcers, shown at the top of the y-axis.

When comparing the resulting metric values for a given time horizon and forcer, GSP_{th} lies in between the corresponding metric values obtained using GWP and GTP, whereas $IGSP_{th}$ ends up at the opposite end on the spectrum of compared metrics, compared to GTP (see Fig. 5). Further, we find that GTP < GSP_{th} < GWP < IGTP < $IGSP_{th}$ for all forcers studied, provided the time horizon used when estimating the metric is longer than the lifetime of the forcer. GSP is greater than GTP for the short-lived species (and for all species given sufficiently long time horizons), since the GSP depends on the temperature of the whole ocean, while GTP only depends on the surface temperature, and the surface temperature relaxes back to its unperturbed value faster than the average ocean temperature once the forcing of the surface has ceased.

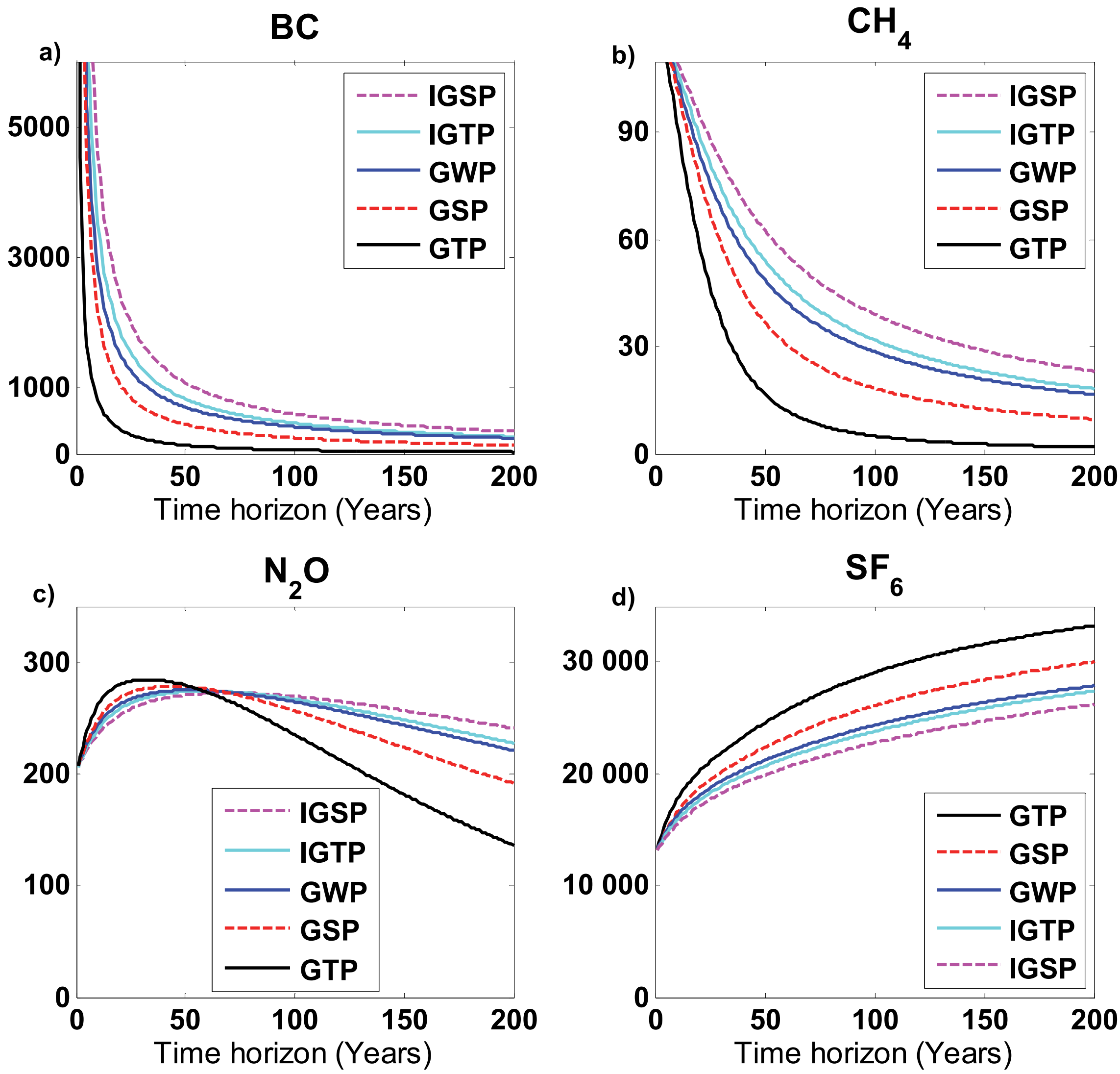

Figure 5. Comparison of metrics over different time horizons for a) BC (note that the y-axis has been cut for clarity), b) CH_4, c) N_2O and d) SF_6. The novel metrics have dashed lines.

We also use a Semi-Empirical (SE) model (Vermeer and Rahmstorf 2009) to estimate the full SLR, and corresponding GSP_{SE} and $IGSP_{SE}$, as alternatives to the thermosteric SLR analysis obtained with the UD-EBM. For SLCFs, the SLR is substantially higher in this case and GSP_{SE} is greater than GSP_{th} for all time horizons considered, while the opposite holds for long-lived GHGs such as SF_6. We find that $GSP_{th} < GWP < GSP_{SE}$ for SLCFs.

Finally, the choice of metric (GTP, GSP_{th}, GWP, IGTP, $IGSP_{th}$) is much more important for SLCFs than for long-lived greenhouse gases since SLCFs are most unlike CO_2 in their atmospheric lifetimes.

In deciding what emission metric to use, the analyst needs to choose both the climate variable to focus on and the time horizon to use. These choices — the choice of climate variable and time horizon — involve value judgments. Deciding what emission metric to use is primarily a political — not a scientific — decision.

2.2 Paper II: The climate-carbon cycle feedback's effect on emission metrics

Background and aim

One of the most significant positive feedbacks in the climate system is the Climate-Carbon cycle Feedback (CCF), which causes the biosphere and the oceans to take up less atmospheric CO_2 the warmer it gets (Arneth et al. 2010; Gillett and Matthews 2010; Ciais et al. 2013). In previous assessment reports by the IPCC, the CCF was only included for CO_2, but not for the non-CO_2 climate forcers, when calculating emission metric values (Forster et al. 2007). This inconsistency was addressed by the Working Group I contribution to AR5 (Myhre et al. 2013) by presenting metric values that included the CCF for all forcers except the SLCFs.

The aim of Paper II is to compare the use of the method suggested in Collins et al. (2013) and adopted by the IPCC in AR5 (Myhre et al. 2013) for including the CCF with that of a simple Coupled Climate-Carbon cycle Model (CCCM) that explicitly models the temperature feedback in the biosphere and the ocean parts of the carbon cycle. We then proceed to estimate GWP and GTP values for these two different approaches.

Method

The methodology used in this study shares many traits with that of Paper I. However, instead of developing new metrics and comparing them to existing ones, two different methods for including the CCF when calculating (A)GTP and (A)GWP are compared. A Linear Feedback Analysis (LFA) approach is used that corresponds to the method used by Collins et al. (2013) and the IPCC AR5 (Myhre et al. 2013). The other method is referred to as the Explicit Climate-Carbon cycle Feedback (ECCF) approach and utilizes the CCCM that explicitly models the mechanisms behind the CCF.

Building on the model of Paper I, we develop a CCCM by implementing and coupling a simple carbon cycle model to the UD-EBM (see Fig. 3). The ocean part of the carbon cycle is modelled as an upwelling-diffusion model (Jain et al. 1995), with a representation of ocean surface inorganic carbon chemistry according to Joos et al. (1996) and temperature dependence (i.e. the CCF of the ocean) of the CO_2 partial pressure of the surface water from Joos et al. (2001). The biosphere part of the model is from Siegenthaler and Oeschger et al. (1987), and its temperature dependence is based on a Q-10 approach (Harvey 1989); Friedlingstein et al. 2006). With the Q-10 approach, the turnover rates of carbon in detritus and soil (B_D and B_S in Fig. 3) increase with increasing temperature.

We calibrate the model to fit the global surface temperature and concentrations (of the greenhouse gases studied) to historical observations, using historical emissions and forcing data (Meinshausen et al. 2011).

Main findings

Both the LFA and ECCF approaches result in an increased atmospheric stock of CO_2, induced by the direct warming of non-CO_2 forcers (see Fig. 6). In general, the ECCF approach leads to stronger feedback in the short run, while in the long run the LFA shows a higher atmospheric CO_2 content. With the LFA approach, a fraction of the warming-induced CO_2 will stay in the atmosphere basically forever, causing the radiative forcing and temperature signal to persist past the 500-year time horizon analysed in the study (Fig. 7). In the case of the ECCF approach, the warming-induced atmospheric CO_2 relaxes back to zero after some time following the removal of the direct warming signal of the non-CO_2 forcer (Fig. 6 & 7).

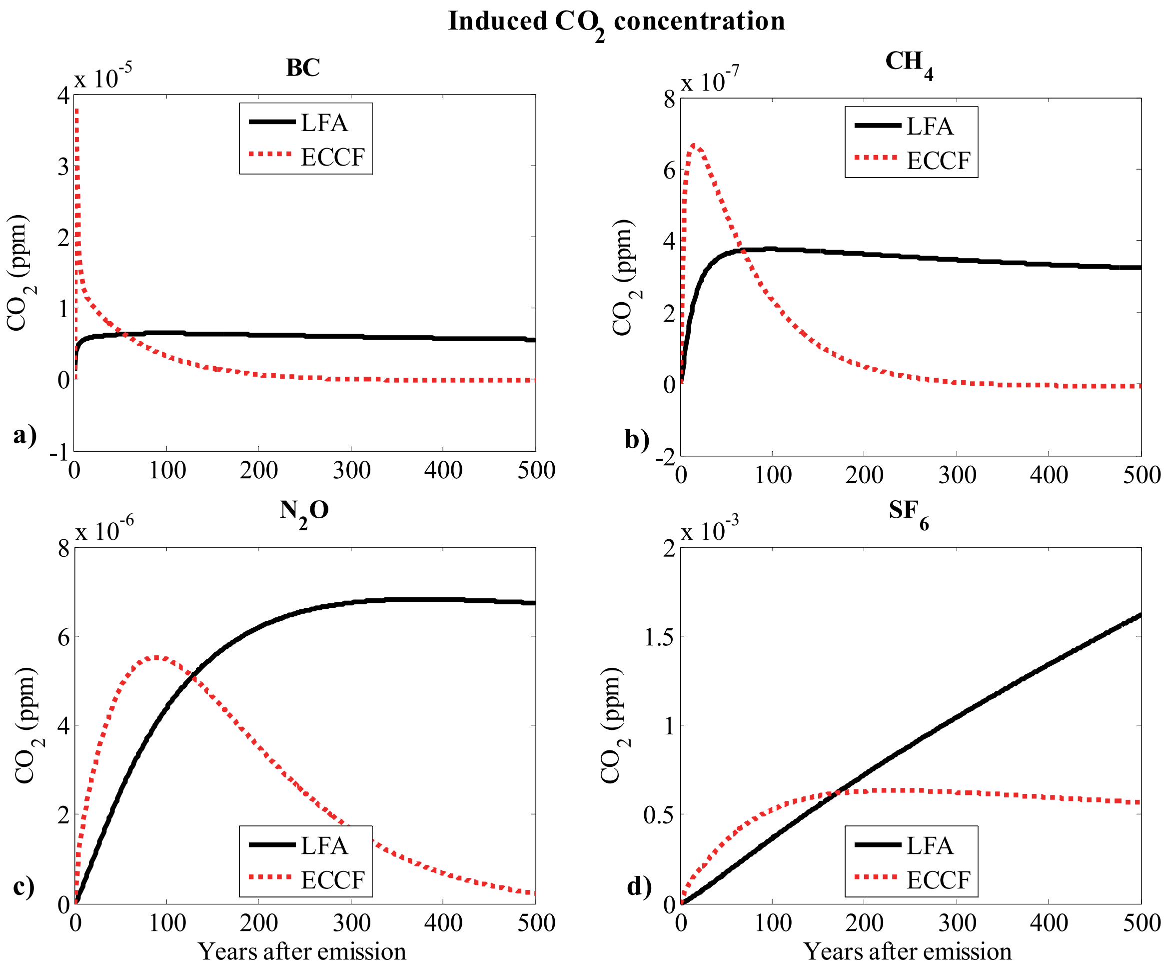

Figure 6. Comparison of the effect of the CCF on induced increases in CO_2 concentration with the LFA approach and the ECCF approach. The 1 Kt pulse emissions of BC in a), CH_4 in b), N_2O in c) and SF_6 in d) are emitted in 2015, and the background emissions and forcing are taken from the RCP4.5 (Meinshausen et al. 2011). Note the difference in the scales of the y-axes.

In figure 7 we compare the AGWP and AGTP values of three cases: without CCF and with CCF according to the LFA and the ECCF approaches. Both of the absolute metric values presented in figure 7 are higher in the case when CCF is included compared to when it is not for all the forcers studied, regardless of the CCF implementation (see Fig. 7). This is expected, as the additional CO_2 entering the atmosphere, caused by emissions of the non-CO_2 forcers through the CCF, contributes a positive radiative forcing (temperature) term to the numerator of Equation 1 (2).

As the climate forcer and the induced atmospheric CO_2 relax back to zero in the ECCF case, the AGTP values will also fall back to zero, albeit slower than in the case of no CCF. The AGWP, on the other hand, reaches a plateau at some final level.

In the LFA approach, the net CO_2 released to the atmosphere through the direct warming caused by the non-CO_2 forcer follows the average atmospheric perturbation profile of a standard CO_2 emission. This means it will end up elevating the atmospheric carbon stock and thus the AGTP will not relax back to zero, and the AGWP values of the non-CO_2 forcer will continue to grow forever.

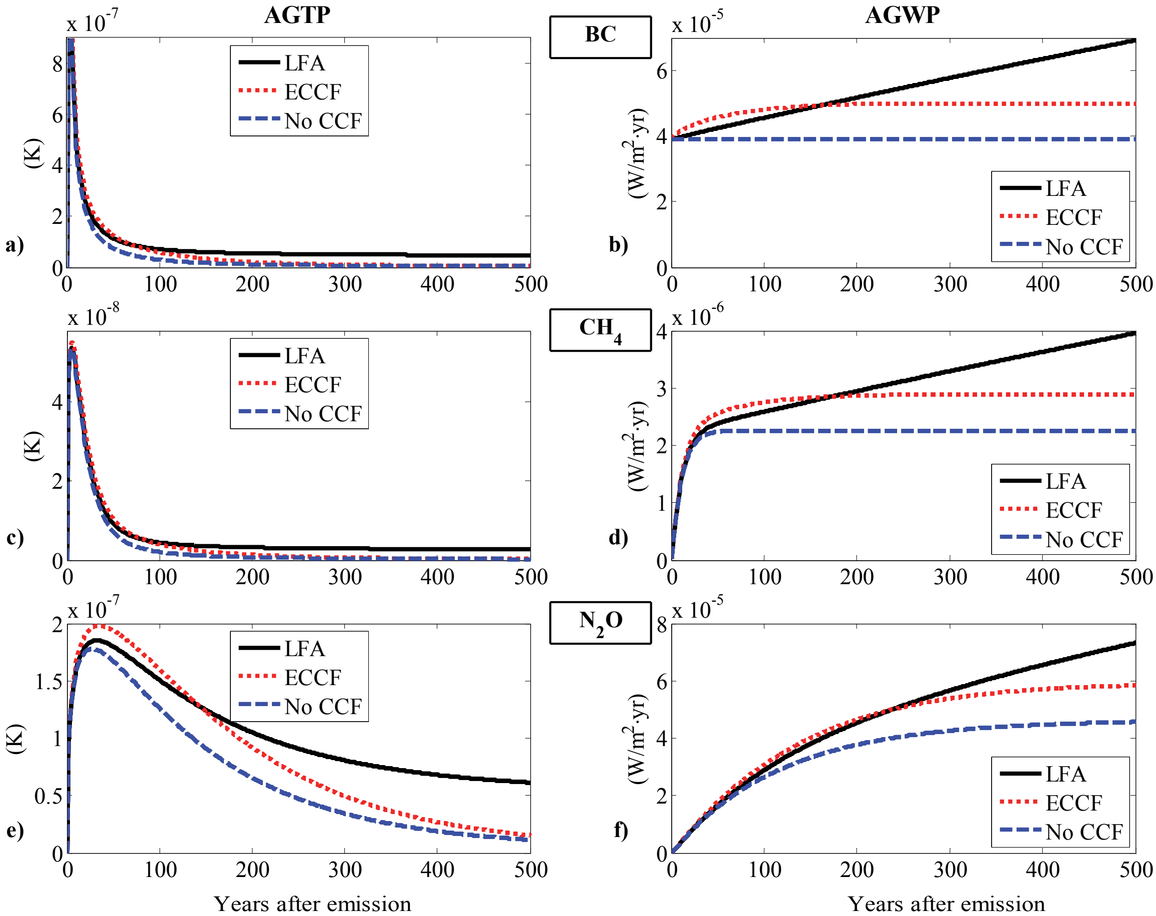

Figure 7. Annual global mean cumulative RF (AGWP) and annual global mean surface temperature changes (AGTP) following 1 Kt emission pulses of a) & b) BC, c) & d) CH_4, e) & f) N_2O for the three assumptions on CCF studied. Note the difference in the scales of the y-axes.

Table 1 presents the results of the different approaches for the final GWP values for the different forcers and commonly discussed time horizons. The effect on the values decreases in relative terms with increasing forcer lifetime (i.e. BC values are affected most and SF_6 values least).

Table 1 Comparison of metrics for different climate forcers using the two CCF approaches: **ECCF** – CCF according to the ECCF, **LFA** – CCF according to the LFA.

Time Horizon / Climate Forcer	Carbon Cycle Feedback	20 years	100 years	500 years
BC	**ECCF**	1,960	612	166
	LFA	1,840	581	230
CH_4	**ECCF**	93	35	9.6
	LFA	88	33	13
N_2O	**ECCF**	349	392	194
	LFA	334	368	243
SF_6	**ECCF**	21,400	32,600	43,900
	LFA	20,500	30,600	49,000

3 PAPER III: SPATIAL-TEMPORAL MODELING OF NON-COOPERATIVE RESOURCE EXTRACTION: AN APPLICATION TO FOREST MANAGEMENT

Background and aim

Forest degradation causes carbon releases, decreases ecosystem service production, and is intricately linked to the well-being of local inhabitants. Protected areas and Reducing Emissions from Deforestation and Degradation (REDD) policies can inadvertently create leakage that affects the net effectiveness of the policies at the landscape level. This study develops and analyses a spatially explicit landscape model of a group of independent villagers engaged in forest extraction. It analyses a spatial Non-Cooperative Equilibrium (NCE) of extraction patterns and compares it to a coordinated equilibrium (referred to as the Social Planner Equilibrium, SPE) for a range of different landscapes and model assumptions.

This work has been performed in collaboration with co-authors E.J.Z. Robinson, at the University of Reading, and H.J. Albers, at the University of Wyoming. In earlier work Robinson et al. (2002, 2008, 2011, 2014) and Albers et al. (2007, 20010, 2011) have investigated the implications of different forest management policies on forest extraction patterns and ultimately on the status of forest reserves and the forest-related revenue of local villagers. These earlier studies have made different kinds of simplifying assumptions, such as using a representative villager or only extracting in one location. The aim of paper III is to develop a model with which to examine how several of these commonly used modelling assumptions affect the predicted spatial degradation patterns.

Method

We construct a model that allows for multiple agents (i.e. villagers) to behave differently when facing the same spatial labour allocation choices (such as from where, and how much, to extract) but taking into account what the other villagers are planning to do. The villagers can choose to extract from one of three rays of forest patches radiating from the village (Fig. 8). On a given ray, the villager can choose to extract from one or several forest patches. This forest extraction labour can optionally be complemented with Non-Forest wage Work (NFW).

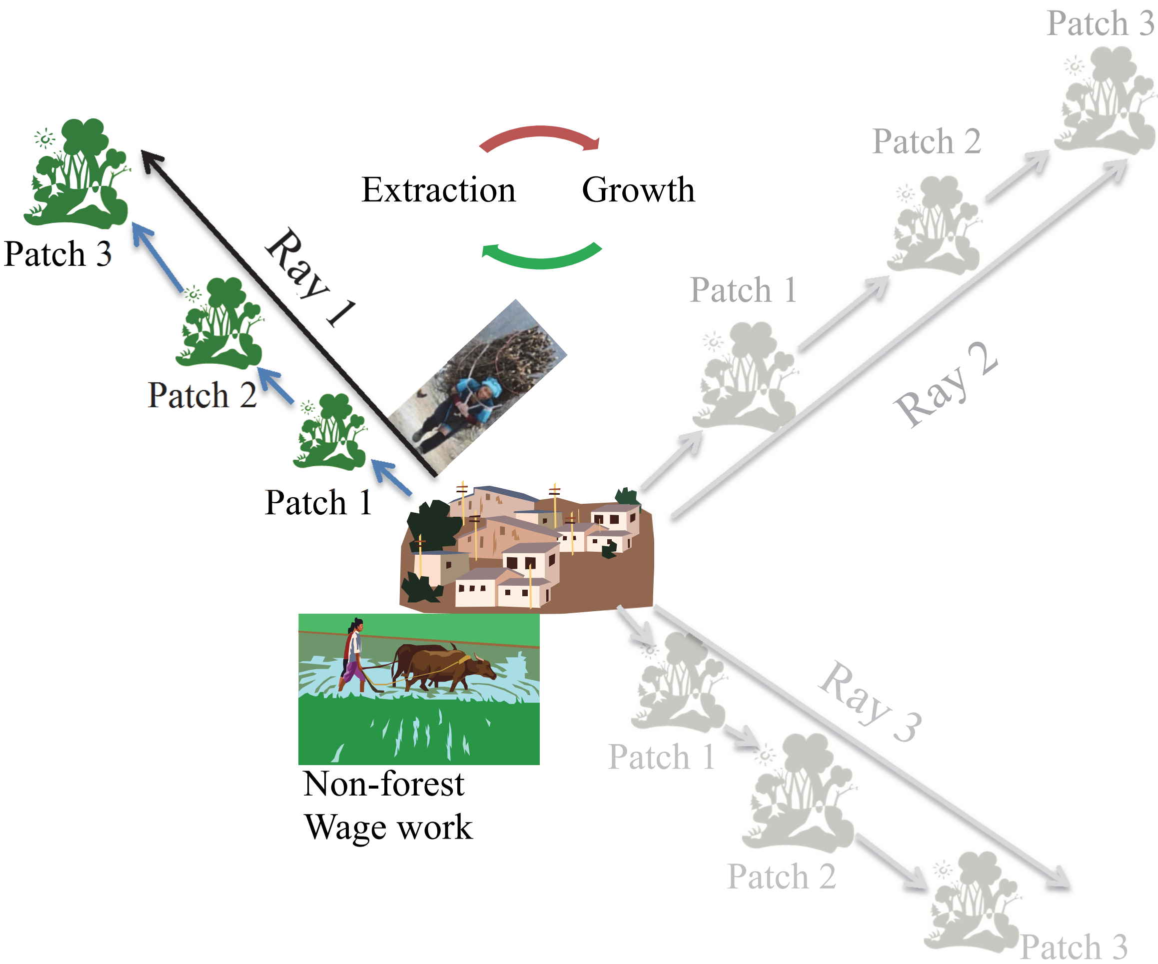

Figure 8. A schematic illustration of the model. Note that it supports up to three rays but most simulations presented in paper III focus on one ray only (hence the focus on one ray here).

This is an agent-based model, which is used to find a labour allocation scheme constituting a Nash equilibrium[7] for the villagers' labour allocations. This procedure, containing an extraction (or harvest) function and a wage function for the NFW, is combined with a logistic growth function used to calculate the amount of regrowth following the extraction of a generic non-timber forest product by the villagers. The first part of the model's procedure is then iterated over time, but in the subsequent time step, the villagers base their decisions on the new level of the resource stock. This is then iterated until a steady state is found in which no significant changes occur.

Main findings

We find that a priori identical agents choose to behave differently in both types of equilibrium, NCE and SPE, for the majority of conceivable spatial forest landscapes. We show that several categories of villager types emerge (see Fig. 9). Some specialize on a patch close or further

[7] In terms of spatial distribution of resource extraction and NFW per villager, which no villager would gain by deviating from.

away from the villager while others spread their time among several patches and NFW. In Figure 9a-c, the distance, d, between the patches varies from small[8] to large. The resulting villager types turn out to be highly dependent on the distance parameter (see Fig. 9). This in turn has consequences for issues concerning equity and forest degradation patterns.

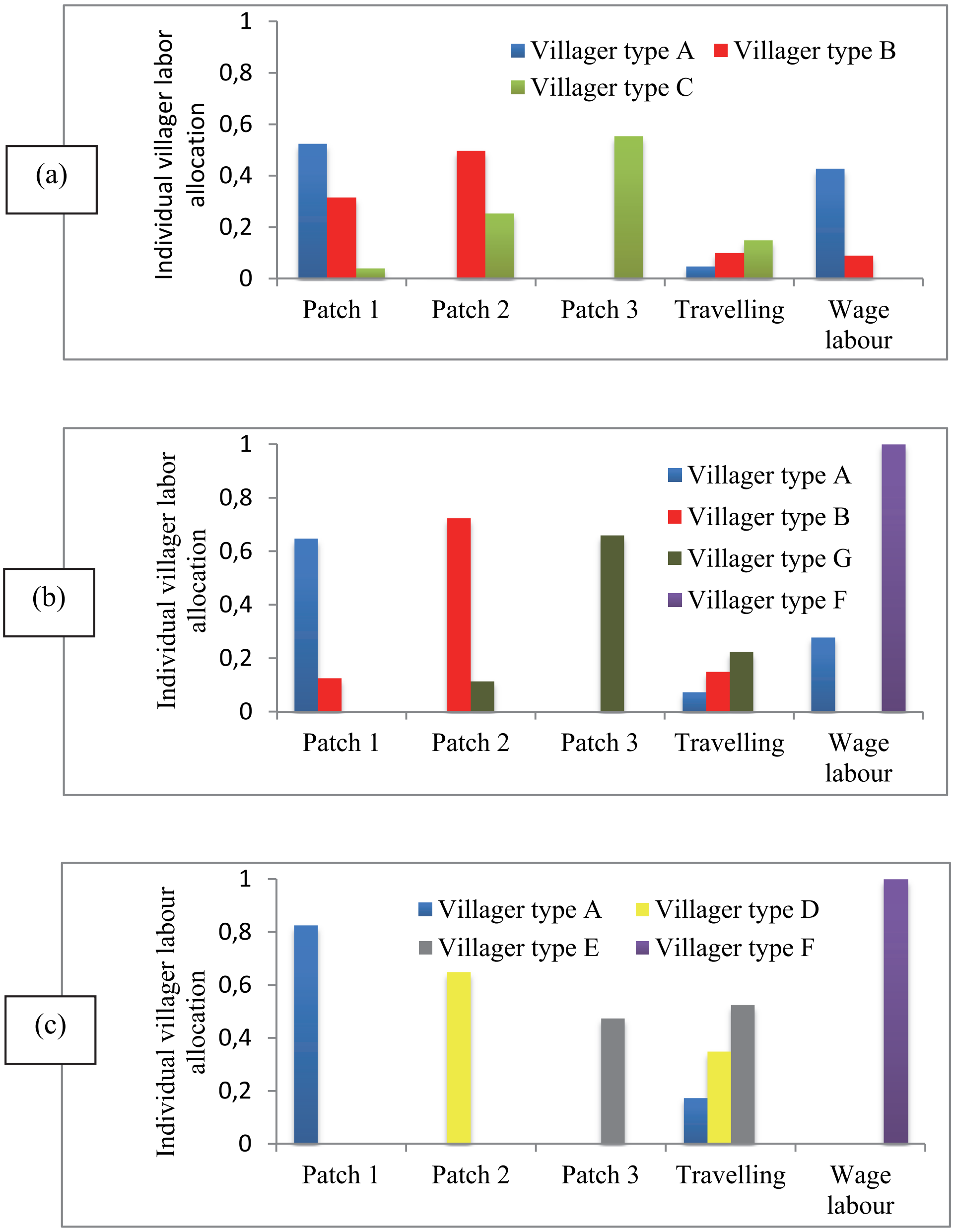

Figure 9 a-c. Long-run predicted labour allocations when distance costs are (a) small (d=0.05), (b) medium (d=0.075), and (c) large (d=0.175), NCE with NFW available. Note that these figures only illustrate the villager types, not the total labour time.

[8] The distance d=0.05 corresponds to travelling 5% of full-time labour (see fourth column of Fig. 9).

When comparing the two institutional arrangements of the NCE and the SPE for a range of distances between patches, we find that more forest degradation occurs in the NCE case (see Fig. 10), given that NFW is available. In the SPE, the majority of the villagers will do NFW, and the rest will specialize fully on one patch per villager to extract from.

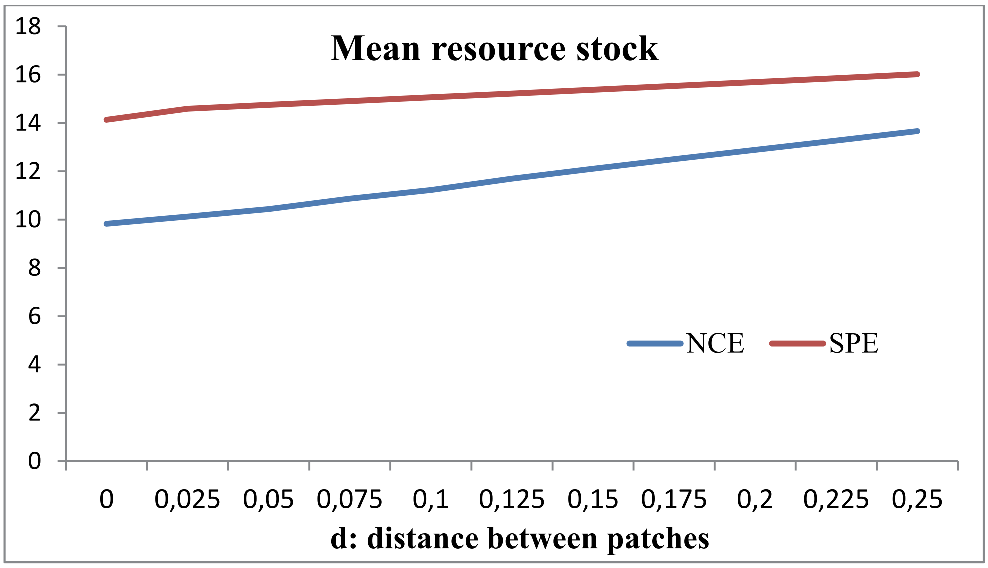

Figure 10. Impact of varying distance between patches on the total resource stocks in equilibrium, when NFW is available. Blue represents the non-cooperative equilibrium and red the social planner equilibrium. Note that the total carrying capacity is 18 units.

4 OUTLOOK

Having constructed, tested, and applied the simple coupled climate-carbon cycle model of Paper II, we now see several interesting possible applications. For example, the model could be used to assess the historical climate debt of different nations given different estimates of the forcing of short-lived climate forcers typically not included in studies, providing relevant and interesting input to future climate negotiations.

If emission metrics are a step on the path toward bringing climate change closer to policymakers, then what might the next step be? How do I make the research I am involved in accessible to a wider audience?

The type of research in Papers I and II and in related studies can be made more accessible by developing pedagogical online models for comparison and visualization of different metrics and the effect of using different metrics.

Likewise, presenting the research insights of Paper III through accessible materials available to those who manage forests in areas with low-income populations and on-going forest degradation through extraction should increase the impact of that research. This is especially relevant for a possible follow-up study to Paper III using the same model to study the effects of leakage due to different forest management schemes.

Finally, a wider audience can also be reached within the research community itself by initiatives that present research results in ways that go beyond conventional modes of publication.

The potential for reaching a wider audience is multi-dimensional and substantial.

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