THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Climate Change:
Models, Metrics and Meaning Making

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CHALMERS

Department of Space, Earth and Environment
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Cover:

The many fruitful ways to look at climate change knowledge.

Illustration By Erik Sterner with graphical contributions by Sofia Toivonen.

Back:

Drawing of me – Erik – while I analyse data from an interview (for paper IV), by my dear mother – Lena Sterner Persson. In addition a popular science description of the thesis.

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ABSTRACT

This thesis, combining research in climate science and educational science, investigates different aspects of climate knowledge. It consists of five papers and covers three major topics: emission metrics, public understanding of atmospheric CO_2 accumulation, and spatial modelling of natural resource use.

In Paper I-II, we study emission metrics that compare the climate impact of different climate forcers in two different ways. For Paper I, we use Sea Level Rise (SLR) as the basis for comparison, proposing two novel emission metrics. We find that all examined climate forcers – even short-lived – have considerable influence on SLR on at least a century time scale. Paper II focuses on how the Climate-Carbon cycle Feedback (CCF) affects emission metric values, in relation to how the CCF caused by non-CO_2 forcers is modeled. For emission pulses, we show that with an approach previously used to calculate climate metrics using linear feedback analysis for the CCF, the effect of it will persist basically forever, while with an approach based on an explicit carbon cycle model, the CCF effect by non-CO_2 forcers eventually vanishes, leading to lower metric values for longer time-horizons.

Paper III-IV, related to climate science literacy, focus on public understanding of atmospheric CO_2 accumulation and its potential link to climate policy support. In Paper III, we identified five qualitatively different ways of reasoning about CO_2 accumulation; only one of these is consistent with mass balance principles. We also found that task formulation has a strong bearing on the assessment of understanding, but that strong climate policy support does not require that people can solve typical CO_2 tasks. In Paper IV, we draw attention to a range of challenges that university students experience when reasoning about CO_2 accumulation, ranging from cognitive to metacognitive and affective challenges. Most notable for the cognitive domain was the failure to understand how uptake of CO_2 depends on emission pathways.

In Paper V, we model low-income villagers' spatial natural resource use while removing constraining assumptions on villagers' behaviour. We find that removing commonly used constraints lead to higher degrees of heterogeneity among villagers' spatial behaviour, especially for intermediate distance cases.

Keywords: Emission Metrics; Sea Level Rise; Short-lived Climate Forcers; SF Failure; Carbon Cycle; Climate Science Literacy; Knowledge-Behavior Gap; Integral Theory; Common Pool Resources; Resource Extraction

To my beloved family for everything you are

&

to my love – Elin – and the future we are creating together

List of Publications and Contribution Report

I. Sterner Erik, Johansson Daniel JA, Azar Christian, "Emission metrics and sea level rise". Climatic Change 127:335–351.
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 derived the analytical findings. ES wrote the paper with contributions from DJ and CA.

II. Sterner Erik O, Johansson Daniel JA, "The climate-carbon cycle feedback's effect on emission metrics". Environmental Research Letters 12.3 (2017): 034019.
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 O, Adawi Tom, Persson U Martin, Lundqvist Ulrika, "All tasks are not created equal: Investigating understanding of atmospheric CO_2 accumulation". *Under review in Climatic Change.*
ES posed the idea with contributions from TA. ES, TA, UL and UMP made the literature review. ES made the design with contributions from TA and UMP. ES performed the data collection. ES and UMP made the analysis with contributions from TA. ES and TA wrote the manuscript with contributions from UL and UMP.

IV. Sterner Erik O, Adawi Tom, Lundqvist Ulrika, Persson U Martin, "Challenges experienced by engineering students when dealing with tasks related to atmospheric CO_2 accumulation". *Draft manuscript, to be submitted to Environmental Education Research*
ES posed the Idea with contributions from TA. ES and UL made the literature review. ES made the design, performed the data collection and the analysis. ES wrote the manuscript with contributions from TA, UL and UMP.

V. Sterner Erik O, Robinson Elizabeth JZ, Albers Heidi J, "Location choice for renewable resource extraction with multiple non-cooperative extractors: a spatial Nash equilibrium model and numerical implementation". Letters in Spatial and Resource Sciences (2018): 1-17.
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.

OTHER RELEVANT PUBLICATIONS

Sterner, Erik, Hagvall Svensson Oskar, Toivonen Sofia, Bill Jim, Adawi Tom, "Evaluating the flipped classroom approach in engineering education: Students' attitudes, engagement and performance in an undergraduate sustainability course." 45th SEFI Conference preceeding, 18-21 September 2017, Azores, Portugal.

B White, HJ Albers, EJZ Robinson, and E Sterner, "Positioning Parks and Enforcement in the Presence of Spatial Ecosystem Service Production Functions and Multiple Non-Cooperative Extractors." 6th WCERE Conference preceeding, 25-29 June 2018, Gothenburg, Sweden

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My colleagues at my second home at Chalmers, EER colleagues – Christian, Jens, Malin, Elisabeth and Sheila Galt, former EER colleagues Patric Wallin and Johanna Lönngren who in different ways have paved the way for the type of work that I'm doing. My co-authors for Paper V: Elizabeth Robinson and Jo Albers. Intize (Lucas, Viktor, Olov, Farid, Hoda, Suvi, Johanna, Eskil, Martin, Karin, Oskar, Nico, Johan, Felix, Fredrik, Maria etc), and all people at Chalmers (and Gothenburg University) who have given me their support and believed in my ideas and the ideas and engagement of Intize – Samuel Bengmark, Torbjörn Lundh, Mats Lundquist, Ulf Petrusson, Michael Christie, Mia Knutson Wedel, Sven Engström, Lennar Lundgren etc.

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Erik Sterner

Göteborg, Oct, 2018

PREFACE

I've been curious about three aspects of reality that come together in this thesis: how nature works at the big scale, what role humans play in the Earth system and especially how we understand and learn about it. I've thought about learning ever since I started helping my classmates—and later my students—in their struggles with mathematics, I've been fascinated by the art of taking the perspective of the other, asking myself: what would make sense if I reasoned like you seem to do, and attempting to take it from there.

Hence learning and its facilitation lie close to my heart. For the topics I've grown interested in, there has often been a common thread to what learning activities I find especially rewarding, and this is modelling. Looking back, I realize that the combination of different forms of modelling has been very useful for my learning and as a teacher I've seen what it can do for my students. Lately I've realized the importance of what can be called *mental* models – or the lack thereof – in my research on understanding aspects of people's *types of knowledge* and *ways of reasoning* (Papers III-IV).

Climate emission metrics (Papers I & II) is a type of model that describes the relationship between the climate impact of emissions of for example methane and carbon dioxide. This is an interesting type of model that highlights an important aspect of modelling. On the one hand – it is perfectly clear what type of knowledge it conveys (relative climate impacts for different emissions) – but on the other hand, it is based on a massive body of knowledge about the climate system that the metric purposely hides. I find this both useful and problematic at the same time. It all depends on: who is to use the model, those peoples' understanding of the climate system and the model, and the application of it.

Access to and use of wisely chosen models and information seems to me – in the Anthropocene (i.e. the current epoch when humans are the, or one of the major, decisive factors for the evolution of life on Earth) – as a key issue for guiding us towards a sustainable development. It has dawned upon me that we are witnessing not only a big change in human influence on the natural world, but also of our view of the natural world. This used to be shaped by experts (e.g. scientists), but for some time now, who has the final say on such matters has been changing. As scientist, I feel that it is worth reflecting on that most people listen not to "experts" but rather to the "interpreters of the experts", whose role is to try to make sense and meaning of what the experts are saying (Newman 2017). In a time of information over-flow it seems that the human intellect prefers to listen to people who can make sense of our world (or perhaps the fraction of it that we experience) in a way that suits us. A recent study showed that the major focus of the most popular tweets after the release of a recent climate report focused on *public understanding of the climate science* rather than the actual climate science itself (Newman 2017).

Let me end this combination of the description of my interests and a miniscule analysis of our times with an observation that: the IPCC's Special Report on Global warming of 1.5 degrees show that scientists and other knowledgeable experts have ramped up their appreciation for the importance of engaging more actively in the sense- and meaning-making processes that seem to shape our world – to a perhaps even greater extent than our knowledge of it. This observation was echoed in a recent interview with Bruno Latour in the New York Times (Kofman 2018) in which he applauds such efforts and reflects on how we can understand and meet climate sceptics.

GLOSSARY & ABBREVIATIONS

IMPORTANT CONCEPTS (ALPHABETICAL ORDER)

Abatement & mitigation: Mitigation refers to human intervention to reduce the sources or enhance the sinks of greenhouse gases, while adaptation refers to measures that reduce the vulnerability of natural and human systems.

Climate forcer: factor that affect the Earth's radiative balance (and hence the climate), in this thesis designated to refer to human caused such factors – for example emissions of greenhouse gases and climate active aerosols.

Climate impacts (or climate effects, in Chapter 3): Refers to any of a number of pre-cursors to – or indicators of – human caused climate change.

Climate science literacy refers to an understanding of your influence on climate and climate's influence on you and society.

Emissions of CO_2 (or emissions, or CO_2 emissions): shorthand for net CO_2 which mainly come from the use of fossil fuels and land use change (deforestation, etc).

Epistemology is the philosophy of knowledge or how we come to know.

Knowledge comes in various forms, including declarative, procedural and situational.

Literacy refers to basic knowledge in a specific area including a basic understanding of the methods used to acquire that content knowledge.

Long-lived climate forcer: climate forcers that stay for a long time in the atmosphere, such as CO_2 and halogenated gases.

Metric or emission metric: a measure that quantifies a specific climate impact of a given climate forcer over time – either in an absolute sense or in a relative sense, which in that case is relative to that of CO_2 – for example Global Warming Potentials.

Metacognition involves thinking about one's own thinking: monitoring and regulating thinking processes.

Short-lived climate forcer: climate forcers that stay for a short time in the atmosphere**,** such as methane, tropospheric ozone and aerosols.

Uptake of CO_2 (or uptake) is short for the net flow from the atmosphere into the oceans and the biosphere. The main uptake is that of the oceans due to an air-sea gas exchange primarily controlled by the air-sea difference in gas concentrations, in which CO_2 reacts with water to form carbonic acid and its dissociation products.

COMMON ABBREVIATIONS

AGTP	Absolute Global Temperature change Potential
AGWP	Absolute Global Warming Potential
BC	Black Carbon
CCF	Climate-Carbon cycle Feedback
CCCM	Coupled Climate-Carbon cycle Model
CH_4	Methane
CO_2	Carbon Dioxide
CSL	Climate Science Literacy
ECCF	Explicit Climate-Carbon cycle Feedback
ERF	Effective Radiative Forcing
GTP	Global Temperature change Potential
GSP	Global Sea level rise Potential
GWP	Global Warming Potential
IGSP	Integrated Global Sea level rise Potential
IPCC	Intergovernmental Panel on Climate Change
LFA	Linear Feedback Analysis
RF	Radiative Forcing
SE	Semi Empirical
SF	Stock Flow
SLCF	Short-Lived Climate Forcer
SLR	Sea Level Rise
UD-EBM	Upwelling-Diffusion Energy Balance Model
UNFCCC	United Nations Framework Convention on Climate Change

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1 INTRODUCTION

1.1 FROM MODELLING AND METRICS TO MEANING MAKING

The present thesis is a somewhat unusual thesis as it combines research in climate science and educational science. In this section, I[1] will first provide a thumbnail sketch of the overarching theoretical perspective of this cross-disciplinary thesis. This is followed by a brief description of my PhD journey, with a focus on introducing the research problems and each of the three topics in the thesis title: “From *modelling* and *metrics* to *meaning making*”.

1.1.1 An integral approach

The overarching theoretical perspective of this thesis is drawn from what has become known as *integral theory* (Esbjörn-Hargens 2010). As explained by Ken Wilber (cited in Esbjörn-Hargens 2010, p. 33):

> *The word integral means comprehensive, inclusive, non-marginalizing, embracing. Integral approaches to any field attempt to be exactly that: to include as many perspectives, styles, and methodologies as possible within a coherent view of the topic. In a certain sense, integral approaches are “meta-paradigms,” or ways to draw together an already existing number of separate paradigms into an interrelated network of approaches that are mutually enriching.*

An integral approach is particularly germane for sustainability issues, such as climate change and use of natural resources. As these issues are deeply embedded in both our societies and natural world, an integral approach is important to not lose insights from different fields, but instead let insights from various perspectives enrich each other (Esbjörn-Hargens 2010). Or, as O’Brien (2010, p.65) puts it:

> *Climate change is now recognized as one of the most challenging and complex problems facing humanity—the problem is real, the stakes are high, and there is no single “solution”. […] It is becoming increasingly clear that fragmented research, as well as interdisciplinary research that is limited to one particular paradigm, based on one worldview, or limited to one way of knowing, is unlikely to be sufficient to meet the challenges of climate change.*

1.1.2 Modelling

To learn about the climate system as well as about the natural resource use of poor villagers, I have used modelling as a central tool in my scientific inquiries. In fact, investigating phenomena of interest through modelling was my way into science.

[1] In Sections 1.1, 1.6, Chapter 2 and 7, I purposefully use first person active voice when the message of a statement describes my personal experiences or opinion. I do this since I believe that the overall message of parts of this thesis benefit and because these are my opinions, experiences or reflections and should be regarded as such, and not be confused with the scientific material that is the major part of the thesis.

Models are powerful tools in several important regards (Epstein 2008). They can be used to become familiarized with a system, a selected phenomenon and mechanisms that are of importance for that phenomenon. The process of isolating a phenomenon, making simplifications, setting the system boundaries, identifying the necessary components, appreciating the important characteristics of those components and relationships between them (mechanisms), are all important parts of modelling (Gerlee & Lundh 2012; Seidl 2017).

A computer model can perform millions of calculations in no-time. This can be compared with the tedious effort of doing tens of thousands of calculations by hand, as Arrhenius did (taking a full year) in the beginning of climate science, in order to estimate the sensitivity of climate to increased carbon dioxide (CO_2) concentrations (Arrhenius 1896). With the help of computer models, we can investigate what would happen at a macro (as well as micro) scale as a result of relationships between objects that interact at different distances, since the necessary calculations can be performed automatically in no-time. We can also study processes that occur over very different time scales of interest to us.

But there are also downsides and limitations to models and modelling (e.g. Winsberg 2012; Baumberger et al. 2017). I will not try to describe all weaknesses of models and modelling, but instead mention two that are important for the work in this thesis. First of all, what models can do on the quest to new knowledge is totally dependent on what knowledge and assumptions that go into the model, how the model is constructed, and how it is used. Second, models can be misleading or deceiving if trusted blindly or if used with a hidden agenda (e.g. Stern 2016).

I agree with Epstein (2008, p.1) who argues that we are all modelers, it is just that typically we use "an implicit model in which the assumptions are hidden, their internal consistency is untested, their logical consequences are unknown, and their relation to data is unknown". In this sense, modelling, albeit not always numerical modelling, is a tool that is used and a theme running through all studies in this thesis.

1.1.3 Becoming a climate scientist and appreciating atmospheric accumulation of CO_2

During my PhD studies, I was first involved in research on comparing different climate forcers (substances) and comparing them on a common scale (Sterner 2015). Due to the different life times of the forcers, this meant that I was practically comparing some climate forcers that accumulate in the atmosphere with others that don't.

My work on climate forcers was based on simple (numerical) modelling that attempts to capture the global average temperature, the energy balance (mainly the heat flows into and out of the ocean), and the carbon cycle, on a very aggregated level. Conducting the studies in Paper I and II, taking courses on the earth systems science and earth system modelling, and being part of creating and teaching a course on environmental mathematical modelling, meant that I became familiar with climate science and modelling environmental systems. I started realizing how advanced the climate scientists' understanding of causes, effects and required remedies to climate change are. Naturally, I compared this understanding with my view of what is common knowledge about climate change among the public, what policies are in place, and what climate-related behaviour that seems to dominate our world. *What dawned upon me was an overwhelming feeling that we are heading the wrong direction*[2]*, and that there seems to be a major gap in understanding related to climate change between scientists and most non-experts* (Moser & Dilling 2011). At the very centre of this realization was the very message that Figure 1 tries to capture – the emission trajectory for the last 50 years followed by the estimated required emissions reductions ahead to be able to meet a 1.5 degree warming target.

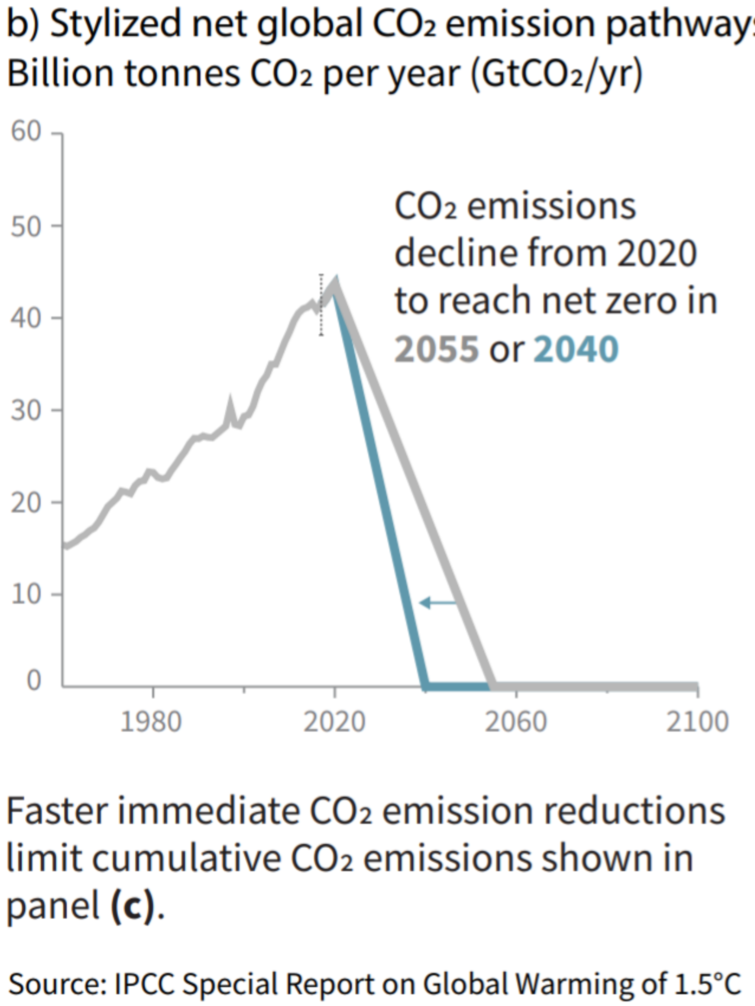

Figure 1 This figure shows the dramatic (to say the least) emissions reductions needed in order to reach the 1.5 degree temperature target analyzed recently by the Intergovernmental Panel on Climate Change (IPCC). In blue:ish color is a stylized scenario of the more stringent emissions reductions needed if no changes are assumed regarding other climate forcers, while in gray is a less radical but still immediate and stringent stylized emission scenario under the assumption that substantial efforts are out into reducing non-CO2 climate forcers as well.

[2] This is a value judgment I make as a world citizen, not as a scientist, based on what expected climate impacts I want to avoid.

To understand why global emissions of CO_2 needs to be reduced to this extent in order to meet a 1.5 degree warming one needs to understand several steps in the cause and effect chain of climate change. But to make sense of the need to go down to zero emissions it suffices to acknowledge that CO_2 causes warming (Arrhenius 1896) and that CO_2 accumulates in the atmosphere. To appreciate to what extent CO_2 accumulates in the atmosphere I include Figure 2 from Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5) – which show that CO_2 emissions cause elevated levels of CO_2 that last for millennia. Perhaps because I had not seen any figure that resembled this or perhaps because I was not ready to understand the message of that image, the meaning of how long lived the climate impact of CO_2 is became truly clear to me only after a couple of years as a climate modeller.

One of the clearest ways to illustrate what these first two graphs tell us and in which direction humanity is heading climate-wise, is in terms of a carbon budget (Allen et al. 2009; Le Quéré et al. 2017). The carbon budget expresses how much emissions the world can likely emit[3] and still meet a chosen climate target. This is hence another way of framing the information in Figure 1. If the two-degree target from the Copenhagen accord and the Paris Agreement is used (Paris Agreement 2015), with the assumption that emissions stay at the average level of the last five years, the budget will run out in about two decades (Friedlingstein et al. 2014). And if we were to try to meet the more stringent 1.5 degree target, the net CO_2 emissions needs to be approximately halved each decade from now, see Figure 1, meaning that we will likely have to develop and use climate change counteracting geoengineering on large scale to be able to meet that target (Akimoto et al. 2018). As a consequence of this realization, I felt compelled to redirect my efforts towards the quests of *how to engage people around the world in climate change learning and how to close the knowledge-behaviour gap that defines our world today* (McCaffrey & Buhr 2008; Moser & Dilling 2011; Wibeck 2014). This meant that I re-directed my research focus towards how people understand the physics of climate change[4].

[3] The exact amount of emissions depends on how sensitive the climate system is to the energy imbalance that increased amounts of CO_2 induces and what happens with the emissions of other substances that affect the climate (both warming and cooling).

[4] To be clear, I appreciate that such an understanding does not necessarily determine people's behavior in relation to climate change, as discussed later on in this thesis.

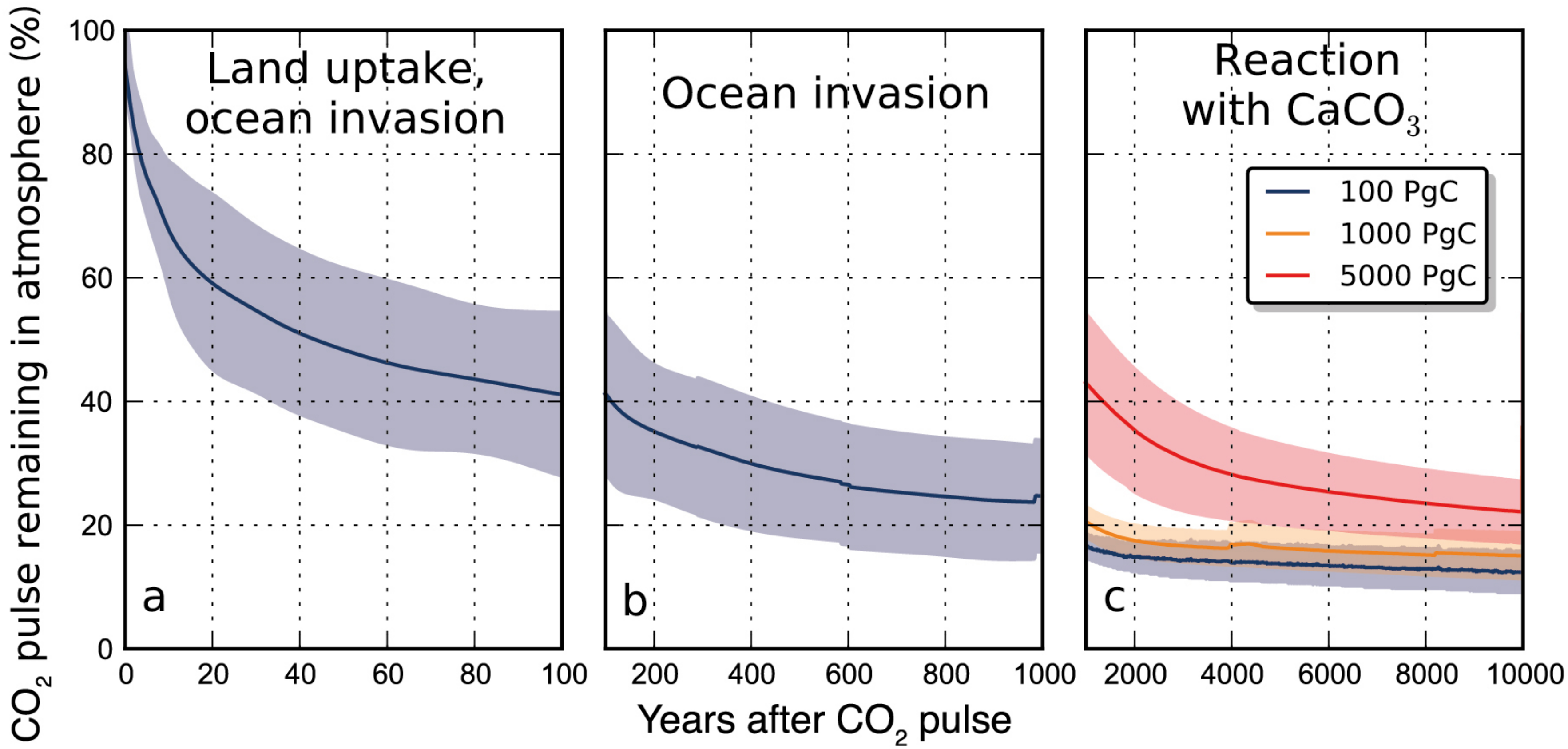

Figure 2 Graph showing a central concept in this thesis – the carbon remaining in the atmosphere over 10,000 years – following a pulse emission in year 0. Isn't it hard to grasp the long-lived impact of CO_2 emissions? Source: AR5 IPCC, Box 6.1 Figure 1 (Ciais et al. 2013).

During this transitional period, my previous supervisor and mentor, Christian Azar, sent me an interesting study showing that most people, even budding scientists and engineers, have a poor understanding of atmospheric CO_2 accumulation (Sterman 2008). This phenomenon, the poor understanding of the relationship between stocks and flows, is in the literature known as *stock-flow (SF) failure* (Cronin and Gonzalez 2007; Cronin et al. 2009; Fischer et al. 2015). According to Sterman and Booth Sweeney (2007), this is tantamount to not understanding the relationship between inflow, outflow, and the amount of water in a bathtub. It has also been suggested that there is a connection between SF failure in a climate context and climate policy support (Sterman & Booth Sweeney 2007; Sterman 2008; Chen 2011; Dutt & Gonzalez 2013; Weinhardt 2015).

I became both surprised and curious about this widespread poor understanding of atmospheric CO_2 accumulation. If the vast majority of people has difficulties understanding accumulation, how difficult must not greenhouse gas metrics and understanding how they are affected by the assumptions that go into them be? After all, the difference between short-lived and long-lived climate forcers, compared using emission metrics, hinges on whether they accumulate or not.

I therefore decided to take a closer look at the previous work on SF failure in general and in a climate context in particular. It soon became clear that most of this work used a quantitative research approach, providing little insight into how people actually reason, or what challenges they experience, when dealing with the types of tasks used in previous studies. Moreover, previous studies on SF failure have mainly focused on the cognitive side of problem solving, overlooking the role of both metacognition and affect. These *blind- or blank spots* (Wagner 1993) in previous work call for a more *qualitative* research approach, focusing on *meaning making* (Krauss 2005).

Furthermore, people's understanding of atmospheric CO_2 accumulation was, in the SF literature, measured by their performance on SF tasks, so I started wondering if it could be the characteristics of the tasks that lay behind the documented poor results.

1.1.4 Acquiring a taste for qualitative research

Before this text goes more into the details of the thesis work, I want to, based on my experiences from doing qualitative research, recommend all scientists to carefully listen to students[5] as they reason about central concepts and phenomena in their field of science. It is a truly transformational experience, and I have understood that the epiphany I enjoyed is common in qualitative research. Krauss (2005, p.763-764), for example, described the transformational power of qualitative research in the following way: *"an important learning facilitator, qualitative research and qualitative data analysis in particular have the power to be transformative learning tools through their ability to generate new levels and forms of meaning, which can in turn transform perspectives and actions"*. This is in perfect alignment with my own feeling as an educator and learner

[5] Or representatives of any target audience that are of interest to you.

when listening to my students as they reasoned freely around atmospheric CO_2 accumulation, revealing a range of interesting perspectives and ways of reasoning.

Coming full circle in this section, the transformational experience of doing qualitative research was also an important step towards fully appreciating the idea behind integral theory (Esbjörn-Hargens 2010). This is not to say that I did not appreciate the research I had done before in pure climate science (Papers I-II), but I started realizing the importance of combining perspectives for their mutual enrichment in efforts to tackle climate change as a societal challenge. I realized that this was what I was doing, by first learning about the carbon cycle and how the different climate forcers compare, and then using this knowledge together with educational theory to explore challenges when students reason about atmospheric CO_2 accumulation.

1.2 Problem and Purpose Statement

1.2.1 Main focus: Climate Change

Climate change is one of the greatest global challenges (Biermann & 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 IPCC's 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).

There is a gap between the trends in projected human caused global warming ahead and the goals set out by the UNFCCC: "*Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*" (Paris Agreement 2015). Efforts to stem global warming are being taken but not at the scale needed to reduce humans' impact on the climate system enough to meet the targets agreed upon.

There is another gap, a huge knowledge gap, between the advanced collective scientific understanding of climate change and the average common understanding of the general public about climate change – its causes, impacts and remedies (Moser & Dilling 2011). Moser and Dilling (2011) term this the *science-action gap* and thereby emphasize that it is the gap between the scientific findings on climate change and its impacts on the one hand, and the public's concern for the issue and lack of engagement on the other.

Together these gaps are highly problematic, especially since the short-term incentives to mitigate climate change for individual actors do not seem to outweigh the benefits reaped by business as usual. Phrased differently, global warming is a global public goods problem (Kaul et al. 2003) that, without proper incentives for all actors that contribute to emissions, is highly challenging. But the global community has agreed to take action on it (Paris Agreement 2015). Schendler and Jones (2018) capture the situation in the title of their recent piece in the *New York Times*: "*Stopping climate change is hopeless - Let's do it.*"

Getting those incentives in place is made harder by the fact that people can, and some do, refuse to *believe* in the ongoing dangerous human induced climate change (Moser & Dilling 2011). For a long-term global socio-ecological challenge such as climate change, that can be rebuked on grounds of different worldviews (for example ideologies or religions) or misconception about the cause-effect chain of climate change, there is a need for access to educational and communicational efforts that can assist people in making sense of the issue in ways that fit them, to create a basis of learning and engagement for treating the challenge (Moser & Dilling 2011; Wals & Jickling 2002). The focus on engaging the public, as opposed to only *providing understanding* for it, has been raised by McCaffrey & Buhr (2008), Moser & Dilling (2011) and Wibeck (2014) who all discuss the interplay between understanding, attitudes and behaviour.

While this thesis is about packaging certain climate change knowledge in order to make it accessible to lay-people (in the forms of emission metrics), it is also about the need to acknowledge and explore difficulties people experience in understanding the science of climate change. More explicitly, the thesis deals with two overarching aspects of this: First, it deals with how to package knowledge about the climate system to make the climate effect of different climate forcers comparable. Second, it deals with what misconceptions and ways of reasoning that make up challenges to correct reasoning on CO_2 accumulation. Finally, we make an attempt to study if there is any straightforward link between understanding CO_2 accumulation (as indicated by performance on SF tasks) and climate policy support, and what can be done to increase understanding.

1.2.2 Additional focus: Spatial Natural Resource Use

Besides the climate change topic, this thesis also presents work on the spatial use of renewable natural resources in poor rural areas where the use of for example non-timber-forest-products often is a substantial part of a villager's livelihood.[6] The main issue explored in this part of the thesis is the effect of removing different constraining assumptions of actors' (i.e. villagers') extraction patterns (Robinson et al. 2002, 2008; López-Feldman and Wilen 2008; Albers 2010). Which is done by developing a non-cooperative agent-based model of villagers resource extraction.

1.2.3 Research purpose

The research presented in this thesis has several purposes, but what binds Papers I-IV together is an overarching purpose that is central to informed emissions abatement:

To contribute to advanced climate science knowledge on how to compare climate forcers with different lifetimes, and to explore and explicate what challenges people experience when dealing with tasks on atmospheric accumulation of the most important climate forcer, CO_2.

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[6] The study on this will, in the thesis, be treated separately from the 2+2 studies in climate change and climate change literacy respectively.

Finally, the research purpose for Paper V is:
To develop a flexible model that accommodates heterogeneous extractor choices and interactions, to provide greater insights into resource extraction, and to explore the implications of various assumptions that constrain extraction choices.

The specific research questions used to address the problems and purposes described above will be presented separately for each respective research field in Section 1.3-1.5.

1.3 Field 1 – Climate science: Emission metrics

This section gives a background to the research field of climate emission metrics which is the field in which I started doing my thesis work which lead to Papers I-II and gave me the basis in climate science knowledge that has been central also for my work with Papers III-IV. After the introduction to the need for emission metrics (which is elaborated more on in Chapter 3) the research questions of Papers I-II are presented.

Different aspect of climate change science can, for example, be divided into the three working groups of IPCC: The Physical Science Basis; Impacts, Adaptation and Vulnerability; Mitigation of Climate Change. When policymakers design a policy or choose between different mitigation options (such as putting a tax on greenhouse gas emissions from meat production or reducing deforestation) they need to be informed about the potential consequences of their choices.

While CO_2 is the single most important contributor (or forcer) to global warming, there are multiple forcers[7] that give rise to global warming. To judge which climate change mitigation alternative that for a given cost reduce climate change effects the most there is a need to be able to compare the climate impacts of emissions of various climate forcers. But the question between mitigation alternatives is never as straight forward as simply picking the alternative that has *the largest favourable effect* on the climate (for a given mitigation cost). To be able to estimate the climate effect of different mitigation actions a core piece of information is the relative climate effect of the different climate forcers. Put in simpler terms how much worse is the emission of 1 kilogram of methane than the emission of a kilogram of carbon dioxide?

Climate emission metrics is the term for used for conversion approaches that places emissions of different forcers on a "common scale,", i.e. where relative climate effect is measured using the same scale. The climate impacts of the different forcers can be compared in a multitude of different ways (for example their impact on the radiative balance of the climate system or on the expected temperature increase). And to get a single value (or factor) that relates the different climate forcers, a treatment of time needs to be specified. With "treatment of time" I here mean what time horizon we are interested

[7] Comparison with mitigative actions that affect land use change (e.g. albedo, evapotranspiration) contribution to climate change are also of importance. For some SLCFs the location of emissions also makes a difference that needs to be taken into account (Bond et al. 2013).

in and how we value the climate impact during the years within that time horizon (more on this in Chapter 3 & 7).

To be able to estimate the climate effect of the different forcers in different ways some type of representation of the climate system is used. In the work presented here, the climate system is modelled using simple[8] numerical climate models (refs). Since the output of climate emission metrics work is intended to be used by decision-makers (often non-scientists) it is of major importance that the process of estimating the emission metric values is as transparent as possible, without being oversimplified. Oversimplification of course risks losing important climate physics dynamics.

As a standard, the (relative) emission metrics use CO_2 as a basis for comparison, meaning that the climate effect of forcer X is divided by the climate effect of an equal amount of CO_2 (by mass). Hence, the value obtained expresses how many kilograms of CO_2 emissions is estimated to produce an *equal* climate effect to the emissions of 1 kilogram of forcer X.

In using a metric value, short-lived climate forcers (SLCFs) – which do not accumulate (over longer periods of time) in the atmosphere – are compared to CO_2, which do accumulate. This means that the longer time horizon that is chosen – the smaller the emission metric value will be – since the CO_2 still in the atmosphere will keep on causing climate change impacts long after the SLCF is gone. This is illustrated in Figure 3 which shows how the Global Temperature change Potential (GTP) value (measuring the relative temperature change at some future point in time following the emission of 1 kilogram of a given climate forcer today) for methane drops dramatically as a function of the chosen time horizon and is thus valued very differently depending on what time horizon is chosen. Choosing a time horizon of 20 years will equate the emission of 1 kilogram of methane with that of approximately 60 kilograms of CO_2, while using 100 years for the comparison estimates methane to only have a climate impact 5 times as big as that of CO_2.

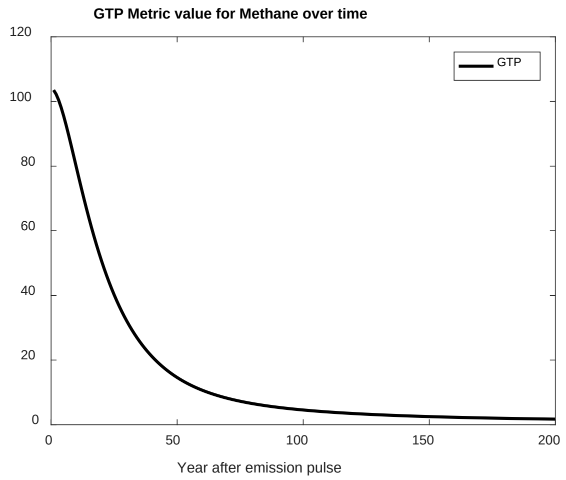


Figure 3. GTP emission metric values for methane showing a dramatic dependence on the time horizon.

[8] Or "reduced-complexity" global average climate models.

It is important to note that there is no scientifically correct time horizon and similarly no scientifically correct climate indicator (i.e. impact) to use when assessing the climate effect of different forcers. Value judgments are needed to be able to make trade-offs between impacts, mainly between climate impacts on the short term and on the long term (Tanaka et al. 2010). To make it even harder, the time horizon and indicator have a decisive effect on the resulting metric value, and for that reason carefully taken choices on what to use needs to be made. There is hence a major pedagogical and communicative challenge to inform the – often non-climate experts – about the importance and effects of the choices they have to make. To deal with this effort Tanaka et al. (2010, p. 191) write "the issues at stake are complex and require multi-disciplinary perspectives (i.e., from climate physics, atmospheric chemistry, biogeochemistry, environmental economics and political science) in addition to value judgments" which sounds much like the call for an integral approach explained by Esbjörn-Hargens (2010) and used as the overarching theoretical perspective of this thesis (Section 1.1.1).

1.3.1 Research questions

Paper I

1) How is Sea Level Rise (SLR) affected by emissions of different climate forcers?
2) How does the persistence of SLR compare with the atmospheric adjustment times and the temperature responses of the different forcers?

Paper II

3) How are the values of two common climate metrics, the Global Warming Potential (GWP) and GTP, affected by a simplification of how the Climate-Carbon cycle Feedback (CCF) is modelled?
4) What is the difference in CCF relaxation time scales between the simplified approach and an approach which explicitly model the interaction between the climate and the carbon cycle?

1.4 FIELD 2 – CLIMATE SCIENCE LITERACY

1.4.1 Climate science literacy – an emerging research area

Climate literacy first surfaced as a term in the academic literature around 1995 (Perry 1995), while *Climate Science Literacy* (CSL) was introduced around 2008 (McCaffrey & Buhr 2008). This research area has grown rapidly from representing an interest among a few scholars to returning some 2000 hits on Google Scholar by mid-October 2018[9]. I choose to use the term "climate science literacy" instead of "climate literacy" because of the important focus on the scientific approach to understanding the concept *climate* and because of the risk that the first term can be misunderstood (Dupigny-Giroux 2010).

[9] Using the two search terms "climate literacy" (≈1900 hits) and "climate science literacy" (≈200 hits) using quotation marks to get exact matches only. Search performed October 15, 2018.

To appreciate many of the complexities of climate change we need the scientific method, since we cannot experience the climate (and less so climate change) *per se* as it by definition occurs over long time-scales[10] and large geographical areas.

The notion of CSL was operationalized in the report “Essential principles for climate science literacy” (US Global Change Research Program 2009), and the collaborative process of developing this framework, involving both scholars and educators, is described in McCaffrey and Buhr (2008). The framework is based on the following definition of what it means to be climate science literate:

> *People who are climate science literate know that climate science can inform our decisions that improve quality of life. They have a basic understanding of the climate system, including the natural and human-caused factors that affect it. Climate science literate individuals understand how climate observations and records as well as computer modeling contribute to scientific knowledge about climate. They are aware of the fundamental relationship between climate and human life and the many ways in which climate has always played a role in human health. They have the ability to assess the validity of scientific arguments about climate and to use that information to support their decisions.*

My reflections from reading this definition are many, but suffice to say that I believe that this view on CSL is by far too ambitious in terms of what a climate science literate person should know and be able to do. I will elaborate on this issue in Section 4.4 and Chapter 6.

Definitions of CSL often vary in terms of to what extent attitudes and behaviour are included in the concept or not. The “Essential principles of climate science literacy” framework (US Global Change Research Program 2009), for example, mentions “an understanding of your influence on climate and climate’s influence on you and society”, and then goes on to describe a climate science literate person as someone who:

1. understands the essential principles of Earth’s climate system,
2. knows how to assess scientifically credible information about climate,
3. communicates about climate and climate change in a meaningful way, and
4. is able to make informed and responsible decisions with regard to actions that may affect climate.

This definition obviously goes beyond knowledge, to include various skills, but the framework is careful not to say too much about the behaviour of a climate science literate person. The definition of CSL used by Wibeck (2014), on the other hand, includes understanding, attitudes, and behaviour. But regardless of whether behaviour is included in the definition of CSL or not, the relationship between knowledge and behaviour is important. Environmental sociologists and psychologists argue that knowledge does not determine behaviour – social norms, attitudes, values, worldviews, and structural

[10] Definitions often refers to statistical data over 30 years or more when referring to climate.

obstacles to environmentally friendly behaviour are also important factors (e.g. Hamilton et al. 2015; Gifford 2011; Wibeck 2014).

Looking at the global scene today, there are trends in the public's level of CSL that move in opposite directions for different countries, at least for the aspect of the level of public opinion on the climate change (Moser & Dilling 2011; McCright et al. 2016). Moser and Dilling (2011, p. 161) express their concern pointedly:

> *This state of public opinion raises critical questions as to the effectiveness of twenty or more years of public education, outreach, and engagement approaches used to render a complex scientific issue meaningful and actionable for lay audiences.*

Looking at these trends and referring back to the urgency in reducing emissions in order to live up to the Paris Agreement (Paris Agreement 2015) or not to overshoot it by too much it seems that the people engaged in the field of CSL will have a lot to do the coming decades.

1.4.2 Research questions

Paper III

A. What is the level of understanding of atmospheric CO_2 accumulation among non-experts, as measured by performance on different SF tasks?
B. Does performance on SF tasks depend on the extent to which the task explicitly focuses on the relationship between the in- and outflow?
C. Does performance on SF tasks depend on if the context is climate change or a bathtub?
D. Can alternative SF tasks – using the bathtub as context or directing attention to the relationship between in- and outflow – be used as educational interventions to improve performance on a more traditional climate SF task?
E. How do non-experts reason when dealing with tasks related to atmospheric CO_2 accumulation?
F. Is there a correlation between performance on climate SF tasks and climate policy support?

Paper IV

G. What challenges do engineering students experience when dealing with tasks involving atmospheric CO_2 accumulation?
H. Are these challenges of a cognitive, metacognitive or affective nature?
I. How do students conceptualize the relationship between CO_2 emissions and uptake?

1.5 FIELD 3 – SPATIAL NATURAL RESOURCE ECONOMICS

A topic within natural resource economics studies is the spatial aspects of resource use and management. It is important to develop spatially explicit models of natural resource use since landscape characteristics and transportation distances affect both the type and degree of natural resource use and the ecosystem services the resource can provide. Certain natural resource uses, such as use of forest resources, affect the carbon cycle by altering how much carbon a certain plot of land (where the resource is based) binds or holds. This implies that certain resource uses may risk releasing large quantities of CO_2, if it is vital to below- or above-ground carbon stocks. However, aspects of biodiversity and other eco-system services are also of crucial importance, as are the potential for poverty alleviation by extractive or non-extractive natural resource use.

Modelling spatial natural resource use can be done via a variety of different models that aim to study or explain various types of questions on different time horizons and for a range of circumstances. One of the first spatial models of land use was the von Thünen model (von Thünen & Heinrich 1966) which pioneered the work on spatial use of natural resources. Von Thünen was one of the first to develop a theory for what will be grown, produced or extracted at what distance from a market-place, thereby introducing a spatial dimension to natural resource use and management.

The model developed and implemented in Paper V exchanges the marketplace for a village and does not look at what will be grown or sold but instead focus on the interactions of a number of villagers extracting non-timber forest products or working locally for wage. The type of model developed can be seen as a tool that is useful for thinking systematically about the interactions between villagers and for testing different types of resources management regimes for the villagers and the forest in order to study both individual and collective behaviour, and effects this has on the natural resource(s) being studied. This work was started early on in my PhD and has been a side-project.

Zooming out and reflecting on the United Nations Sustainable Development Goals (SDGs), it soon becomes clear that many of the SDGs revolve around natural resources management and poverty alleviation projects of the kind studied by this field. It also becomes clear that improved site-specific understanding by both managers and locals (and often institution-building) is required in order to improve livelihoods, while maintaining or restoring eco-systems that villagers in poor rural areas of low-income countries depend upon.

1.5.1 Research questions

I. How can we build a multi-agent numerical model that allows us to explore interactions of actors' (villagers) spatial extraction choices for different spatial landscapes and access to labour market?

II. What are the effects on patterns of extraction of non-timber forest products and returns to villagers from the following simplifying assumptions: using a representative agent and restricting the patterns of extraction?

2 THE THREE RESEARCH FIELDS: PARADIGMS AND RESEARCH GAPS

> *[T]he world only seems to get more complex and cacophonous as we confront the major problems of our day: extreme religious fundamentalism, environmental degradation, failing education systems, existential alienation, and volatile financial markets. Never have there been so many disciplines and worldviews to consider and consult in addressing these issues: a cornucopia of perspectives. But without a way of linking, leveraging, correlating, and aligning these perspectives, their contribution to the problems we face are largely lost or compromised.*
>
> Esbjörn-Hargens (2010, p. 33)

This chapter covers three topics related to fundamental aspects of the research I have conducted in the three different fields introduced in 1.4-1.6 (see Box 1 for new conepts):

1) A set of reflections on some differences in the paradigms used in the fields that I've been working in.
2) An attempt to position my contributions to the fields in relation to those paradigms using a theoretical framework by Wagner (1993) that describes research as working on blank spots or blind spots.
3) A light description of the view of the nature of reality and the view of knowledge and knowledge acquisition (epistemology) I use.

Box 1: **Paradigms** are a set of theories, concepts, methods and basic facts that researchers in a given discipline or research community have agreed upon using (Kuhn 1970).
Epistemology is here seen as *"the philosophy of knowledge or how we come to know"* as expressed by Kraus (2005) in referring to Trochim (2000).
Blank spots are research gaps in the form of yet unexamined phenomena or objects of inquiry that scientists study using established ways of doing research (to fill in the blanks) as mandated by their paradigm. **Blind spots** are phenomena or objects of inquiry (i.e. research gaps) that are unobservable or obscured when using the standard theories, concepts, methods etc. of a paradigm (Wagner 1993).

The research communities in which the respective studies have been performed are the following. Paper I and II have been situated within the natural sciences but been performed in an engineering research environment at Chalmers University of Technology. The research of Paper V was performed within natural resource economics together with an interdisciplinary team. Since a couple of years back, my focus now, reflected in Paper III and IV, is in the field of CSL with colleagues from both climate science and the educational science at Chalmers University of Technology. Working in multiple research traditions has been a challenge, but thanks to great guidance and the course in philosophy of science I took at Chalmers University of Technology, the challenge has provoked important insights that lay the basis for this chapter.

One of the giants of the philosophy of science, Thomas Kuhn (1970), defines “normal science” to be the research that is being performed in a discipline using a common paradigm. Based on this view of research, Wagner (1993) established a terminology to describe two forms of potential research. The first is the normal science research in which scientists study the blank spots of their fields without questioning their paradigm. The second type of research suggestion is an alteration of the paradigm or introduces new elements to the paradigm, often borrowed from another paradigm. This is only done when found necessary due to identified limitations of the current paradigm that restrict what can be studied (i.e. blind spots).

As a part of the reflections on the different paradigms, I will briefly explore differences in how the role of human reasoning is viewed and treated in the “normal science” of each respective field I have worked in. As the type of reflections of this chapter are not standard to share in the research tradition of my research school I will first elaborate briefly on why this may be useful to do.

Firstly, since a doctoral thesis is a pedagogical product by itself—an effort to try to provide a learning opportunity for its readers—it seems only reasonable that I also elaborate on my thoughts on epistemology (Wagner 1993). I believe that this elaboration serves as an extended introduction to my work by providing a more nuanced description of some fundamental assumptions of the research presented in this thesis. Secondly, I have a modest hope that this part of my thesis may inspire others to reflect upon these types of questions and one’s own role, willingly or not, to be a representative of a certain view of the world and what knowledge and science is. Thirdly, in doing inter- or transdisciplinary efforts (as opposed to single or certain multi-disciplinary efforts) I agree with Petrie (1976, p. 14) that the type of questions discussed here, or more metaphorically to be able to “*Only when you see what I see does interdisciplinary work have a chance*”, is important to fruitful collaborations. Lastly, I feel that the process of reasoning about these questions is meaningful and helpful for my own professional as well as personal development. Which is in line with the usefulness of it for the personal and professional development of budding academics, stressed by Hunter et al. (2006) in their work on “Becoming a scientist”, using a model for epistemological reflection, developed by Baxter Magolda (2004).

Two guiding epistemological questions from Krauss (2005) that I have used while reflecting on the topic of this chapter are: 1) What is the relationship between the knower and what is known? 2) What counts as knowledge?

These questions together will, with the concept of blank- and blind spots and the question of the difference in how the three fields view and treat human reasoning[11], be

[11] I.e., what assumptions about human reasoning are used and what aspects of it are central for the disciplines scientific inquiries.

the central focus for the reflections on each field in Section 2.1-2.3. I will also continue the discussion on the use of models in the different studies, which is a re-occurring tool used for both quantitative simulation of systems (Papers I, II and V) and conceptualization and presentation of knowledge (Papers I-V).

But before I present the reflections on the respective fields, I will illustrate the idea of viewing a phenomena or topic of scientific inquiry from different perspectives and with different lenses. Figure 4 illustrates examples of theoretical viewpoints (text in italic), modes or ways of studying (different observational equipment such as a satellite) and typical aspects or levels of the object studied (such as a group of students discussing) for six disciplines involved in CSL. Reflecting on the different views of a topic that different scientists (from different disciplines) have, it is not surprising that they will identify different blank spots (when they use their different perspectives and methods) and that different important aspects of an object of inquiry will be obscured, just because of the view they have (i.e. blind spots are created). The object chosen for this illustration is "climate knowledge" which is one of the cornerstones of CSL and central for Papers I-IV of this thesis. On purpose I choose not to define climate knowledge, but instead let it be as multifaceted as one likely would find it if representatives from different perspectives were to describe it.

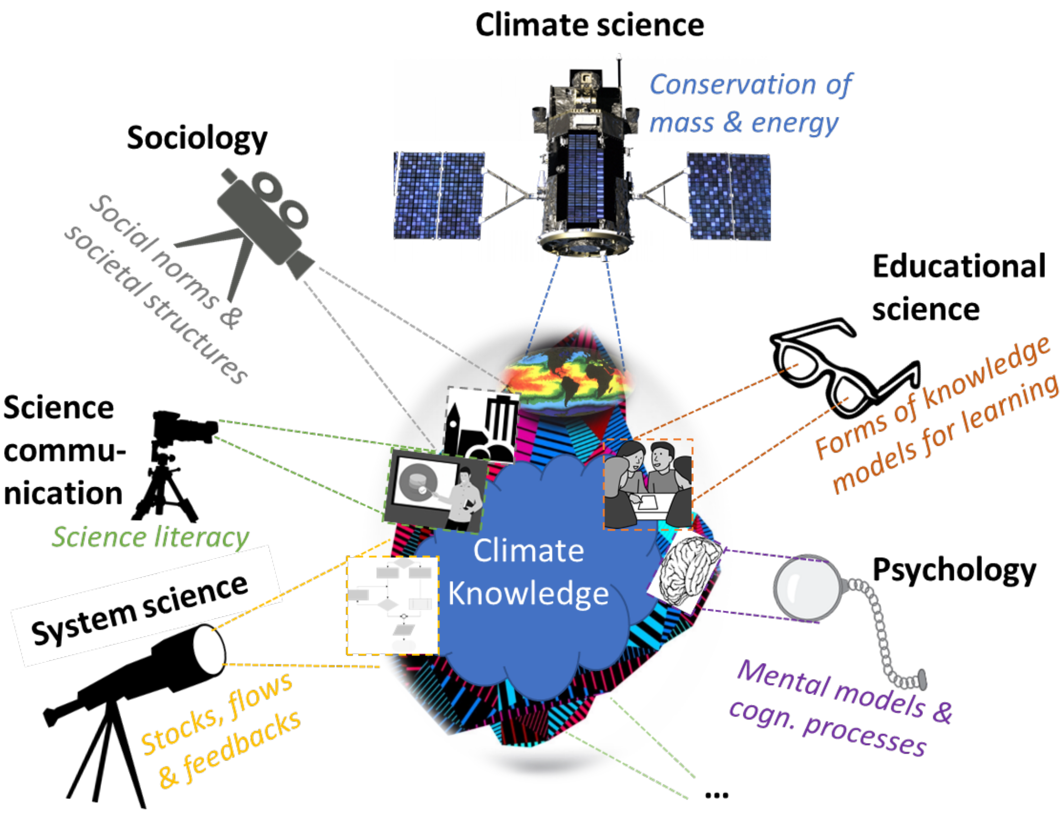


Figure 4. An illustration of disciplinary perspectives and examples of theoretical viewpoints and objects studied for six different disciplines.

On the topic of CSL, an example of a blank-spot inquiry could be to apply the theories and methods used in the Sterman and Booth Sweeney (2007) study on a new group of individuals, for example the country representatives to the UN climate negotiations, to test their performance on SF tasks and compare it with other groups. It could be argued that this would amount to determining if these representatives understand the principles of accumulation (but as further reading will show, that is not the position of this thesis), which is at the core of appreciating the need for CO_2 emissions abatement.

While blind spots are per definition obscured to a researcher who has been working in a field using a certain paradigm, I interpret Wagner (1993) to suggest that new interdisciplinary teams can contribute with new perspectives and identify these. Given this and drawing upon perspectives from fields previously not well represented in the literature on people's understanding of atmospheric CO_2 accumulation, I would argue that important blind spots include: how people actually reason when dealing with different types of SF tasks in a climate science context, what challenges they experience, and how metacognition and effect come into play in problem solving of SF tasks. I dare argue that these would be blind spots since the combination of borrowed perspectives, object of study and level of study are new to the research topic. A team that combines educational researchers—who appreciate the importance of qualitative research, the affective side of learning who use a nuanced view on knowledge —and climate scientists—who identify the importance of understanding certain properties of the carbon cycle, such as the uptake of CO_2 — could however identify this potential research inquiry.

In Section 2.1-2.3, I will deal with these three fields and the questions mentioned above, and in 2.4 I will conclude this part of the thesis with a few words on how to manage to accommodate several paradigms in the field of CSL and what my current views on knowledge and epistemology.

2.1 Climate Science, IPCC and my work

This section presents a series of reflections of epistemological nature that I have made on the topics of climate science and my work in it. It ends with an example of how Paper I contributes to filling a blank spot in the emission metrics research field.

2.1.1 Climate Science and IPCC

At the same time climate science offers a meeting arena for different research fields, for example in the form of collectively contributing to the IPCC assessment reports. Here different researchers using different paradigms are working towards the same overall goal of assessing and describing the state of knowledge in and relating to climate science. It thus becomes important to be able to handle or cope with the presence of several paradigms, and while this is a challenge, the IPCC community has so far managed to deal with it. But part of being able to deal with it is probably the separation of the works of vastly different disciplines into different workings groups (mentioned in Section 1.4). There is also further separation of work on different topics which are described in different chapters of the AR, which to some extent separates different research communities from each other. In making the main insights from the vast literature that IPCC assesses available, there is a very clearly structured and well-defined procedure (see Skodvin 2000; Appendix A to the Principles Governing IPCC Work). This requires the coordinating lead authors, lead authors and chapter authors to agree upon how the summary of the chapter should look. To agree on this they meet and argue back and forth for extensive periods of time about suggestions for each sentence, rewriting or removing if not enough support for a text passage can be garnered (T. Sterner, personal communications, May 2017). It is interesting to reflect on this strenuous procedure which is so essential to be able to collectively produce an assessment report which can be used for society in facing the challenge of global warming. If scientific knowledge would be objective and stand alone, separate from the observer (a positivist standpoint) it would possibly not be so hard to assess and summarize the new findings. But instead I view these accounts of how hard it is to agree upon even a summary of already reviewed and published work, to be a clear indication of the sometimes subtle, sometimes grand, differences in how we interpret the same description of reality. But the importance of trying to agree, of trying to take each-others perspective and trying to reconcile the differences faced (i.e. deal with using different paradigms) also becomes very clear. Alas, if we would give up, wouldn't the modest action that is happening also be threatened then?[12]

As a final note on the work by IPCC on the AR. Their work is not over when they have managed to agree upon what should be included in the summary for each chapter (that feeds into the technical summary), on the contrary, the daunting task of producing the so-called Summary for Policy Makers remains. This in principle requires representatives from all nations of the UNFCCC to agree upon each single word or phrase that goes into the Summary for Policy Makers. Here there is not only a clash between different paradigms, there is also a full out clash between worldviews, ideologies and different governments agendas. Sure, the representatives have to paraphrase their objections in terms of questioning the state of scientific literature or the portrayal of the science or the conclusions that can be drawn from it, but, if it isn't clear elsewhere that you can view knowledge about the world different, it is clear here (T. Sterner, personal communications, May 2017).

2.1.2 My work

The paradigm of my climate science research belongs to that of the natural sciences, physics, biology and chemistry most pronouncedly and is based on using mathematics to describe the climate system in an objective and deterministic way. What may be noted, that perhaps could signal a trace of the engineering environment of this research, is that our work does not focus on producing full scale so-called earth system models that try to model as many relevant processes of the Earth system as possible, as accurately as possible. Instead it is designed to include as few processes as needed at a level that is as basic as possible but that still on average can reproduce the necessary basic climate

[12] By indicating that too little is being done to deal with climate change, this sentence expresses a personal opinion of mine.

variables for the purpose at hand with acceptable accuracy. Meaning that, if it is physically sound and approximates the important processes well, the model may be used. This may be seen as an “engineering approach” that may be more pragmatic than some hardcore natural scientists would feel comfortable with. Instead characteristics such as the transparency of the model construction and use are valued, which may be in line with realizing the importance of being able to control, understand and use the models as learning and communicational tools. In a sense this offers the scientist that master this type of modelling, educational and communicational practices a position similar to that of Pasteur (Latour 1983) which by being able to ask and answer key questions of societal importance got a very large influence in society. I dare suggest that this could be one of the main reasons behind the high societal impact that the division of Physical Resource Theory at Chalmers University of Technology has had over the years as described by central evaluations by the communication and marketing division at our university (F. Hedenus, personal communications, Oct 2018).

The aspects of climate change modelled in Paper I and II do not include any endogenously modelled dynamics related to human reasoning but instead treats the input of the effects from anthropogenic activities as given (exogenous). The scenarios of anthropogenic climate forcings are designed to represent different possible future developments of the human interference with the climate system. Certain other types of climate models on the other hand do include dynamics to reflect the human part of the climate system. Economists for example develop models in which what humans do in the future depend on costs and benefits of performing mitigation and adaptation measures (hence tries to capture the role of human reasoning at some level).

Looking at the different types of “implications for practice” that studies, in the strand of research I’ve been involved in, suggests and knowing that the knowledge deficit model still is a common way of reasoning (Wibeck 2014) – I think I can highlight some interesting aspects of the paradigm that underlies at least parts of the climate science. One such aspect is that I lack a discussion around aspects of the field’s knowledge and research in terms of the role these can play for the evolution of the object of study. Potential feedbacks from climate change to human interaction with the climate system is one of them. It is left out of the models I’ve used and the discussions of my research findings. Figure 5 illustrates that knowledge, either gained by observing current changes or by making projections about the future can potentially affect how the climate system evolves which in turn needs to be taken into account in the projections for the projections to be as good as possible. Bruno Latour mentions this cyclical feedback in a recent interview in the New York Times (Kofman 2018) when commenting on the role of climate scientists for the system they study.

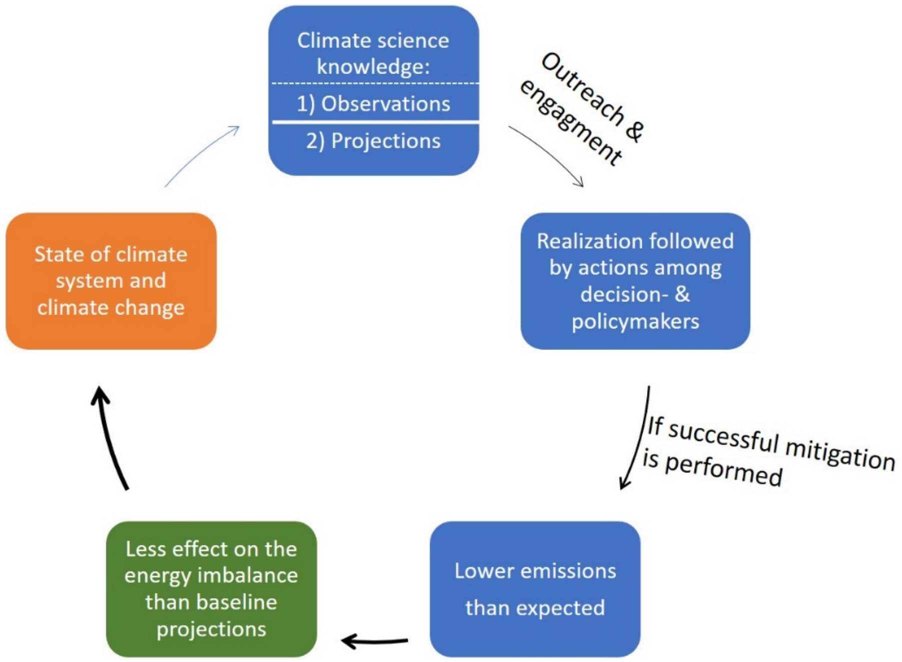


Figure 5. A conceptual cyclical feedback-loop in the climate science-climate system sphere of reality.

This type of feedback is not likely on the scale of a single research study, but taken at the scale of the impact from a whole research field or, yet larger, on the scale of what is being examined in the IPCC AR. This could possibly, or even likely have an important affect "by the mere fact that someone sets out to study or describe it". I.e. the results may depend on the publication and assessment of the results, so to say.

When I realize how counter-intuitive and hard it is to grasp and make sense out of certain aspects of the physics of climate change, for all audiences (even some of my very well-educated colleagues), then this role of knowledge and of science literacy in the world becomes both overwhelmingly clear yet puzzling. Since I sense a potential in making much more out of the science-action gap (Moser & Dilling 2011) while it is not yet clear to me what factors affect fruitful climate science education, communication and engagement. My conclusions, which probably comes as no surprise, are that in order for our global society to develop peacefully and with increased prosperity for all, we cannot rely on everyone knowing how everything works. Instead we need the combination of great education, science literacy and independent science striving for sustainable development (which is also the motto of Chalmers University of Technology).

2.1.3 An example of a blank spot within the work of climate emission metrics

In describing a research field or topic such as the area of climate emission metrics research, which Paper I and II belong to, one can create a matrix which maps the research area (Wagner 1993) for potential identification of research gaps (blank spots) or blind spots in the form of entire columns or rows that the paradigm of the field obscures. Table 1 can be thought of as a sub-matrix to the field of climate science. The methods and theories used are placed as rows and the phenomena and level of the phenomena studied as columns[13]. Depending on the level of exploration already performed (i.e. a fields maturity) this matrix will have fewer or more explored cells. The purpose here was mainly to introduce the idea of the matrix which will be used again in Section 2.2, if it would have been used used to map out the filed of emission metrics today, many more columns and rows would have been added and most cells would have been filled with references to studies performed. By studying cells within this submatrix, that have not been studied before, scientists fill in *blank spots* that can be identified using the current paradigm (Wagner 1993). Our work in Paper I and II fills in blanks, for example by studying a climate effect (sea level rise) that had not previously been studied as a metric end-point for an emission metric. In Table 1 we have marked one cell with SLR/Paper I to exemplify a blank spot in the area of emission metrics that the paper addressed. To position Paper II in this matrix we could have added a sub-row that specified whether and how the model used included CCF for non-CO_2 climate forcers.

Table 1. A matrix that spans part of the emissions metrics research area to map the research territory. Most cells have already been filled by previous literature

	Climate effects or metric endpoint		Treatment of time	Evaluating effects of using different metrics	Finding cost-efficient mitigation	…
Simple climate model	SLR Paper I					
Integrated assessment model						
Earth system climate model						
…						

2.2 CLIMATE SCIENCE LITERACY: PARADIGMS AND EPISTEMOLOGIES

Blind spots in the area of climate science literacy

CSL, as a research area, is situated at the intersection of different research fields and the disciplines that host them. This follows naturally from being an area with the multifaceted background that climate science has (see Section 2.1). But it is also a result of the positioning/framing it has received by studies such as those by McCaffrey and Buhr (2008) and Wibeck (2014), which to a smaller or larger degree suggest that CSL has not only to do with knowledge but also with behaviour. This means that CSL also receives attention from fields or disciplines that study people's behaviour. One of the results of this is that natural scientists and systems scientists who quite often, in my

[13] The rows and columns of this matrix could be divided still more to describe the different variations of approaches (theories and methods) or objects of study and the level of study.

judgment, tend to believe in the so-called *knowledge deficit model* (see Box 2) (Moser & Dilling 2007; McCaffrey & Buhr 2008; Wibeck 2014) get fierce opposition by psychologists and sociologists that have long since shown that behaviour (and attitudes) is a complex function of factors such as social norms, scepticism towards science, and political orientation (Hamilton et al. 2015; Gifford 2011; Wibeck 2014). Consequently, what counts as scientific knowledge worth pursuing in the area of CSL will likely depend

> **Box 2: Knowledge deficit model –** Is the commonly used and misguided idea that "*people are assumed to make informed decisions once their cognitive deficiencies and gaps have been filled*" McCaffrey & Buhr (2008) based on Moser & Dilling (2007)

on who you ask, but what seems to be a common thread is the interest in common misconceptions and useful mental models (e.g. Sterman & Booth Sweeney 2007; Moxnes & Saysel 2009; Chen 2011; Dutt & Gonzalez 2012).

My research in the area of CSL (Paper III and IV) is a collaborative research project between two divisions at Chalmers University of Technology: Physical Resource Theory and Engineering Education Research. The research in Paper III speaks directly to systems science research and cognitive psychology, which are the two main research fields that have studied SF failure. This means that different paradigms have been brought to bear on the study of SF failure, as I will now discuss.

Systems scientists tend, not surprisingly, to focus on "the system" and being able to accurately work with the system. When studying SF failure, they move or alternate between different systems, or contexts, such as a bath tub, bank account, people in a store, marbles in a jar, and CO_2 in the atmosphere, without always considering which system is in focus and how the systems actually do differ (Guy et al. 2013; Newell et al. 2013). The central idea seems to be that understanding the principles of accumulation in one of these contexts should imply that these principles have been understood universally. Another assumption that this paradigm seems to be based on is that there is only one degree or type of understanding, which can be assessed using (most often written) SF tasks, and that this is unaffected by the social and cultural context in which the tasks are answered. The focus of this research is mainly on external factors, such as task formulation and context, but demography and educational background are also variables that have been studied in relation to performance (Cronin & Gonzalez 2007; Sterman & Booth Sweeney 2002; 2007; Guy et al. 2013; Fischer et al. 2015; Newell et al. 2016).

Cognitive psychology research addressing the topic of SF failure tend to, like systems science research, treat the climate system as any other system, but focuses on priming, cognitive burden of task or the mode of thinking people apply when dealing with SF tasks (Cronin et al 2009; Fischer & Gonzalez 2015; Weinhardt et al. 2015). This paradigm typically highlights the participants' focus on details versus whole, and on the effect of the task format (Cronin et al 2009; Fischer et al 2015; Fischer & Gonzalez 2015).

We have focused on the phenomenon that mainly concerns us and chosen methodologies thereafter (Falconer & Mackay 1999): How do people reason about atmospheric CO_2 accumulation, and what challenges do they experience when dealing with SF tasks in a climate context? What does it mean to understand CO_2 accumulation, and what interventions are effective in addressing SF failure? In keeping with a qualitative research tradition, I deem this approach to be more explorative, trying to be less presuming and more interested in understanding things from the perspective of the participants. Such an understanding can inform education and communication in useful ways. The underlying belief here is that human reasoning can vary between contexts and situations, that it can be inconsistent, and that there can be several factors that come into play when people reason about different phenomena, such as CO_2 accumulation. I therefore believe, reflecting my epistemological stance, that it is of paramount importance to study people’s reasoning about different phenomena, and that I – as a climate scientist – can acquire valuable insights from analyzing people’s ways of reasoning around open-ended questions related to the phenomena. Comparing our work to previous work on SF failure, I dare say that the work in Papers III and IV add a row or two and a column or two to Table 2, which is made by the same principle as introduced in the previous section (Wagner 1993). Table 2 illustrates this by rows and columns in bold that have previously received little attention (For a more detailed discussion, see Section 4.1). For clarity I’ve chosen not to include all rows and columns already explored and only use this as a tool to position our work to show how it contributes.

Table 2. Matrix of the research of public understanding of CO_2 accumulation: blank- and blind spots.

		Groups “understanding”			**Individuals “understanding”**	
		STEM-Students	Non-STEM-Students	Other groups	**Ways of reasoning**	**Experienced Challenges of different kinds**
Tasks to assess “understanding”	Formats			Paper III		Paper IV
	Contexts			Paper III		
	Interactive Simulations					
	…					
Types and forms of knowledge				Paper III		
Qualitative research					Paper III	Paper IV

A climate scientist, on the other hand, is more concerned with the importance of the properties and implications of CO_2 accumulation as a part in the cause and effect chain of climate change. From this disciplinary perspective, one might argue that it is of major importance for people to understand CO_2 accumulation to build opinion for stronger climate policy support[14]. In studying the "Essential principles of climate science literacy" (US Global Change Research Program 2009) which was produced in a dialogue with many researchers in the climate science community in the US (McCaffrey & Buhr 2008), I enthusiastically welcome the comprehensive effort made in mapping the climate change challenge and the cause and effect chain of it. At the same time, I cannot avoid reflecting on how overwhelming this framework must seem to most educators, communicators and students – it contains seven principles detailing no less than 39 points to become familiar with. Many of these points are described in a way that seems to require extensive training in multiple climate science fields. As an example, consider the following point:

> Covering 70% of Earth's surface, the ocean exerts a major control on climate by dominating Earth's energy and water cycles. It has the capacity to absorb large amounts of solar energy. Heat and water vapor are redistributed globally through density-driven ocean currents and atmospheric circulation. Changes in ocean circulation caused by tectonic movements or large influxes of fresh water from melting polar ice can lead to significant and even abrupt changes in climate, both locally and on global scales.

Striking a balance between being too detailed or complex and being too brief and simple, and adapting to different audiences, in order for the material to be meaningful and enticing is a major challenge. Indeed, what counts as knowledge and useful/valuable knowledge is not always the same thing. As Wibeck (2014) puts it, climate science communication is experiencing a paradigm shift from focusing on "climate change understanding" to focusing on "climate change engagement", and in this transition, doing research on what type of material is engaging and interesting will be of the utmost importance.

2.3 Resource Economics

I've been involved in this third field of research in the role of a modeler and not a content knowledge expert. Although I've taken a couple of courses related to the subject, I'm in this sense an outsider which has its pros and cons to it. On the one hand, my perspective is not marked too much by the central ideas of the discipline on the other hand my appreciation of the very same ideas is not as rigid as they would be if it was my main discipline. This text will therefore be concise and mainly serves the purpose of elaborating on the difference in the role human reasoning can have in different disciplines.

It seems to me that what counts as knowledge in this field depends on which subdiscipline you look at, since different competing schools of thought relies on different assumptions of what best explains both aggregate and individual reasoning and behaviour of people in different economic situations in society.

[14] This would be the opinion of a climate scientist who has let his/her values affect what he/she believes should be done.

In neoclassical economics, the assumption of the rational decision agent (from rational choice theory), is a central cornerstone for theory building. The rational decision agent maximizes individual expected utility (often some kind of profit) under perfect access to information. This means that the rational agent do not take others utility into account at all as long as it does not affect the agent's own expected utility. The agent is also assumed to go through all alternative strategies available that may affect his/her expected utility and choose the one that maximizes it. This means that the role of human reasoning in this work is dynamic. Specifically, the role humans play in the socio-ecological system I've studied is dependent on the preconditions of the system and is determined endogenously in the models used. However, the agents are assumed to behave according to very strict rules of reasoning and there are no "real humans" with "real reasoning" in the system.

The assumption of perfectly rational decision agents has been questioned and critiqued by both economists and non-economists for example by comparing empirical findings with those analytically derived from game theoretical concepts such as the Nash equilibrium. In doing this the field of behavioural economics and the concept of bounded rationality has presented themselves as steps towards dealing with certain weaknesses due to the imperfection of the rationality assumption. That can be viewed as at least part-paradigm shift (Kuhn 1970). I would argue that this paradigm shift, at least to some extent, is a product of an increased appreciation of the importance of the *social context*, much like Mendelsohn (1977) argue for scientific knowledge to be regarded as "social knowledge". The next section will elaborate more on paradigm shifts and I will connect back to the idea of "social knowledge" when I give my view on my current paradigmatic and epistemological beliefs as well as my view on "the objective researcher".

2.1 MULTIPLE PARADIGMS AND MY PARADIGMATIC AND EPISTEMOLOGICAL BELIEFS

I will conclude this part of the thesis with a reflection on the use of different paradigms when researching SF failure. In doing so, I will first compare and contrast the paradigm that we bring to the research on SF failure with the dominant paradigm. I then turn to a description of my ontological and epistemological beliefs, and my view on the "objective" researcher.

2.4.1 Researching SF failure – towards an integral approach

Previous research on SF failure has mainly focused on *external* factors related to problem solving (i.e. characteristics of the *problem*) and to some extent the background and interests of the participants. This focus seems to rely on the epistemological belief that the best, if not the only, way of gaining insights into SF failure, also in a climate context, is by analysing performance on different SF tasks using quantitative methods (e.g. Sterman & Booth Sweeney 2007; Dutt & Gonzalez 2013; Reichert 2015). Within this paradigm, what constitutes understanding seems not to have been problematized: either you understand or you don't. In a manner of speaking, this paradigm treats the participants as "black boxes", presented with an input (task) and producing an output (task performance).

The paradigm that we bring to the research on SF failure is one that focuses on *internal* factors related to problem solving (i.e. characteristics of the *problem solver*). That is, a paradigm that forefronts experiences, meaning making, and reasoning related to dealing with CO_2 accumulation tasks. In keeping with such a paradigm, we use a qualitative research approach. By bringing a new paradigm to the inquiry on SF failure, echoing the call for an *integral approach* to meet the challenges of climate change (O'Brien 2010), we hope to provide new theoretical insights that, in turn, can inform educational practice. I will return to the specific contributions and implications of using such a paradigm in Section 4.4, Chapter 6, and Chapter 7.

2.4.2 My ontological and epistemological beliefs

My ontological position is that there is a natural "objective" reality that we can only try to measure and comprehend. And because of our differences as (mental and biological) beings, we will interpret the same reality differently, and from that perspective there exists multiple interpretations of reality. Those interpretations and the meaning making processes we use to make sense out of the world around us and inside us, make the study of aspects of the world that are influenced to a large degree by the role of human reasoning, tricky. While we interpret the world as a unique ever-changing function of our biological and mental selves, which changes as we age and accumulate experiences, by socialization we also develop a vast amount of "shared meanings". Take language and social norms as a couple of examples that we to a large extent have shared meanings of, and compare it to watching a movie or going on a vacation, which are activities that we can share with others but that may end up meaning totally different things to us. Krauss (2005) talks about "common meanings" and "unique meanings". It seems to me that in order to understand what is common meanings and what are unique meanings in the area of reasoning about climate change physics, there is a need to use a mixed methods approach to get both depth and width in the data collection and data analysis (Krauss 2005).

2.4.3 My view on the objective researcher

Following the arguments about how I believe that our interpretations of the world are affected by who we are and in what social context we create meaning about different phenomena, it should come as no surprise that I believe it to be impossible for a researcher to be perfectly objective. For the phenomenon of my main interest – climate change – Ryghaug (2011) provides examples of how different social groups make sense of global warming in several different ways, and end up with different messages or narratives on the topic.

The social context in which research is conducted affects all stages of the research process: 1) what we set out to research (and why), 2) what we analyse and how we interpret our results, 3) how we discuss the findings, 4) what we conclude, and 5) what we do with the new insights. I am not alone in considering that these choices are affected by both who we are and in what social setting they occur (e.g. Mendelsohn 1977; Latour 1983). To phrase it differently, all knowledge is, in essence, social knowledge (Mendelsohn 1977).

To me, it is crucial to be transparent about what I do as a researcher and why I do it, as well as to try to be as objective as possible when I do quantitative research to find "common meanings". An example of such a common meaning could be what fraction of a population that can construct a graph over inflow and outflow of CO_2 for the amount of CO_2 to stabilize.

In doing qualitative research, on the other hand, I wish to use a range of social skills to try to see things from the perspective of the participants, and to give justice to those perspectives, while at the same time also drawing upon what I see from my point of view (as a climate scientist and educator). An example of this could be to study the way people reason (and why) when they answer the very same CO_2 accumulation task mentioned above.

I echo the conclusion by Krauss (2005) that it is the nature of the phenomena I am interested in studying that, most often, determine which methodology that makes most sense to use. Using the terminology of Krauss (2005), I strive to make my work as value-free as possible and value-conscious where necessary or preferable. What's most important is that the work does not become value-ladened and that it does not become misinterpreted to conclude or suggest things that are based on any hidden (intentional or unintentional) value-judgements. However, I follow Latour's advice (Kofman 2018) to scientists and make it no secret that behind the choices of choosing what to study there is a wish to work towards the research purpose- and problem statement described in Section 1.2.

3 Comparing Climate Forcers: Emission Metrics

3.1 Background

Climate change is already happening. So far, the global mean surface temperature has risen by about 0.7-0.9 °C since 1901 (Hartfield et al. 2018), 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 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 climate forcers, most notably by CO_2 (Myhre et al. 2013). However, CO_2 is not the only climate forcer (see Figure 6) 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 UNFCCC has chosen the emission metric 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.

3.1.1 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 6, from IPCC AR5 (8.18 in Myhre et al. 2013), presents the total effective radiative forcing[15] (ERF) over time, split into nine categories of anthropogenic sources and two natural sources of ERF. By studying Figure 6 it becomes clear that anthropogenic forcing (red line) of the climate system has accelerated since the 1950s.

[15] 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.

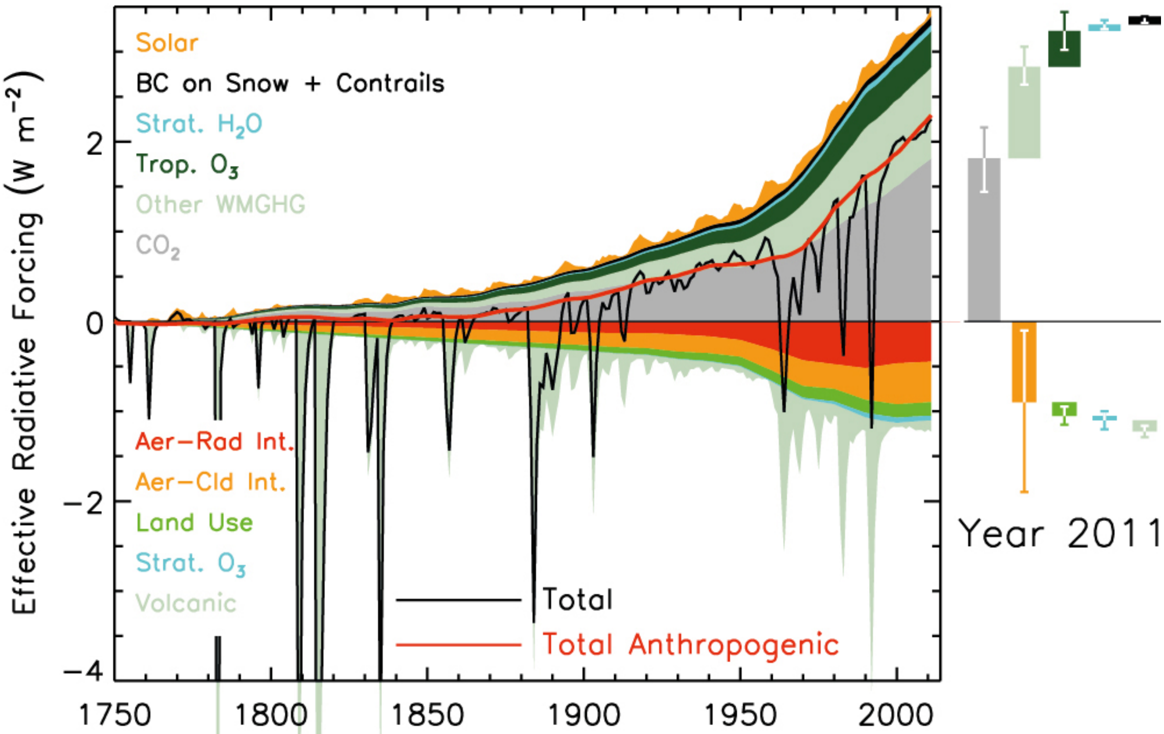


Figure 6. Time evolution of forcing for anthropogenic and natural forcing mechanisms. Bars with the present forcing and uncertainty ranges (5 to 95% confidence range) are given in the right part of the figure. For aerosols, the ERF due to Aerosol–Radiation Interaction (Aer-Rad Int.) and total aerosol 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.

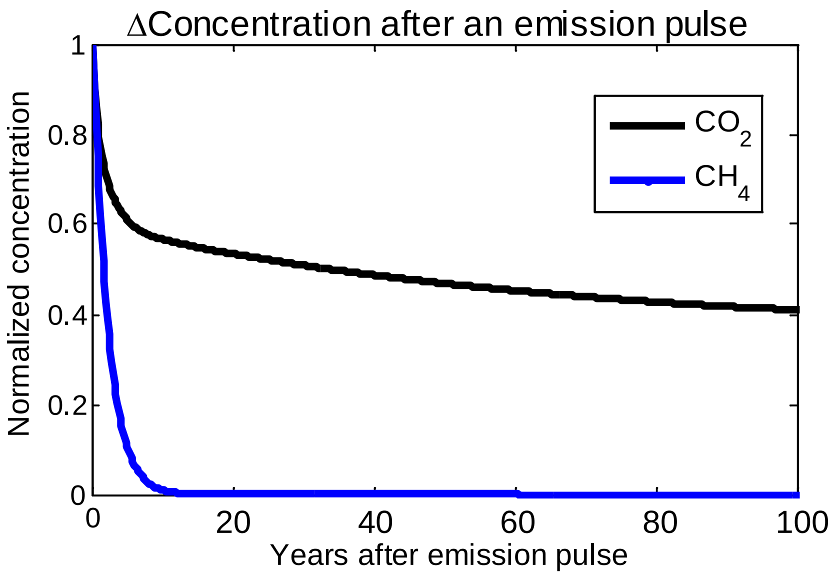
To understand what Figure 6 means for the potential future temperature change, we note that the equilibrium temperature change is proportional to the climate sensitivity parameter (see Equation 1).

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

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 Figure 7). These differences mean that choosing a method for comparing emissions of different climate forcers requires answering these questions, whether explicitly or implicitly. Figure 7 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 7. Illustration of the different atmospheric lifetimes of CO_2 and CH_4 emissions[16]. 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.

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

3.1.2 Metrics

The GWP is the most commonly used metric, originating from work by Rodhe (1990), Lashof & 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 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 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 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.

3.1.3 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 8 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 Figure 8); only simpler gas cycle models are included for the other greenhouse gases.

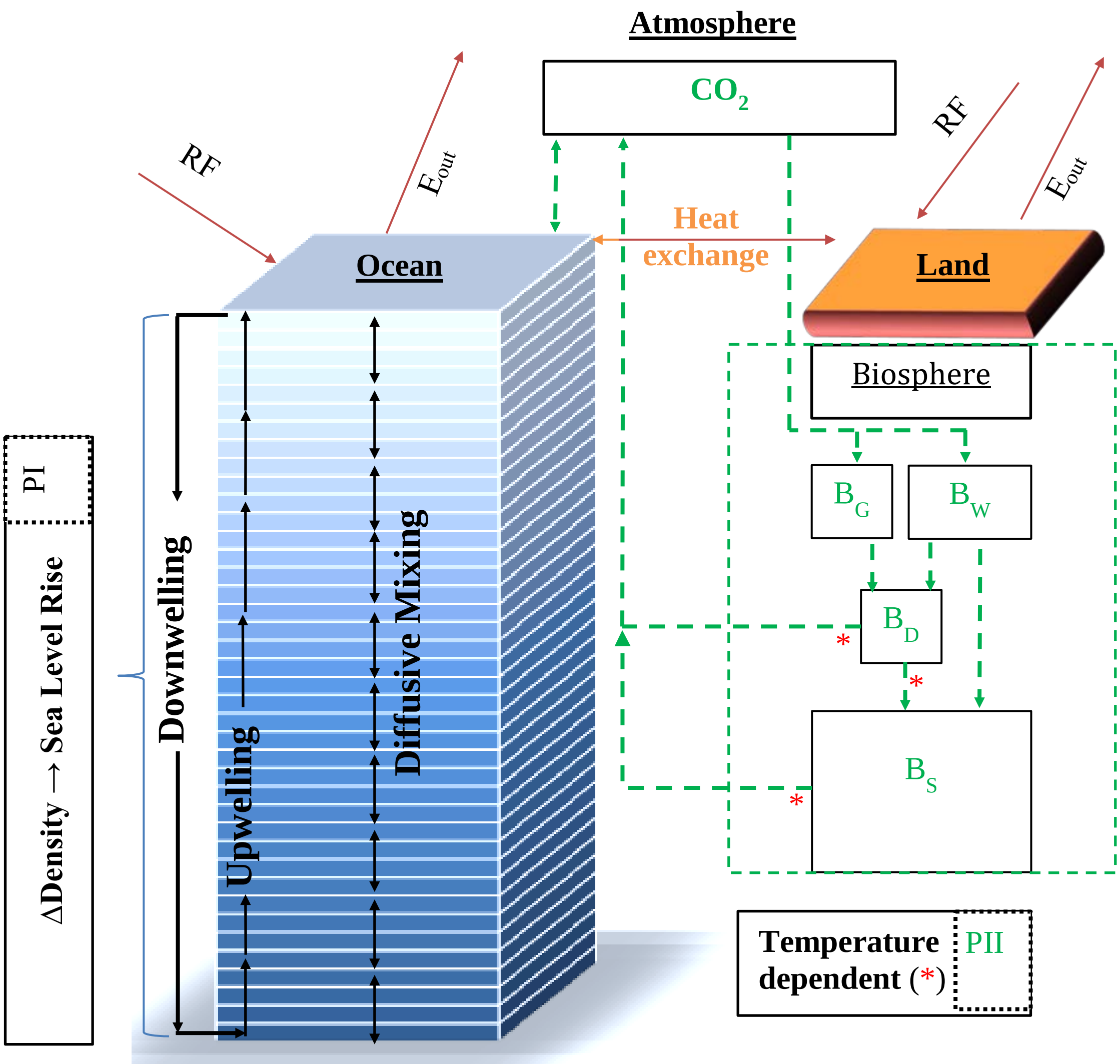


Figure 8. Schematic illustration of the main model features for Papers I and II. The energy balance is modelled with the flows of energy processes as illustrated (orange and black arrows). E_{out} denotes the energy that goes out to space through thermal radiation. Paper II also models the carbon cycle 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 radiative forcing (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.

3.1.4 Climate 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 (such as Black Carbon – 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[17], 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 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[18].

The latest global inventory and report on BC by Bond et al. (2013) pins down some of the uncertainties about its climate impact. These uncertainties 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 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

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17 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.

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

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 Figure 6 for their estimated aggregated effect), is also considered very high (Myhre et al. 2013).

Limitations

The limitations of the modeling approaches used in Paper I-II are similar, except for the difference in how the carbon cycle is modeled (as an impulse response function in Paper I and as a box-model in paper II). These types of models are designed to simulate the dynamics governing the atmospheric concentrations of the climate forcers studied, as well as the global average annual temperature using an Upwelling-Diffusion Energy Balance Model. These and similar models (Shine et al. 2005; Hoffert et al. 1980) are constructed and calibrated (Baker and Roe 2009; Olivié and Stuber 2010; Meinshausen et al. 2011a) to reproduce observed or modeled climate variables[19] and depend both on the numerical implementation of the equations that govern the conservation of mass and energy, and their redistribution in the climate system, as well as on the data used to calibrated the models (Jones et al. 2012; Levitus et al. 2012). The limitations hence belong to the accuracy of the data and the mechanistic descriptions of the climate system at an aggregate scale. Fortunaely, for emission metric studies such as Papers I-II the main results are not dependent on the model simulating the absolute climate effects of the different forcers perfectly – since it is the relative value that is the main output. Given the rate of ongoing warming it is possible that the climate will change to an extent that the used data and models do not manage to capture the feedbacks and changes that may occur in the climate system (Ciais, 2013). In Paper I we also modeled SLR using a semi-empirical model (Rahmstorf et al. 2012) as an alternative, to provide a best estimate of what the full SLR could be (since the science of the melt-off of land-based snow and ice are uncertain).

[19] The model results for surface air temperature, OHC, and thermosteric SLR following a 100 GtC pulse fall in the middle of the spectrum reported by Joos et al. (2013), who compare the results of a range of Earth System Models (of varying complexity) and reduced-form models.

3.2 PAPER I: EMISSION METRICS AND SEA LEVEL RISE

3.2.1 Background and aim

Depending on the scenario[20] 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[21], 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 and 5). IGSP has the same structure but instead compares the integrated (or cumulative) SLR of the different forcers up to a chosen time horizon (see Equations 6 and 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.

Research questions Paper I:

1) How is Sea Level Rise (SLR) affected by emissions of different climate forcers?
2) How does the persistence of SLR compare with the atmospheric adjustment times and the temperature responses of the different forcers?

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[20] The scenarios are the RCPs (Meinshausen et al. 2011).

[21] 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).

3.2.2 Method

We define GSP as follows:

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

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:

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

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:

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

where AIGSP is the Absolute time-Integrated AGSP:

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

We model and assess these metrics using the simple climate model (UD-EBM), presented earlier, to estimate the thermosteric SLR (see Figure 9). The thermosteric SLR is calculated using the polynomial approximation of the equation of state for the density of water by Gill (1982).

3.2.3 Main findings

All of the examined climate forcers have long-term influence on the thermosteric SLR on the century to millenia time scales (see Figure 9). 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.

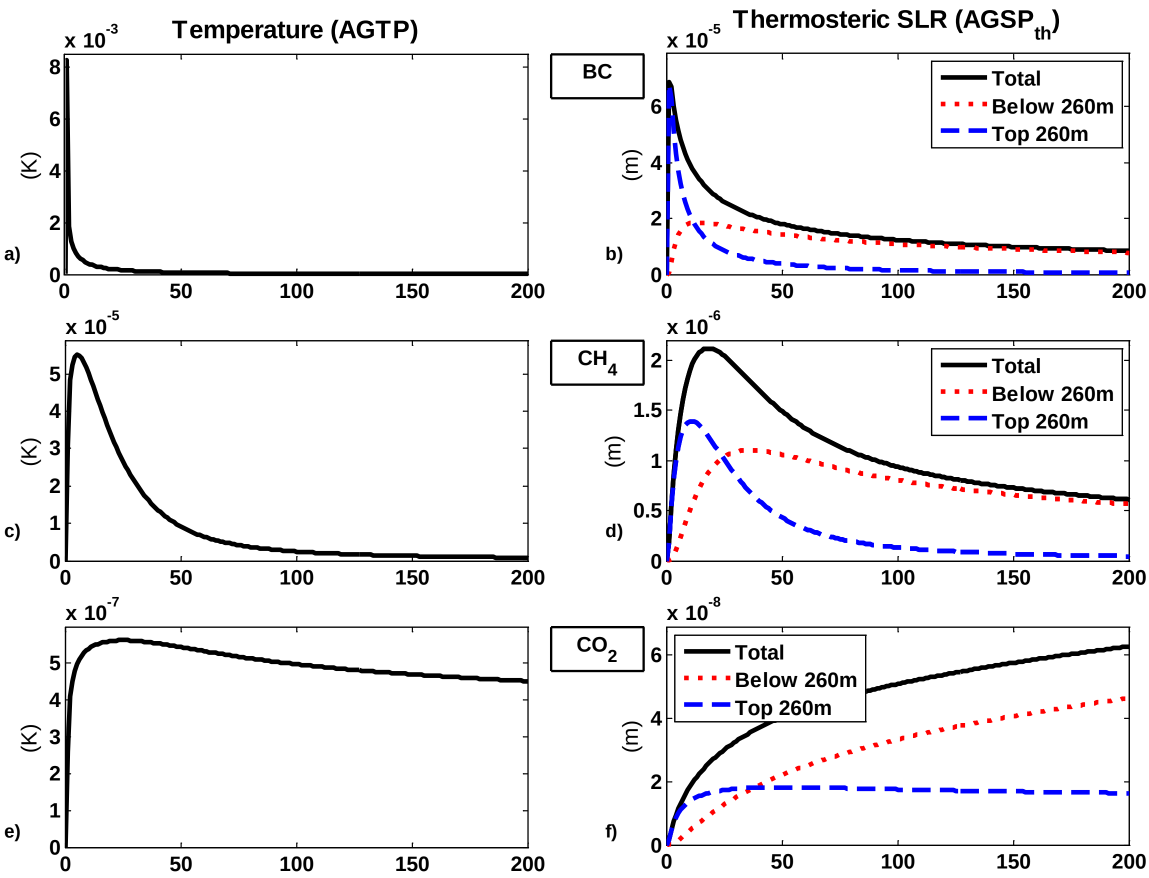


Figure 9. Absolute Global Temperature change Potential (AGTP) and thermosteric SLR ($AGSP_{th}$) following 1 Mt emission pulses of three of the forcers studied: a) & b) BC, c) & d) CH_4, e) & f) CO_2. The $AGSP_{th}$ figures on the right show the total rise as well as the contributions from the top 260 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 Figure 10). 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.

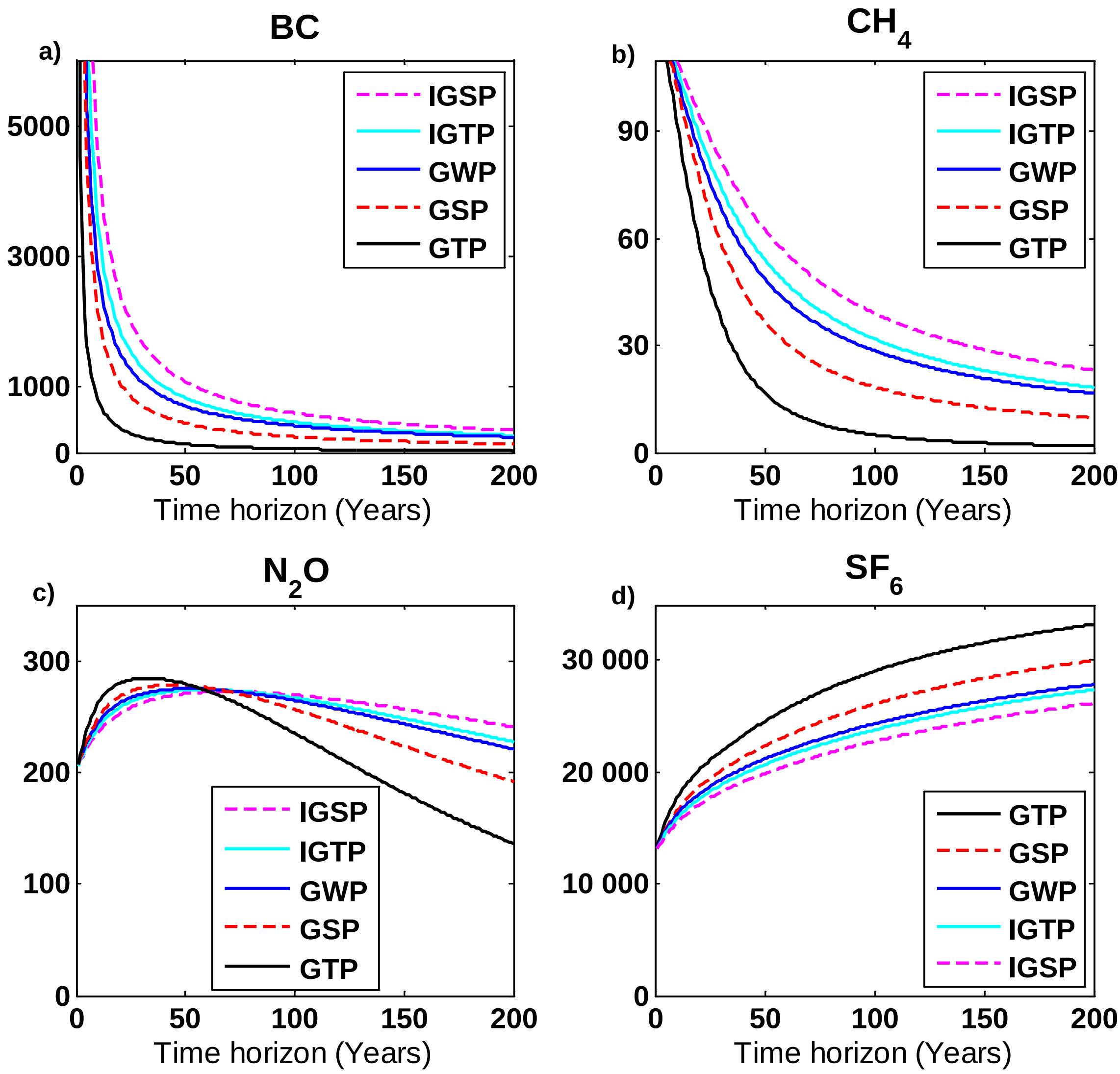


Figure 10. Comparison of metrics over different time horizons for a) BC (note that the y-axis has been cut for clarity), b) CH_4, c) N_2O and d) SF_6. The novel metrics have dashed lines.

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 greenhouse gases 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.

3.3 PAPER II: THE CLIMATE-CARBON CYCLE FEEDBACK'S EFFECT ON EMISSION METRICS

3.3.1 Background and aim

One of the most significant positive feedbacks in the climate system is the 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.

Research questions Paper II:

1) How are the values of two common climate metrics, the Global Warming Potential (GWP) and GTP, affected by a simplification of how the Climate-Carbon cycle Feedback (CCF) is modelled?
2) What is the difference in CCF relaxation time scales between the simplified approach and an approach which explicitly model the interaction between the climate and the carbon cycle?

3.3.2 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 CCCM by implementing and coupling a simple carbon cycle model to the UD-EBM (see Figure 8). 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 Figure 8) 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).

3.3.3 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 Figure 11). 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 (Figure 12). 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 (Figures 11 & 12).

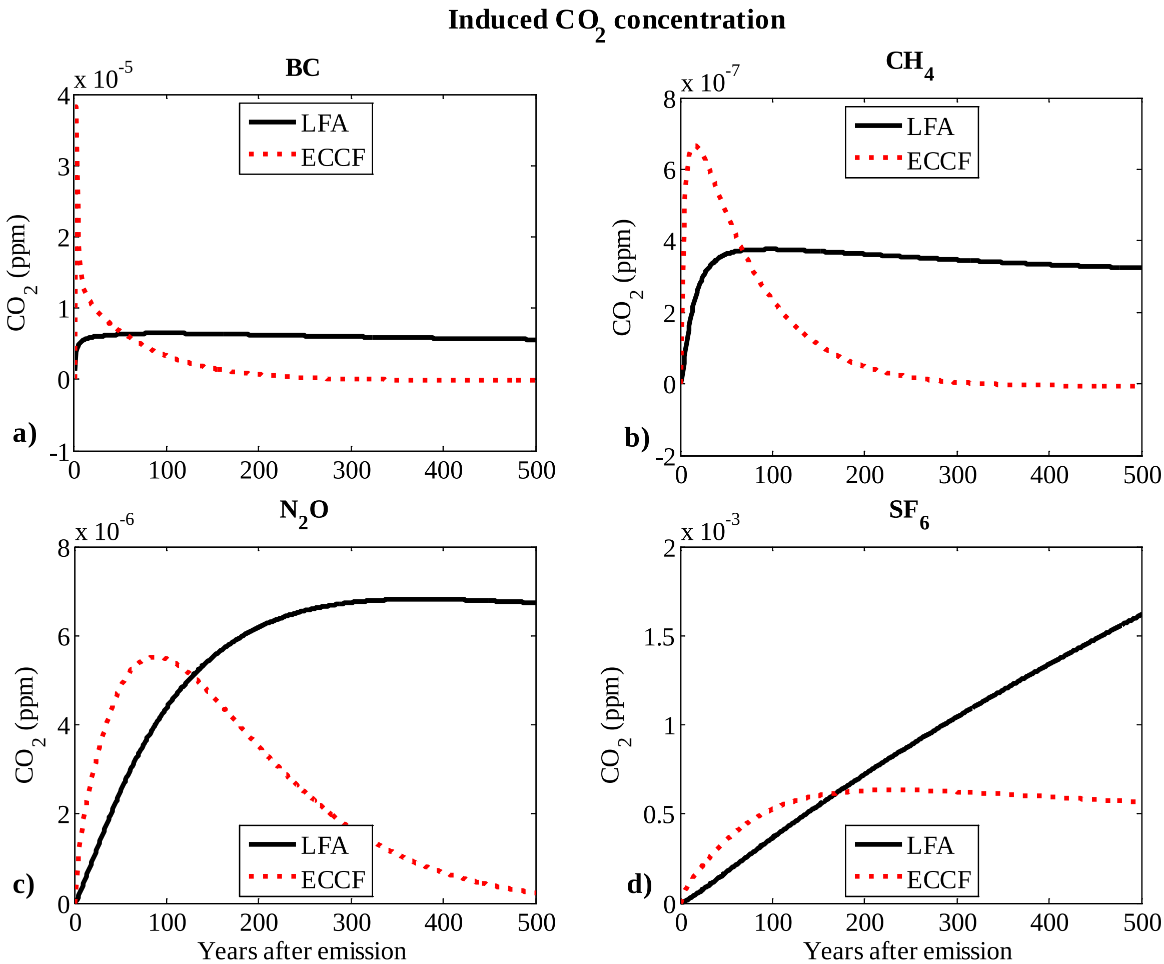


Figure 11. Comparison of the effect of the CCF on induced increases in CO_2 concentration with the linear feedback analysis (LFA) approach and the explicit climate-carbon cycle feedback (ECCF) approach. The 1 Kt pulse emissions of BC in a), CH_4 in b), N_2O in c) and SF_6 in d) are emitted in 2015, and 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 12 we compare the annual global mean cumulative RF (i.e. Absolute GWP – AGWP) and the annual global mean surface temperature changes (i.e. Absolute GTP – AGTP) values of three cases: without CCF and with CCF according to the LFA and the ECCF approaches. Both absolute metric values presented in Figure 12 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 Figure 12). 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 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.

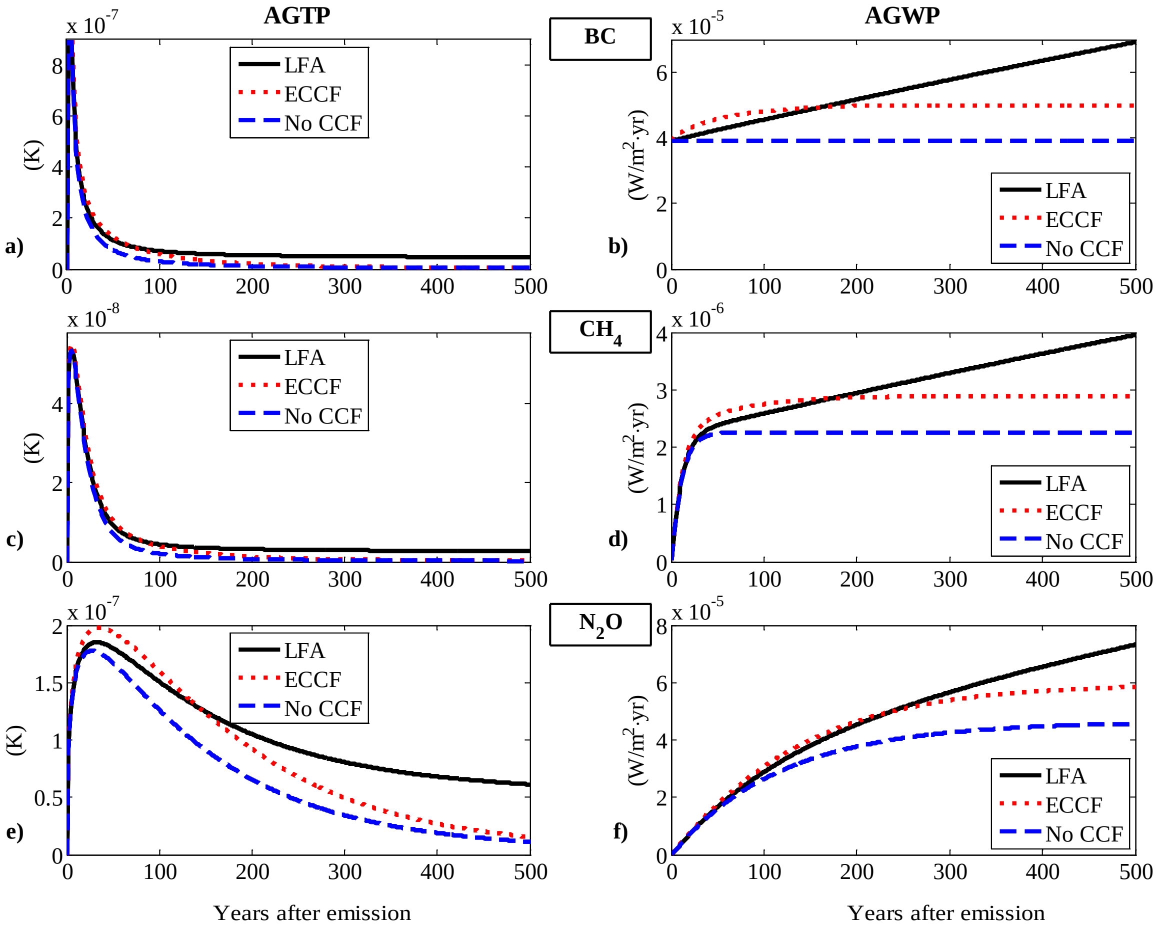


Figure 12. Absolute Global Warming Potential (AGWP) and Absolute Global Temperature change Potential (AGTP) following 1 Kt emission pulses of a) & b) BC, c) & d) CH_4, e) & f) N_2O for the three assumptions on CCF studied. Note the difference in the scales of the y-axes.

Table 3 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 3.** Comparison of GWP values for different climate forcers using the two climate-carbon cycle feedback (CCF) approaches: explicit climate-carbon cycle feedback (**ECCF)** – CCF according to the ECCF, and linear feedback analysis (**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

4 PUBLIC UNDERSTANDING OF CO_2 ACCUMULATION

In this chapter, I will focus on the understanding dimension of CSL, focusing on aspects of public understanding of atmospheric CO_2 accumulation. I will first review previous research (Section 4.1), which is followed by a summary of the work in Papers III-IV (Section 4.2-4.3), ending the chapter with a synthesis of this part of the thesis (Section 4.4).

4.1 LITERATURE REVIEW

This section reviews research on people's understanding of atmospheric CO_2 accumulation, a central component of CSL. In doing so, it reviews studies that have explored the extent of SF failure in a climate context, including whether there is a link between understanding CO_2 accumulation and climate policy support (see Section 4.1.1), studies that explore potential reasons for SF failure (4.1.2), and studies that have evaluated the efficacy of different types of interventions that address SF failure (Section 4.1.3). This review ends by identifying some gaps (blank- or blind spots) in the literature on SF failure in a climate context (Section 4.1.4). What follows is hence the inspiration and motivation for the research presented in Paper III and Paper IV.

Before diving into the literature review, it is worth noting that research on SF failure in a climate context sits within the larger literature on SF failure, with little or no apparent interest in climate change as such. Needless to say, what distinguishes the climate context from other contexts used in SF research, such as a bathtub or marbles in a box, is the societal and environmental importance of the climate change context. In addition to this, there is a series of unique or highly specific properties that are of unknown but plausibly high importance, which makes it important to treat the climate context with extra care. These belong to the cause and effect chain of climate change, and include multiple feedbacks, time delays and connections between systems of different nature. While the hardest to predict is likely the human factor in the system, there are also several SF systems connected to each other, such as the carbon cycle, the energy budget and the water cycle, which are all of importance for the climate system. With this background, my main focus will be on the SF literature in a climate context. While other SF systems and other aspects of understanding climate change are important, most of this literature has focused on the carbon cycle.

4.1.1 Stock-flow failure in a climate context

The first study to document the widespread poor understanding of atmospheric CO_2 accumulation was that by Sterman and Booth Sweeney (2007), and the results were later published in *Science* (Sterman 2008). The participants in that study were graduate students at Massachusetts Institute of Technology (MIT) within science, technology, engineering, mathematics, or economics. In brief, Sterman and Booth Sweeney (2007) found that 84% of the respondents provided answers that violated conservation of matter on a CO_2 stabilization task were students were asked to draw emission and uptake trajectories. Most of the participants seemed to use what has been dubbed *pattern* *matching* or a *correlation heuristic*, where the stabilization of human emissions of CO_2 is perceived to result in stabilized CO_2 concentrations in the atmosphere. Two further aspects of this study are worth noting. First, the suggestion that there would be a link between misunderstanding CO_2 accumulation and lack of stringent policy support (Sterman & Booth Sweeney 2007), though this was not investigated explicitly. Second, while the authors stated that the net removal or uptake of CO_2 is expected to reduce in the future, they chose not to include any aspects of this relationship between the emissions pathway and the expected uptake in their tasks or the analysis of the answers. These two aspects caught our attention and were after a literature study identified as two possible research gaps.

Several studies have set out to test the alarming finding by Sterman and Booth Sweeney (2007), and a majority of these studies have demonstrated a strong tendency for pattern matching or correlational reasoning (e.g., Dutt & Gonzalez 2013; Reichert et al. 2015; Cronin et al. 2009; Sterman 2008). However, as Korzilius et al. (2014) noted, these studies have mainly used *quantitative* research methods:

> *Thus far, research on SF performance has focused on the outcomes of reasoning processes and inferred that individuals use correlational reasoning while estimating SF behaviour, assuming that the flow(s) immediately and directly affect the stock. The actual reasoning process of participants remained hidden from the researchers. […] We may say that the correlation heuristic has the status of a hypothetical idea, a presumption that still has to be tested in research (p. 269).*

In relation to SF failure, researchers have also looked at variables such as educational background (discipline and educational level), gender, interest in science, environmental awareness, concern about climate change and support of climate policy action. Reichert et al. (2014), for example, in a study with undergraduate students in introductory geology courses at a large U.S. research institution, found that males and those interested in science performed better on SF tasks in a climate context. However, it is likely that these two variables are dependent, as only 14% of the females, compared to nearly twice as many males, reported being interested in science, which likely reflects attitudes toward science in society in general (Jones et al 2000). In the same study, it could not be shown that the participants' understanding of stocks and flows was connected to how serious they thought climate change was or their understanding of the scientific consensus for climate change.

4.1.2 Exploring reasons for SF failure

Various studies have focused on exploring potential *reasons* for SF failure. Difficulties related to understanding the *task format*, especially formats including graphs, have been suggested as an explanation for the poor performance, rather than poor understanding of stocks and flows. Depending on educational background, participants can have more or less experience with graphs, and there is also a risk that graphs could trigger pattern matching. An additional critique directed towards studies in which the participants are asked to draw graphs is that these studies do not test understanding of stocks and flows but merely skills in drawing graphs, since it can be more difficult, and require different types of competences, to draw a graph compared to understand a graph that is presented (Fischer et al. 2015).

Studies focusing on task format compare formats such as graphical representations, tables, physical representation, or plain text. Guy et al. (2013), Fischer et al. (2015), and Newell et al. (2016) found that SF tasks based on graphical representations are associated with lower performance, compared to tasks based on plain text. Fischer et al. (2015), when using a plain text task without a lot of quantitative information (which they refer to as a *verbal* format), found that an average of 86% of the participants could arrive at a correct solution for the different questions, which indicates that people are able to correctly solve SF problems when they are presented in an accessible format. It is, however, difficult to compare the success rates in this study with other studies, since it was based on multiple-choice questions with only three answer options, which can have affected the level of difficulty. Moreover, when scrutinizing the results in Fischer et al. (2015), we note that the overall result reported does not hold in the case of only looking at the CO_2 context (which is our main focus). For the CO_2 case, the performance on a task using a graphical format was actually better (79.3%) compared to a task using the verbal format (70%). So, to be clear, the overall result reported by Fischer et al. (2015) is an average for tasks belonging to one of three different contexts: a bathtub, a piggy bank, and atmospheric CO_2.

Finally, Dutt and Gonzalez (2013) compared the effectiveness of a physical representation with that of graphical- and text-based representations. They also used two different contexts, a climate context and a non-climate context in the form of marbles in a box. The physical representation consisted of a picture that illustrated accumulation in the form of circles entering or leaving a black box. The results indicated that the physical representation led to better performance on the SF tasks, regardless of the context. In summarizing their findings, Dutt and Gonzalez (2013, p. 61) concluded:*"Using the physical representation over other forms such as text or graphs could improve our estimation on atmospheric CO_2 and its associated climate change, ultimately reducing people's wait-and-see behaviour."*. This quote exemplifies both a belief in a high transferability of knowledge between contexts and a belief in a causal link between knowledge and behaviour that many studies have questioned (Moser & Dilling 2011; Wibeck 2014; Hamilton et al. 2015)

Another aspect that has been highlighted as a potential reason for SF failure is the *context* of the task, and several studies have used more than one context to study the potential impact of context on task performance. Examples of alternative contexts that have been used are: water in a bathtub (Booth Sweeney & Sterman 2000), financial savings and debts (Newell et al. 2013; 2016), marbles in a box (Dutt & Gonzalez 2013), and people in a store (Gonzalez & Wong 2012).

4.1.3 Interventions addressing SF failure

Different types of *active-learning situations* have been used as interventions to find out whether they lead to improved understanding of atmospheric CO_2 accumulation, as measured by improved performance on SF tasks. For example, Reichert et al. (2015)

compared understanding of stocks and flows for students who were taught through a lecture alone with students who were taught through a lecture and an additional two-hour instructional laboratory session. Students in the lecture-laboratory treatment performed significantly better and exhibited fewer misconceptions after the intervention compared to students in the control group. However, we note that it seems that the students in the treatment group had not only experienced different learning activities, but actually spent substantially more time on the topic, which makes it hard to assess the benefits of the intervention relative to the benefits solely stemming from spending more time on the topic.

As another type of active-learning situation, *computer simulations* have formed the basis of some intervention studies. Dutt and Gonzalez (2012b), for example, let participants use a dynamic simulator for climate change, and studied the influence of repeated feedback on the control of a CO_2 concentration in the atmosphere to a goal level. Even though the study showed some positive effect on performance due to repeated feedback in this situation, it did not reveal whether the participants developed any generic understanding about accumulation, or learned how to handle time delays. In another study, Dutt and Gonzalez (2012a) used the same dynamic simulator for climate change to test if participants' experience of using the simulator led to improved performance on an SF task, compared to a group who did not use the simulator. The results showed a significant reduction in misconceptions for the treatment group compared to the control group. However, this reduction in misconceptions was mainly for participants with a science background, and it is not clear to what extent the participants developed generic and long-lasting understanding, since the problem used in the simulation was identical to the problem that was used to evaluate the impact of the simulation.

Alternative contexts have also been used as interventions to study whether it is possible to transfer knowledge from one context to another, such as the familiar context of a bathtub to the abstract context of the atmosphere. Guy et al. (2013) reported that the introduction of a bathtub analogy can improve performance on SF tasks in a climate context. Newell et al. (2013; 2016) however, compared performance on SF tasks involving either a financial context, a climate context or a financial and climate context (with four different task formats) and did not find this trend to be true in general. For the double context treatment, the financial context was made available as an optional tool, in the form of a corresponding task, to guide thinking on CO_2 accumulation. Newell (2016) found that performance was better for the context of financial debts but not for financial savings. This result indicates that context familiarity is not sufficient to increase performance CO_2 tasks nor to attain higher success rate on all tasks relative to the climate task.

Moxnes and Saysel (2009) used analogies in combination with some information and questions to provoke cognitive conflicts (Waxer & Morton 2012) and thus facilitate the development of more appropriate mental models. The analogy that had the largest positive effect was that of a leaky air mattress. The intervention took just a few minutes, but led to improved performance on a SF task, especially among students with a science background. However, they found that many of those who reduced the inflow to the atmosphere (emissions) failed to do it to a sufficient degree to achieve a stabilization of

CO_2 in the atmosphere. This, they discuss, could be seen something other than having performed a complete shift from one mental model to another. They argue that the anchoring (i.e. sticking to close to an initial estimate) and other cognitive fallacies may be at fault (Kahneman & Tversky 1974) may play a part here.

4.1.4 Summary and blank/blind spots

In summary, previous studies have predominantly used a *quantitative* research approach to show that there is a widespread poor understanding of atmospheric CO_2 accumulation, and some have suggested that this leads to serious errors in reasoning about how to handle climate change (Sterman & Booth Sweeney 2007; Sterman 2008; Chen 2011; Dutt & Gonzalez 2013; Weinhardt 2015). A dominant focus has been on altering the format of the task or the context in an attempt to understand potential reasons for SF failure. In terms of the distinction between internal- and external aspects of problem solving (Jonassen 2007), the previous literature has mainly focused on *external* aspects, that is, aspects of the *problem* rather than the *problem solver* to understand SF failure. Some studies have also investigated the efficacy of different types of interventions, based on active-learning situations or analogies, to address SF failure.

The relation between understanding atmospheric CO_2 accumulation and *climate policy support* is largely underexplored and thus calls for some attention. But mainly, this literature review points to four blind- or blank spots in the literature on SF failure in a climate context:

1. What it means to *understand* atmospheric CO_2 accumulation has not been problematized;
2. There is a paucity of studies using a *qualitative* research approach to better understand how people actually reason – and what challenges they experience – when dealing with SF tasks;
3. Previous studies have mainly focused on the cognitive side of dealing with SF tasks, overlooking how *metacognition* and *affect* could come into play;
4. The relationship between CO_2 *emissions pathway and uptake* has not been problematized;

Let me end this background with a few words by Søren Kierkegaard from his “A point of view on teaching”, which serve to remind us of the idea that to teach we must first be able to take the *perspective of the learner,* which is central for at least point 2-3 above. In 1864, Søren Kierkegaard wrote[22]:

> *If real success is to attend the effort to bring a man to a definite position, one must first of all take pains to find him where he is and begin there. This is the secret of the art of helping others. Anyone who has not mastered this is himself deluded when he proposes to help others. In order to help another effectively I must understand more than he–yet primarily I must understand what he understands. If I do not know that, my greater understanding will be of no help to him.*

[22] This is the first part of the quote; the second half is presented at the end of Section 4.4.

4.2 PAPER III

4.2.1 Rationale and research questions

The background for this paper was the intriguing finding that most people, even well-educated adults, have a poor understanding of atmospheric CO_2 accumulation, which according to Sterman (2008) is like not understanding how a bathtub works. Moreover, as described in the literature review, the poor performance on SF tasks is over-all independent of task formulation. These findings notwithstanding, we surmised that most people do have an intuitive understanding of accumulation, or mass balance – but for some reason, this understanding is not revealed in the types of SF tasks that have been used in previous research. Against this background, we designed a mixed methods study (i.e. a study mixing quantitative and qualitative methods) addressing the following research questions:

A. What is the level of understanding of atmospheric CO_2 accumulation among non-experts, as measured by performance on SF tasks?
B. Does performance on SF tasks depend on the extent to which the task explicitly focuses on the relationship between the in- and outflow?
C. Does performance on SF tasks depend on if the context is climate change or a bathtub?
D. Can alternative SF tasks – using the bathtub as context or directing attention to the relationship between in- and outflow – be used as educational interventions to improve performance on a more traditional climate SF task?
E. How do non-experts reason when dealing with tasks related to atmospheric CO_2 accumulation?
F. Is there a correlation between performance on climate SF tasks and climate policy support?

By addressing these research questions, we contribute to filling some of the research gaps (blind and blank spots) in the climate SF literature identified above (Section 4.1.4), primarily: the first – what it means to understand atmospheric CO_2 accumulation (A-B); the second – what challenges people experience when dealing with climate SF tasks (B-E). In addition we also contribute to exploring the largely underexplored link between understanding and policy support (F).

4.2.2 Methodology and methods

Participants (N=214) were students enrolled in an online course on sustainability geared towards the general public. As illustrated in Figure 13, the participants were randomly assigned to one of three intervention groups, and a *pre-post-test design* was used to evaluate the efficacy of the interventions. An SF task similar to the one used by Sterman and Booth Sweeney (2007) was used both as a pre-test and post-test; a brief version of this task is shown in Figure 14.

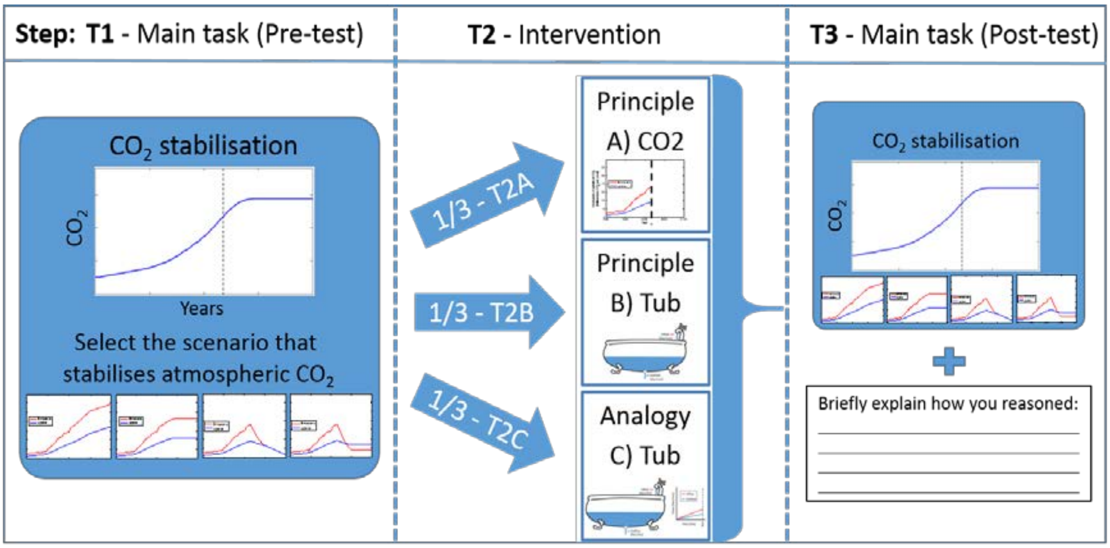
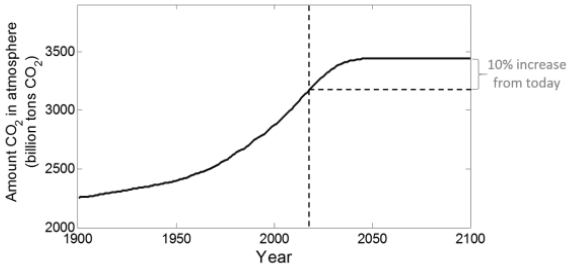
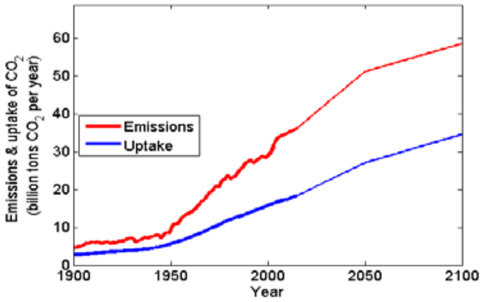


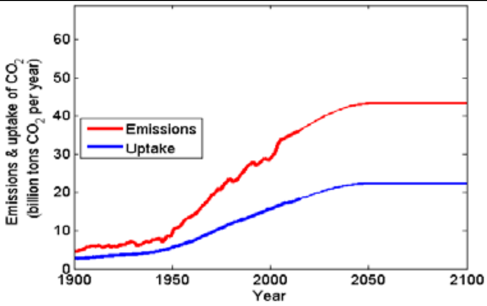
Figure 13. An illustration of the study's experimental design – which combines an A/B-test with a pre-post-test. All participants first performed three tasks (T1-T3) of which all but T2C contained a question. After the third task T3 (which was a post-test copy of the first task T1) the participants were also asked to briefly explain how they reasoned when choosing to keep or change their answer from T1 to T3. The exact number of participants in each of the three interventions can be found in Table 4.

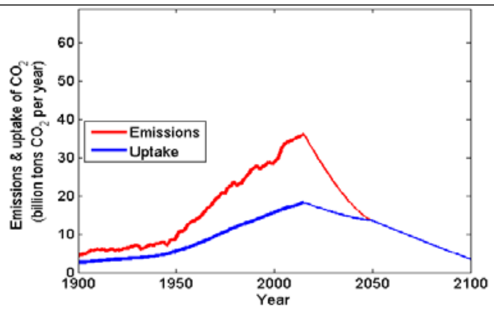
Each intervention consisted of an online activity, where participants either answered a multiple-choice question or read a short explanation. The interventions were designed to direct the participants' attention towards the principles of accumulation. This "zooming in" on the principles of accumulation was done by explicitly asking about or describing the relationship between the flows into and out of a stock in order for the stock to stabilize at a certain level. Another idea behind the interventions, was to create a cognitive conflict (Waxer & Morton 2012) between two different ways of reasoning, if incorrect reasoning was used when answering the SF task in the pre-test. The first intervention used the carbon cycle as context, while the second intervention used a bathtub as context. The third intervention, which did not involve a question, used a bathtub analogy to explain atmospheric CO_2 accumulation in a simple way. Brief versions of the first two interventions are shown in Figure 14. It is important to note that these interventions also served as alternative ways of formulating SF tasks in this study, and were used to answer research questions B and C.

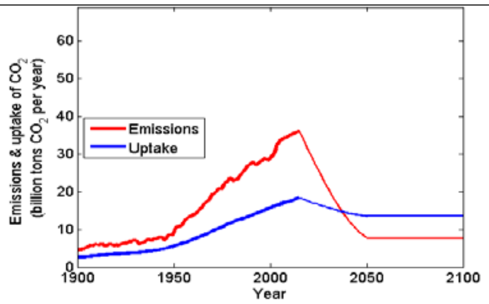
<table>
<tr><th>Main SF task</th><th>Interventions T2A and T2B</th></tr>
<tr><td>What would the levels of emissions and uptake look like for the rest of this century in order for the amount of CO2 in the atmosphere to follow the scenario below?


Alt.</td><td>T2A – CO_2 task:
What is required of the relationship between the emissions and uptake of CO2, in order for the amount of CO2 in the atmosphere to stop increasing and stabilize at a certain level in the future?

T2B – Bathtub task:
What is required of the relationship between the inflow and outflow of water, in order for the amount of water in the bathtub to stop increasing and stabilize at a certain level?</td></tr>
<tr><td>1.

</td><td>CO_2:
Emissions and uptake should continue growing but keep their current difference.

Bathtub:
Inflow and outflow should continue growing but keep their current difference.</td></tr>
<tr><td>2.

</td><td>CO_2:
Emissions and uptake should stop growing and keep their current difference.

Bathtub:
Inflow and outflow should stop growing and keep their current difference.</td></tr>
<tr><td>3.

</td><td>CO_2:
Emissions should reduce to and stay equal to the uptake.

Bathtub:
Inflow should reduce to and stay equal to the outflow.</td></tr>
<tr><td>4.

</td><td>CO_2:
Emissions should reduce to and stay at a level below the uptake.

Bathtub:

Inflow should reduce to and stay at a level below the outflow.</td></tr>
<tr><td>5. I don't know.</td><td>CO_2 & Bathtub: I don't know.</td></tr>
</table>

Figure 14. A brief version of the pre/post-test together with two of the intervention tasks.

To explore participants' ways of reasoning when dealing with the SF tasks (research question E), we asked them to provide a short, written explanation of how they reasoned when choosing to keep or change their answer in the post-test compared to the pre-test.

To answer the last research question, participants were asked (prior to the SF tasks) what climate policy they would support. A multiple-choice question was used with five alternatives[23], ranging from wait-and-see to immediate strong actions. Together with the performance on the SF tasks this allowed us to investigate if there was a correlation between understanding and indicated policy support.

Turning to data analysis, a chi-square test of homogeneity was used to determine if the rate of success was significantly different between any pair of treatment groups on the same task or any pair of tasks for the same group. The participants' answers to the open-ended question were analysed using inductive thematic analysis (Braun & Clarke 2006) to identify different ways of reasoning when dealing with SF tasks.

Limitations

The study is limited by the fact that the participants were among the interested general public with a high stated climate policy support. Performing a similar study with participants that do not support a strong climate policy would provide a valuable comparison. Another limitation of this study was the briefness of the answers provided by most participants to the open-ended question. The possibility to skip ahead and take the tasks in another order than intended was a limitation but no such tendency was found.

4.2.3 Results and discussion

As shown in Table 4, participants performed significantly better on the SF tasks that explicitly asked about the relationship between the flows into and out of a stock (54% and 70% success rate respectively), compared to a task more typical of those found in the SF literature (i.e. the task used as a pre- and post-test with 21% and 28% correct answers). This large difference in performance between different types of tasks indicates that these tasks may assess *different types of knowledge*. In the paper, we argue that traditional SF tasks pose additional knowledge demands, thus making them more difficult: participants not only have to *apply* the principles of accumulation, thus demonstrating declarative and procedural knowledge, they also must realize that this is what the task *requires them to do*, thus demonstrating situational knowledge[24]. We note that the idea that different kinds of SF tasks may assess different types of knowledge of accumulation seems to be largely overlooked in the literature on SF failure; there is, at

[23] One of which allowed the participants to answer "I don't know/I haven't formed an opinion".

[24] Knowledge can be sorted into several types, including declarative, procedural, and situational (de Jong & Ferguson-Hessler, 1996). Declarative knowledge (knowing what) is knowledge about facts, concepts, and principles, whereas procedural knowledge (knowing how) is knowledge about various kinds of (mathematical) manipulations required to solve the problem. Situational knowledge (knowing when to apply what knowledge), on the other hand, enables the problem solver to "sift relevant features out of the problem statement […] and, if necessary, to supplement information in the statement" (ibid., p. 106).

least, no explicit discussion of different types of knowledge or what it means to "understand" accumulation.

None of the interventions produced any impressive improvement in performance, even though the fraction of correct answers rose somewhat (see Table 4).

Table 4. Success rates for the different intervention groups and a Chi-square test of homogeneity (statistically significant differences are in bold).

Intervention group		**Share of respondents answering correctly**			**Chi-square homogeneity test (p-values)**	
	Pre-test (T1)	Intervention (T2)	Post-test (T3)	T1 – T2	T2 –T3	T1 – T3
Full sample (214)	21%	62%*	28%	**3E-15**	**4E-11**	0.14
T2A-CO_2 task (74)	26%	**54%**	24%	**4E-04**	**0.0002**	0.85
T2B-Bathtub task (77)	17%	**70%**	29%	**3E-11**	**2E-07**	**0.08**
T2C-Bathtub analogy (63)	22%	-	30%	-	-	0.31

*This is the average success rate for interventions T2A and T2B.

Based on the thematic analysis of the answers to the open-ended question, we identified three overarching ways of reasoning when dealing with SF tasks:

1. *System* reasoning, which focused on the system in terms of a relationship between emissions and uptake.
2. *Pattern* reasoning, which incorrectly focused on matching graphical patterns between the amount of CO_2 in the atmosphere and the annual emissions or uptake.
3. *Phenomenological* reasoning, which focused on a variety of phenomena, related to climate change, that are not needed for solving the SF tasks.

To our knowledge, phenomenological reasoning has not been documented in the previous literature on SF failure. Table 5 presents the frequency of these different ways of reasoning, together with illustrative quotes. These ways of reasoning about accumulation provide additional theoretical insights to explain the large difference in performance between the different SF tasks.

Finally, the support for stringent climate policies was very strong: almost all (91%) agreed with the statement that "Society should take strong action to reduce emissions of greenhouse gases today". Hence, given the high stringent policy support for the sample group (91%) and the varied performance across the different kinds of SF tasks, climate policy support does not require the understanding of CO_2 accumulation tested by commonly used SF tasks.

Table 5. Ways of reasoning when answering SF tasks with frequencies and illustrative quotes

Category / subcategory	Frequency	Illustrative quotes
System reasoning	**44%***	
Conservation of mass	23%	In order to get a concentration of CO_2 stable, we want a net flow = 0, thus we want uptake = emission.
		For the amount to stabilise, input and outflow have to have the same value. The only graph showing this is the third one. The absolute values are irrelevant. The trend could as well be positive, providing the lines for input and outflow are coincident.
No accumulation	7.5%	The amount CO_2 in the atmosphere is dependent on inflow minus outflow. In order to stabilize the total, you need to stabilize this difference, as seen in [alternatives] 1 and 2.
Historic debt balancing	7.5%	The historical CO_2 emission shows that the difference between intake and uptake has been increasing and is getting bigger over the years. This means that in order for the level to stabilize, the intake needs to make up for all of these past bigger increases and that can only happen if over the coming years intake is inferior to uptake.
Pattern reasoning	**25%**	The leveling off in [alternative] 2 seems to match the graph in my answer.
		If CO_2 stabilizes then everything stabilizes.
Phenomenological reasoning	**17%**	The emissions levels will keep rising on our current course and uptake will stay the same because of deforestation and population growth.
		My reasoning is based on the premise that at the early stages of human existence, there was less population and less pressure on the environment because early humans were basically hunter gatherers who moved from one place to another and depended less on the environment. As the population increases there became an immediate need to sustained the growing population, accompanied by industrial revolution with increasing technology. All these resulted to a systematic increase in emission of Carbon dioxide into the atmosphere because the forest is systematically exploited, creating a scenario where the emission of carbon dioxide far exceed the absorptive capacity. Maintaining the emission capacity from now until the end of the century means that exploitation of natural resources that emits carbon dioxide will systematically be reduced, and at the same time maintain the absorptive capacity of carbon dioxide.
Not categorized	**24%**	

* Includes a 6% that that cannot be placed into one of the three subcategories

4.2.4 Conclusions

The question of whether the general public understands CO_2 accumulation is not as simple as it seems. In this mixed methods study of public understanding of atmospheric CO_2 accumulation and climate policy support, we extend previous research on SF failure by showing that:

- Seemingly similar SF tasks may assess different types of knowledge, and people perform significantly better on tasks assessing declarative and procedural knowledge compared to tasks assessing situational knowledge.
- When faced with a climate SF task, most respondents use one of three overarching ways of reasoning: system reasoning, pattern reasoning, and phenomenological reasoning.
- Supporting strong climate policies does not require an understanding of climate science, as measured by performance on the SF tasks used.

Taken together, our findings show that SF failure can be due to an incorrect mental representation of SF tasks, rather than a poor understanding of the principles of accumulation.

4.3 PAPER IV

4.3.1 Aims and research questions

Previous research has demonstrated that even university students perform poorly on tasks that ask about the relationship between CO_2 emissions and uptake for the amount of CO_2 in the atmosphere to stabilize. However, less is known about what difficulties the students experience in dealing with such seemingly simple tasks, only involving mass balance, but placed within the carbon cycle and climate context. Against this background, the aim of the qualitative study reported in Paper IV was to explore university students' reasoning about atmospheric CO_2 accumulation and to identify challenges to correct reasoning. A secondary aim was to explore students' conceptual understanding of the carbon cycle, with a focus on the nature and role of the uptake of CO_2.

In this paper, we addressed the following research questions:

G. What challenges do engineering students experience when dealing with tasks involving atmospheric CO_2 accumulation?
H. Are these challenges of a cognitive, metacognitive or affective nature?
I. How do students conceptualize the relationship between CO_2 emissions and uptake?

4.3.2 Methodology and methods

A *purposive* (rather than random) sampling strategy was used to select students (N=10) from the third-year engineering course in environmental mathematical modelling that I teach. The main reason for selecting students from my own course was that I expected that my understanding of the student group and their educational context would be beneficial for my analysis of the students' way of reasoning (Krefting, 1991). The purposive selection of students was done based on the notion that "certain categories of individuals may have a unique, different or important perspective on the phenomenon in question and their presence in the sample should be ensured" (Robinson 2014, p. 32). Consequently, the results of this study should not be viewed as representative of a larger population. Rather, the main purpose was to provide a "thick description" (Geertz, 1973) of how the students in the sample experienced dealing with the tasks. It is then up to other teachers to judge whether the results are relevant to their teaching context (Merriam 2009). While the sample size may have limited the diversity in the challenges identified and described, if nothing else is stated at least two of the students experienced the challenges here described, which is to say that the challenges are not unique to one student but may be more or less frequent in the population of engineering student.

Data was collected through *semi-structured interviews,* allowing each student "*to express meaning in his or her own words and to give direction to the interview process*" (Brenner 2006, p. 357). During the interview, the students were, for example, asked to draw a conceptual model of the carbon cycle, and discuss different scenarios for emissions and uptake. The tasks were largely designed to probe students' conceptual and mathematical understanding of the relationship between stocks and flows that determine the amount of atmospheric CO_2.

The interview transcripts, together with the drawings and diagrams produced by the students during the interview, was then analyzed using an *inductive thematic analysis* (Braun & Clarke 2006). As the name suggests, this means "letting the data speak" and looking for themes that cut across the data. After testing various ways of formulating such themes, or categories of difficulties, we realized that there were similarities between our themes and a framework for mathematical thinking proposed by Schoenfeld (1983;1992). According to his framework, beliefs metacognition and different types of cognitive resources are all important and interacting components in mathematical thinking. In what follows, we interpret beliefs to also include attitudes and the affective side of reasoning.

4.3.3 Results and discussion

We identified five categories of challenges to correct reasoning about atmospheric CO_2 accumulation, ranging from purely cognitive challenges to both metacognitive and affective challenges. These categories of challenges, examples of specific challenges, and the corresponding domain in Schoenfeld's framework (Schoenfeld 1983, 1992) are summarized in Table 6 (see Paper IV for the full table).

While the majority of the students readily understood that emissions need to equal uptake for the stick to stabilize, none of the students conceptualized the uptake of CO_2 as a function of the emissions pathway (without priming). Consequently, none of the students relied on a mental representation of the carbon cycle that could make sense of the need to reach zero emissions to stabilize the amount of CO_2 in the atmosphere, which is a pre-requisite for a stable climate[25]. People's reliance on incorrect mental models and people's confusion on wether ozone is involved in the carbon cycle are examples of several challenges identified that have been documented before (McCaffrey 2008).

Table 6. Summary of findings: Examples of challenges, categories of challenges, and domain

Domain	Category of challenges	Challenge
Cognitive	1. Identifying and conceptualizing components of the carbon cycle	Role of uptake Role of oceans Emissions going out into space
	2. Applying principle of mass balance	Pattern matching Writing atm. CO_2 amount as a math expression
	3. Uptake's dependence on emissions pathway	Uptake as a function of emissions pathway What happens at zero emissions?
Metacognitive	4. Being aware of and regulating thought processes	Controlling qualitative problem representation Controlling results and implications of used model
Affective	5. Beliefs, attitudes and affections	Subcategory 5A – The climate change context: What is going to happen; What I want to happen; Apocalyptic thoughts Subcategory 5B – Problem solving as an eng. student: Feeling uncertain; Not knowing enough maths

In addition to the cognitive challenges, the students faced metacognitive challenges. Much like Schoenfeld Schoenfeld (1983;1992), we found that metacognitive skills were not used to monitor and control the problem-solving process: the students spent a significant amount of time talking beside the point of the question, or started out using the first mathematical problem-solving approach that came to mind without reflecting on if it was an appropriate approach to use. This lack of reflection and proficiency in problem solving was striking to me. While my impression was that the students did their best in dealing with the tasks, there was clearly room for improvement as the students (on average) neither applied background knowledge (that they showed signs of having) consistently nor were they able to use data presented to them to control the answers they provided. One possible explanation for this is that the students lacked experience of dealing with real-world problems (Jonassen, Strobel & Lee 2006; Wedelin et al. 2015). Experience is an important (internal) factor in problem solving and "experiences are phenomenological and are normally conveyed through stories" (Jonassen 2007, p. 17). At the same time, such "stories" or dominant narratives can also hamper problem solving, as demonstrated by sub-category 5A. This sub-category describes how the tasks triggered different types of "stories" related to climate change, resulting in lengthy discussions on system details or what needs to happen, instead of focusing on the data provided and the relationship between emissions, uptake and the amount of CO_2 – what was dubbed *phenomenological* reasoning in Paper III.

[25] Assuming no significant geo-engineering efforts are put in place.

While some of the affective challenges, like feeling stupid for not being able to directly solve the tasks, may pertain to the nature of the interview situation and the group of students, others, like wishful thinking and apocalyptic thoughts, are likely to exist more gnerally, and under other social circumstances as well.

4.3.4 Conclusions

This study contributes to the literature on SF failure in a climate context by using a qualitative research approach and by moving beyond a focus on purely cognitive challenges to include both metacognitive and affective challenges. This turned out to be a most fruitful approach, as serious challenges were identified in all three domains.

Turning to practical implications, we suggest that educators and communicators focus on what uptake is, how it works, and that descriptions of it may benefit from including an explanation of the role of the natural carbon cycle. This involves explaining that the carbon cycle and the climate[26] will be in balance only if zero net emissions is reached. Moreover, given the importance of metacognition and the poor metacognitive skills demonstrated by the students, we see a strong need to focus more on such skills in engineering education.

Finally, the identification of several affective challenges suggests that future research in this area should pay more attention to emotions, attitudes and beliefs. A particularly interesting and important avenue for future research would be to develop and test affective scaffolds, that is, strategies for helping students to deal with emotions, attitudes and beliefs that might hamper problem-solving.

4.4 SYNTHESIS FOR PAPERS III & IV

4.4.1 Overarching insights

Combined, the two papers on understanding CO_2 accumulation (Papers III and IV) tell us about the multitude of ways of reasoning used[27], and the variety of challenges experienced, by individuals when faced with different SF tasks. In Paper III, we draw attention to five distinct ways of reasoning, which are then categorized into *system* reasoning, *pattern* reasoning, and *phenomenological* reasoning. In Paper IV, we explore the challenges experienced by university students when dealing with SF tasks, and classify these as *cognitive*, *metacognitive*, and *affective* challenges. We also note substantial inconsistencies in the ways of reasoning used by the students on similar CO_2 accumulation tasks, which likely imply that they are not using a single stable mental model, but rather have a limited confidence in what knowledge to draw upon, highlighting the role of *situational knowledge* in solving these tasks (de Jong &

[26] This assumes no other changes in climate forcings from other climate forcers. Which is a fairly strong assumption, but here serves a pedagogical point.

[27] By two different groups – see the method section of respective paper for a short description of the groups.

Ferguson-Hessler, 1996). Finally, as climate scientists, our emphasis on the students' conceptualization of uptake and its dependence on the emissions pathway, tell us that students' prior knowledge of how the uptake of CO_2 in the atmosphere respond to human emissions is very low.

With these insights – and the methods used to arrive at them – we demonstrate the value of mixed methods and qualitative research to explore the breadth and depth of a phenomenon – *SF failure* (Sterman & Booth Sweeney 2007) – that mainly has been studied using quantitative research methods. In this way, the present thesis makes an important methodological contribution. However, the endeavour to address blank- and blind spots in this research area has only just begun. Achieving the main aim of this research—to inform educational and outreach practices related to climate change—will require substantially more research.

4.4.2 Contributions and implications for research

The use of theoretical perspectives and research methods in this thesis which have not been standard tools of the SF failure research so far have contributed to shining new light on SF failure. The emphasis on the role of experience and reasoning related *internal factors* (Jonassen 2007) in dealing with CO_2 accumulation tasks and the notion of *different forms of knowledge* needed for different types of tasks (de Jong & Ferguson-Hessler, 1996), suggests new entry points for future research using theoretical and methodological tools borrowed from other disciplines and contexts to study reasons for SF failure. The goal of CSL, to contribute to understanding that can inform attitudes and behaviour that in various ways could limit people's impact on the climate, remind us of the importance to see to the big picture and focus SF failure research on tasks of CO_2 and climate stabilization which rely on an accurate representation of the uptake of CO_2.

An appreciation for the potentially many and context dependent reasons behind SF failure would in turn lay the ground for research on how to design effective learning experiences, for both formal and informal learning contexts. Studying the complex interplay between cognition, attitudes/values, and behaviour – and the knowledge-behaviour gap at the centre of the climate challenge (McCaffrey & Buhr 2008; Moser & Dilling 2011; Wibeck 2014) – is from my perspective one of the most important research topics ahead. Research on this topic, conducted in an inclusive[28] way, may lead to increased public understanding of what atmospheric CO_2 accumulation means for the limits needed to human activities that emit CO_2. This will require some kind of *integral approach*: the best use of the many tools of the many disciplines related to it (Esbjörn-Hargens 2010; O'Brien 2010).

[28] For example in the form of so-called citizen science with different activities aimed for climate science engagement and mutual learning.

4.4.3 Contributions and implications for practice

Educators and communicators have a daunting but very important task ahead. The work presented in Papers III and IV reveals many misconceptions, several ways of reasoning, and several challenges (from cognitive and metacognitive to affective) that people face when dealing with CO_2 accumulation tasks. Regarding the general public, and different audiences around the world, the sample studied (in both papers) represents a highly educated group of mostly pro-sustainability students. Even though the group studied in Paper III came from many different countries, it should be expected that additional challenges (such as religious, ideological or total incomprehension due to severe lack of prior knowledge) will be present to various extent for other target audiences.

Given the level of complexity of CO_2 accumulation, and the limited attention climate science gets in school as well as in teacher education (e.g. McCaffrey 2008), it is likely that most educators and communicators will first need to deepen their own understanding before assisting others with theirs (Plutzer et al. 2016). It is a challenge for educators and communicators, perhaps with the assistance of a "content knowledge expert" (see Figure 18 in Chapter 7), to engage in education or communication on the subject of CO_2 accumulation. Kierkegaard (Section 4.1) frames the need to get to know your audience beautifully. I suggest that you focus on getting to know your audience weak points, strengths and interests in the topic. From there the route towards a sound appreciation of how CO_2 emissions cause CO_2 accumulation will be context dependent but likely deal with some combination of:

1) the physical properties and fate of the emitted CO_2 as well as the audience preconceptions about them;
2) the natural carbon cycle and the balancing dynamics of the carbon reservoirs as well as the audience preconceptions about the natural carbon cycle;
3) sources and sinks of CO_2 emissions and the uptake's dependence on CO_2 emissions (including audience preconceptions and mental model applied);
4) preconceptions of what will happen or needs to happen with CO_2 emissions in the future;
5) confusion or mix up of the issue with other (often sustainability related) concerns such as depletion of the ozone layer; and
6) affective sides of reasoning about an issue that is politically debated and associated with policies that will be disliked by some and appreciated by others, and related climate impacts that will vary dramatically between different parts of the world.

I would like to end this chapter on public understanding of CO_2 accumulation with an additional few words by Søren Kierkegaard, emphasizing the importance of taking the perspective of the learner, which has been a re-occuring realization of mine during the work with Papers III-IV. Kierkegaard (1864) wrote:

> *For to be a teacher does not mean simply to affirm that such a thing is so, or to deliver a lecture, etc. No, to be a teacher in the right sense is to be a learner. Instruction begins when you, the teacher, learn from the learner, put yourself in his place so that you may understand what he understands and in the way he understands it.*

5 PAPER V

Title: Location choice for renewable resource extraction with multiple non-cooperative extractors: a spatial Nash equilibrium model and numerical implementation

5.1 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 non-timber forest products extraction. It analyses a spatial non-cooperative equilibrium of extraction patterns 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, only extracting in one location or across one dimension of a forest. The aim of Paper V is to develop a model with which to examine how these commonly used modelling assumptions affect the predicted villager interactions and extraction patterns as well as the spatial degradation patterns. The research questions were:

I. How can we build a multi-agent numerical model that allows us to explore interactions of actors' (villagers) spatial extraction choices for different spatial landscapes and access to labour market?
II. What are the effects on patterns of extraction of non-timber forest products and returns to villagers from the following simplifying assumptions: using a representative agent and restricting the patterns of extraction?

5.2 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 any combination of patches in the two rays of forest patches modelled on a symmetrical grid a distance from the village (see Figure 15). This forest extraction labour can optionally be complemented with or fully exchanged to non-forest wage work.

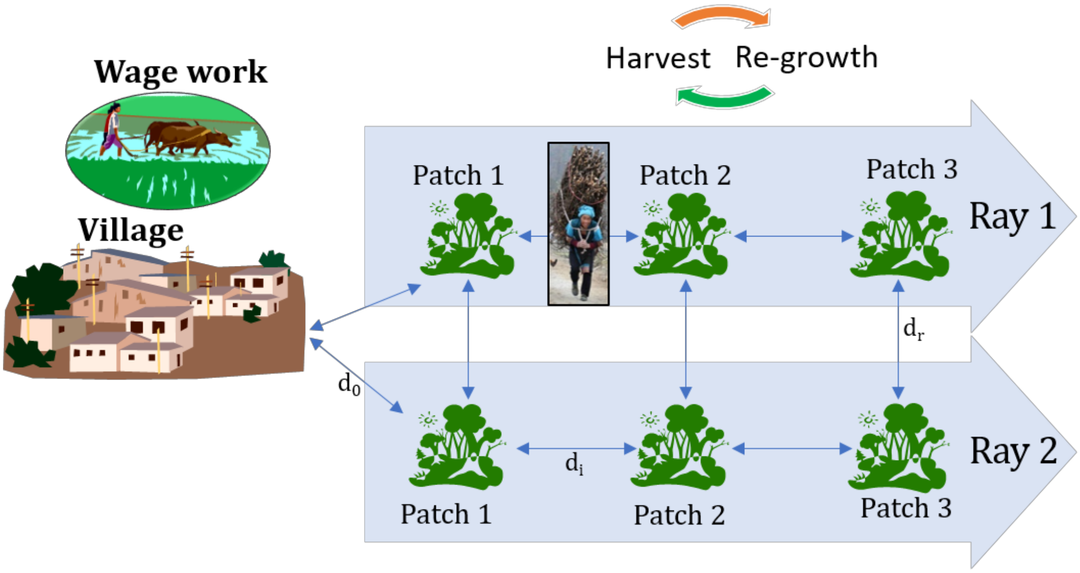


Figure 15. A schematic illustration of the model were villagers (N=18 in this analysis) can choose to extract NTFP from any combination of forest patches and or spend time doing wage work. After each round of harvesting the forest resource is assumed to re-grow following a logistic growth function.

The numerical solution method is set up as an agent-based model, which is used to find a labour allocation scheme constituting a spatial Nash equilibrium[29] for the villagers' labour allocations. This procedure, containing an extraction (or harvest) function and a wage function for the non-forest wage work, is combined with a logistic growth function used to calculate the amount of regrowth following the extraction of a generic non-timber forest products 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. By restricting the agents (i.e. villagers) to perform in accordance with commonly used assumptions of earlier models in the literature (Robinson et al. 2002, 2008; López-Feldman and Wilen 2008; Albers 2010) we explore the effect of using: representative agents, single-patch extraction and single ray extraction.

5.3 Main findings

Villagers that face the same landscape, objective function, and labor endowment choose very different sets of patches from which to extract (see Figure 16 for an intermediate distance), with these choices highly sensitive to the distances between resource patches. For example when distance costs are sufficiently large, for each distance there is one unique spatial Nash equilibrium in which each villager either extracts from just one patch or only engages in wage labor. Using a spatial agent-based method of sequential labor allocation plans that iterates towards a Nash equilibrium, our solution method reveals the spatially heterogeneous extractor behaviour.

[29] In terms of spatial distribution of resource extraction and non-forest wage work per villager, which no villager would gain by deviating from.

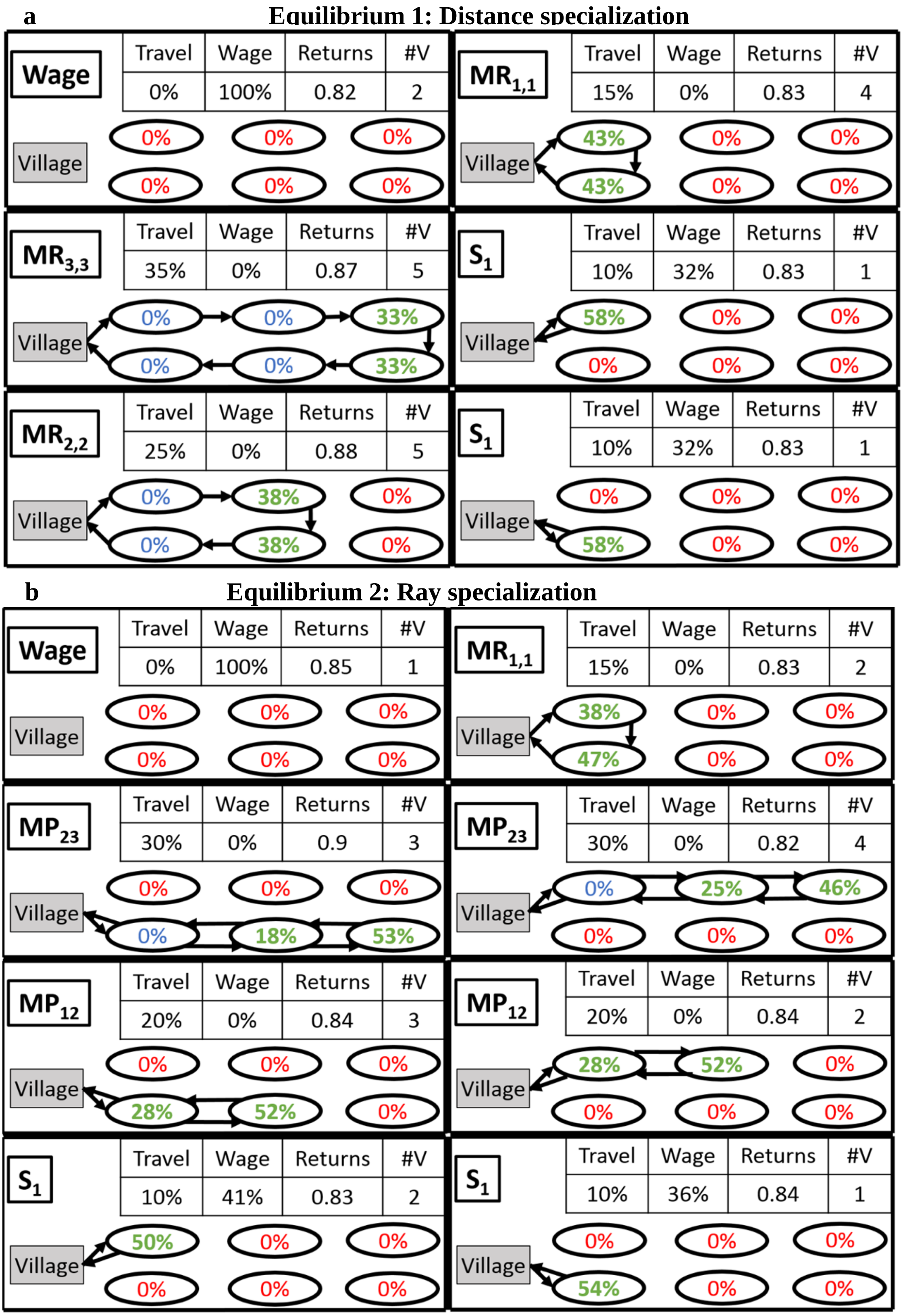


Figure 16. Extractor types and labor choices for two Nash equilibria for the "Intermediate" distance (d=0.05) scenario. In the first equilibrium (16a), the majority of the extractors extract at a certain distance away from the village. The second equilibrium (16b) is characterized by a majority of extractors going to only one ray.

For the simplifying assumptions that use a representative agent we find that for both small and intermediate distances, extractors enter all six patches, behaving as identical extractors. For the intermediate distance in this one-patch extraction only constrained case, we find fewer extractors on average in each patch, with those extracting from patch 3 obtaining returns to their labor almost 20% greater than for the unconstrained individuals who extract from patch 3, but those extracting from closer patches obtaining lower returns. These solutions show that simplifying assumptions such as representative agents and single-patch extraction can misrepresent the extraction patterns across the spatial setting and cannot reveal complex patterns of extraction pathways or heterogeneity in choices even from ex ante identical extractors. A representative agent assumption is most likely to misrepresent the extraction patterns of villagers when distances between patches are larger, and underestimate total extraction and thus degradation. A single patch extraction assumption is most likely to misrepresent the extraction patterns of villagers when distances between patches are smaller. Multiple equilibria are found and exhibit a variety of differences in villagers' extraction pattern that do not affect the overall extraction.

5.4 IMPLICATIONS

Different model assumptions generally suggest small differences in resource profile and overall stocks, but much greater differences in the number of extractors found in each patch. The unconstrained model typically finds many more individuals extracting in each patch. This outcome has implications for conflict between extractors, and for species that are not extracted or hunted, but are sensitive to human presence. Differences in the returns to individuals are also found for the variously constrained model assumptions explored. Such differences in the returns to individuals are much smaller for the unconstrained model suggesting that models using simplifying assumptions may overestimate inequities between villagers.

This model provides flexibility to explore important policy options relevant particularly to a lower-income setting, in contrast to more constrained models. For example, our model finds that we should expect relatively large numbers of villagers extracting in any one area, with a risk for conflict between these villagers under open access settings. This model is particularly useful for exploring explicitly spatial management of a landscape, in which policy makers can choose to introduce protected zones, managed zones, and open access zones; or alternatively to restrict the total amount extracted and allow extractors to choose from which locations they collect the resource.

6 DISCUSSION AND CONCLUSIONS FOR PAPERS I-IV

What to do about climate change?

What mitigative actions should be taken?

Different human activities affect the climate in different ways depending on what climate forcers are emitted[30] as a result of the activities. *Comparing different climate forcers* entails valuing climate impacts on *different time scales* and making trade-offs between short-term and long-term climate change. To be able to do this in an insightful way there is a need to understand how different climate forcers affect the climate over different time scales. Central to this is *understanding the atmospheric residence time and accumulation of CO_2*, a feat that to many have proven challenging. Learning about these aspects of climate change can be facilitated using models, metrics and meaning making.

That is the core of what this thesis is all about. In this chapter, I weave together key insights from Papers I-IV to discuss more overarching insights, and this is followed by a discussion of some contributions to and implications for research as well as policy and practice.

6.1 OVERARCHING INSIGHTS AND DISCUSSION

Appreciating the long-lived nature of climate impacts from emissions of climate forcers is challenging. Several aspects of this have been found (e.g. all climate forcers affect SLR over long time and people face many challenges to understanding CO_2 accumulation) and explored by using different perspectives and tools belonging to different disciplines from both natural and social sciences. Designing metrics to compare short- and long-lived climate forcers requires a careful consideration of: 1) what climate impact to compare, 2) how to model or assess the climate impact chosen for comparison, and 3) over what time horizon and with what treatment of time[31] should the impact from the forcers be compared. Climate scientists have performed numerous studies which vary these aspects of climate metrics. Two contributions of this thesis were to explore, explain and quantify the following two aspects (belonging to point 1 and 2, respectively):

- The climate impact of different forcers in terms of their estimated future contributions to sea-level rise (i.e. developing the metrics GSP and IGSP), which lead to the conclusion that even SLCFs have long-lived climate impacts (Paper I).
- How differences in how the CCF is modeled affects GWP and GTP metric values. We conclude that for emission metrics to be internally consistent, the

[30] Or by affecting the climate in other ways such as affecting Earth's surface reflectivity (albedo).

[31] Climate impacts can be valued at one point in time, for a time interval or using a discount rate.

way this feedback is modeled should be the same for all forcers and should capture how the carbon cycle responds to warming (Paper II).

But if the emission metrics should be used to inform analysis as intended, the implications of the choices with regards to point 1-3 above needs to be clear to the practitioner. The practitioner will also need to have at least a basic understanding of the climate impact of CO_2 emissions[32] over time, to be able to appreciate the implications of the trade-offs the use of emission metrics implies (for example when choosing to compare to emissions abatement alternatives).

Papers III and IV draw attention to the many different ways people reason about CO_2 accumulation when solving CO_2-stabilization tasks. In Paper III, these ways of reasoning were categorized into system reasoning, pattern reasoning, and phenomenological reasoning. In Paper IV we identified and described many challenges that university students experience when reasoning about CO_2 accumulation, and these were categorized as cognitive, metacognitive, or affective challenges. These challenges, including the identified and major challenge of understanding why uptake of CO_2 depends on the emission pathway, may contribute to a better understanding of the reasons for the knowledge-behaviour gap our global society finds itself in (McCaffrey & Buhr 2008; Moser & Dilling 2011; Wibeck 2014).

While climate science iterates the message that global emissions of CO_2 need to drop rapidly to meet any climate target that stabilizes the climate within this century. To meet the 1.5 degree target for example (see Figure 1), CO_2 emissions need to drop by the, largely unimaginable, rate of about 50% per decade, it should perhaps be considered a blessing rather than a curse that people's behaviour is decided by more factors than knowledge (e.g. Hamilton et al. 2015; Gifford 2011; Wibeck 2014). It is also possible that the traditional approach of assessing conceptual understanding of CO_2 accumulation, mainly using multiple-choice questions based on a certain type of SF tasks (see Paper III), provides a misguided measure of people's understanding of CO_2 accumulation. Indeed, using a "plain text" format and a question that directs the participants' attention towards the relationship between emissions and uptake of CO_2 resulted in a success rate of 50% in Paper III (and more than 70% in Fischer et al. 2015, p. 262). And a vast majority (8 out of 10) of the students whom I interviewed managed at some point to appreciate that emissions must equal uptake (see Paper IV). However, these findings do not include the fact that it is also necessary to understand that uptake will fall with diminishing emissions, meaning that emissions need to go to zero rapidly for a CO_2 stabilization.

The complex interplay between cognition, metacognition, and affect/attitudes when reasoning about CO_2 accumulation reminds us of what role knowledge may play in attitude formation and vice versa. The fact that half of the students interviewed for Paper

[32] Because of its role as the most important climate forcer, CO_2 is used as the reference point for the most common emission metrics.

IV spontaneously said that *"CO_2 emissions should be reduced"* (as their intuitive first-thought to a task[33]) is an example of how attitudes may override cognition, as the students automatically referred to the importance of reductions in emissions when answering a general question about atmospheric CO_2. The ideas behind transformative sustainability learning by Sipos et al. (2008) come to mind, as we see how knowing (head), acting (hands) and being (heart) are all involved in challenges experienced when reasoning about CO_2 accumulation tasks. Which is perhaps not a surprise and reminds us of the many aspects of resolving the knowledge-behaviour gap (McCaffrey & Buhr 2008; Moser & Dilling 2011; Wibeck 2014).

6.2 CONTRIBUTIONS AND IMPLICATIONS FOR RESEARCH

The main contributions of Papers I-IV to research are:

- The illumination of two blank spots of emission metrics research: SLR as a basis for comparison and the importance of including the CCF for all climate forcers in a way that reflects how warming affects the carbon cycle.
- A problematization of what it means to "understand" CO_2 accumulation and an exploration of challenges that university students experience when dealing with CO_2 accumulation tasks.
- Together, these papers and the thesis as a whole highlight the value of combining different perspectives to advance the ways in which climate science knowledge is made available and engaging to the public. In other words, the value of an *integrative* approach.

Implications for research range from the need for studies on how practitioners understand and use metrics (which rely on an understanding of the atmospheric residence time of CO_2), to under what circumstances knowledge plays an important part in attitude and behaviour formation. On the note of understanding the physics captured by emission metrics: If SLR metrics (Paper I) were to be used as the basis of comparison of different climate forcers[34], I argue that it would be necessary to study how people conceptualize the link between emissions of climate forcers and SLR. This is a topic that to my understanding has received very little attention – a quick search only yielded one hit of an empirical study related to the topic (Danielson & Tanner 2015), but which focused on ocean acidification. Danielson and Tanner (2015) finds that SLR is mentioned as a climate change impact on the oceans, in an free text question, by 50 % of teachers (small sample size, N=12) and a similar number among students. I believe the link from CO_2 emissions to SLR will be even more challenging to comprehend than the accumulation of CO_2 (which is only "one link" in the cause and effect chain of climate change).

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[33] In response to a question on what is important for the amount of CO_2 in the atmosphere.

[34] Which may be an option for decision makers whose primary concern for climate mitigation actions is SLR and related impacts and damages.

Further research into the challenges people experience when reasoning about CO_2 accumulation and taking part in different types of learning activities in different stages of schooling, would be of high relevance for developing learning material and activities to overcome these challenges. Varying the cultural context for data collection would likely also contribute to a broader understanding of how to adapt or design learning material for the different cultural contexts. Likewise, there is a great need to further assess and suggest improvements for the type of material IPCC and other similar bodies give out to inform decision makers and the general public about climate science. Examining the working group 1's Summary for Policymakers of AR5 (Stocker et al. 2013) it looks like the style of presenting results has not changed significantly since the seminal study by Sterman and Booth Sweeney (2007), drawing on material from the IPCC's Third Assessment Report and Summary for Policymakers (Houghton et al. 2001).

Finally, my take on the global situation today is that if universities are to step up to the challenge of providing the knowledge needed (and possibly being an active agent in other regards as well) for a transformation of the global society to respond to the threats of climate change, a lot needs to happen. This includes that the focus in many disciplines and among many researchers and educators needs to be adjusted towards this challenge. If the international academic community does not try to show the way towards a sustainable future, who will?

6.3 CONTRIBUTIONS AND IMPLICATIONS FOR POLICY AND PRACTICE

The main policy implication of Paper I is that even SLCFs have long-lived climate impacts and that this impact is to a large extent captured by the GWP emission metric, but not by the GTP. Paper II highlights the effect of using emission metric values that take into account the CCF in a way that captures the dynamics of how the feedback affects the carbon cycle.

The main implication of Papers III and IV for educational practice and policy is straightforward: there is a need for more learning objectives and research-based learning activities within the area of CSL, and specifically on CO_2 accumulation. These learning activities should start from the point of view of the learner in the sense that they should address common misconceptions and different types of challenges. To this end, the present thesis makes a valuable contribution by providing a rich description of such misconceptions and challenges.

Another important message to educators and communicators is that the "knowledge deficit model" (Moser & Dilling 2007; McCaffrey & Buhr 2008; Wibeck 2014) has limited value as an explanatory model since it posits that a lack of knowledge is the main reason for the limited climate policy support and action on climate change. Indeed, the knowledge deficit model has been questioned (Hamilton et al. 2015; Gifford 2011; Wibeck 2014) and it is not in line with the results of Paper III. There is a big support for emissions reductions in Sweden: in some polls, climate change comes out as the main environmental challenges facing our society, which also shows that Swedes are among the most environmentally concerned in Europe (Eurobarometer 2008). On the one hand, this is true despite the limited focus on climate physics in school (see Box 3) which iterates the message that a lack of knowledge does not necessarily hinder the formation of attitudes around the seriousness of climate change. On the other hand, the Swedish school system does integrate climate change and other environmental and sustainability related topics throughout mandatory schooling (see Box 3) – and in addition the dragons of inaction (Gifford 2011) and other barriers seem to be too many since the average carbon footprint, even for Swedes, is far from zero (Naturvårdsverket 2017).

Box 3. Analysis of Integration of Climate Change & the Carbon cycle in Swedish educational curriculum age ~13-19

The concept of *sustainable development* is well-integrated in the curricula of the Swedish school. At both elementary and "high school" level (actually "gymnasium" age ~16-19), sustainable development is integrated in the curricula of biology, physics, geography, chemistry and social sciences.

Climate is also a very well-integrated subject in the curricula of Swedish schools and mentioned in the curricula of physics, geography and chemistry at elementary level, and in the curricula of physics, geography, chemistry and natural sciences at high-school level. *Climate change* in particular is part of the central content of the courses in physics and geography at elementary level, as well as in the course in geography at high school level.

The *carbon cycle*, on the other hand, is not frequently mentioned in curricula of the Swedish school. In a review that we undertook, we found that the carbon cycle is only explicitly mentioned in the curricula of chemistry at elementary level, and in the course *biology – natural resource management* ("Biologi – naturbruk") at high-school level. While the first of these courses is mandatory for all students, the second course is hardly taken by a large proportion of Sweden high school students. It is noteworthy that the carbon cycle is not part of the general course in biology, chemistry or physics in high school (it is at least not part of the central content that the curricula explicitly mention; to what degree it is thought anyway is not known).

This survey was performed by Maria Nordborg (Oct 2018), on behalf of me. To find relevant information the following keywords were used: carbon cycle, carbon, climate, environment, global, warming, greenhouse effect and sustainable to search in the documents: "Läroplanen för grundskolan, förskoleklassen och fritidshemmet (Lgr 11)", "Grundskolans kursplaner", "Läroplanen för gymnasiet (Gy 2011)" and "Gymnasieskolans ämnesplaner". The following documents were also searched: "Skollag (2010:800)", "Skolförordning (2011:185)" and "Gymnasieförordning (2010:2039)" but yielded no relevant keyword matches.

Providing behaviour-relevant knowledge and knowledge with some level of complexity has been found to contribute to attitude formation and attitude-behaviour consistency (Edwards 1990; Fabrigar et al 2006), and was also suggested by Wibeck (2014) as ways to engage the public. If these findings are applicable to narrow the knowledge-behaviour gap related to climate change as Wibeck (2014) suggests, then it is possible that new learning and communication activities (Macintyre et al 2018) – which explicitly address and overcome the challenges (of cognitive, metacognitive and affective nature) outlined in this thesis and primarily in Paper IV – could contribute to attitude formation that can induce behavioural change. As also suggested by Wibeck (2014), I believe that these climate learning and engagement activities benefit from being concrete (in which visualisations and physical representation can aid) and from focusing on people's personal climate footprints with direct and personalized suggestions on how to reduce one's own footprint. If it is made easy and attractive to change I believe that this could contribute to change in consumer behaviour as a part in a heads, hands and heart transformation towards more sustainable life styles. In Sweden we start to see trends of a shift in some areas, with a lowered meat consumption (Kihlberg 2018), a heated debate about aviation's climate impact (Sandahl & Lexén 2018) and even elite athletes turning vegetarian in a bid to reduce their climate impact and affect misconceptions about vegetarian food (Sveriges Radio 2018). I believe these movements, including natural role models which can affect people who identify with them, is a necessary complement to policy instrument for reduced societal climate emissions, if the Paris Agreement (Paris Agreement 2015) is to be lived up to. It is also my personal view that such efforts go hand in hand for making real progress on climate change in a meaningful way.

7 Outlook and Reflections on Doing a Cross-Disciplinary PhD

In this final chapter, I will use my PhD journey – and the cross-disciplinary approach of this thesis – as a narrative to try to highlight the need for an integral approach when working on sustainability challenges like climate change (Petrie 1976; Wagner 1993; Esbjörn-Hargens). I will do this first through a brief chronological recapitulation of my way towards CSL (including the presentation of a pedagogical interactive model I developed while working on metrics), which is followed by my reflections on the benefits of carrying out a cross-disciplinary PhD thesis, and a brief outlook for CSL. The outlook for CSL is based on the insights I've garnered in writing this thesis and instead of focusing on what topics should be added to educational curricula around the world or which misconceptions are key to improve CSL, it focuses on the actors around CSL and the changes in their roles that I believe needs to come about. Finally, the thesis ends with notes on the, to me, very important question of what people need to know about climate change in order to bridge the knowledge-behaviour gap (Moser & Dilling 2011).

7.1 A recap of my PhD journey

7.1.1 From climate science…

In my MSc thesis and in the beginning of my PhD I created simple (or "reduced-complexity") climate models to study the climate impacts of emissions of SLCFs. Naturally we compared these effects with the climate impacts of emissions of long-lived climate forcers, mainly with carbon dioxide. The modelling work and the model results were insightful, and I appreciated and learnt from the effort of trying to describe the climate system and its dynamics in terms of the energy balance, the carbon cycle, climate sensitivity and human forcing. What we learnt about the relative climate effect of SLCF compared to that of CO_2 was (Paper I and II) expressed in the most concise and potentially clearest format imaginable: metric values.

But, as I have explained and elaborated on in Chapter 3 and in Papers I and II, there is not only one way to compare climate impacts. I saw this as a pedagogical challenge, since when there is more than one important way to compare things (here climate forcers), where there are nuances that can have dire consequences for the livelihoods of many people and financial implications for big corporations and even nations, there is also a need to emphasize shared understanding – sometimes referred to as collective mental models or shared mental models (Jones et al. 2011).

In trying to explain the implications of using different climate forcers, I created an interactive model which I called the Climate Metrics Comparison (CMC) model. Instead of only producing one number for the relative climate effect of a climate forcer compared with CO_2, it displays in a graph-format a few climate impacts (or indicators) as they evolve over time for both the climate forcer that is being assessed and for CO_2 (see

Figure 17). By doing this, it allows the user to explore trade-offs between climate impacts resulting from the choice of emission metric and time horizon.

An example of this is displayed in Figure 17, comparing CH_4 and CO_2 using the GWP metric (which is based on integrated radiative forcing), with the time horizon chosen to be 100 years. This sets the model to find the amount of CO_2 that needs to be emitted so that the exact same integrated radiative forcing is caused (blue line) – as that caused by 1 kilogram of CH_4 (orange line). This is visualised in the top-right hand side graph with a black arrow pointing at the two curves having equal value (i.e. crossing) after 100 years in the graph of the integrated radiative forcing.

A different choice of time horizon will move the arrow to the new time horizon and the model will calculate how much CO_2 is needed for the two curves to cross lines at that point in time instead. Note also how different the curves are in temperature after 100 years; this indicates that using GTP with a 100 year time horizon would yield a totally different result (see Papers I-II).

While I believe this type of tool can be very useful in supporting learning and appreciation of what emission metrics are and how they work, I felt, at the same time, that if a metric number is too much information put into a single number, this was still too much climate science knowledge put into a few graphs (for non-experts). To be able to grasp what this model was telling me, I had been a climate modeler for a few years and for someone who has not, there is most probably a few basic parts of the climate system that one needs to have a basic understanding of. Naturally I thought of the most important parts of the climate system (the carbon cycle and the energy budget) that we included in the simple models that we use in Papers I and II, which although simple still capture the yearly averages of some of the most important climate variables (Shine et al. 2005; Hoffert 1980).

7.1.2 … to CSL and public understanding of CO_2 accumulation

At that point I was shown the *Science* paper by Sterman (2008) and realized the need[35] for people to properly understand the nature of how CO_2 effects the climate over time (to contribute to the legitimacy of climate policies and encourage individuals reduced climate footprint). This is mainly because of the limited carbon budget and the emission reductions needed (Section 1.1), but also because CO_2 is used as the reference gas in metrics, which I experienced that few understood the meaning of. Because of the positive transformative experience my change of research field has meant to me, the next section will be dedicated to acknowledging what the experience of doing a cross-disciplinary PhD entailed for me.

[35] This need portrayed in this paragraph is based on value judgement as previously explained, which is an interpretation of what is needed to be able to avoid dangerous human interference with the climate system.

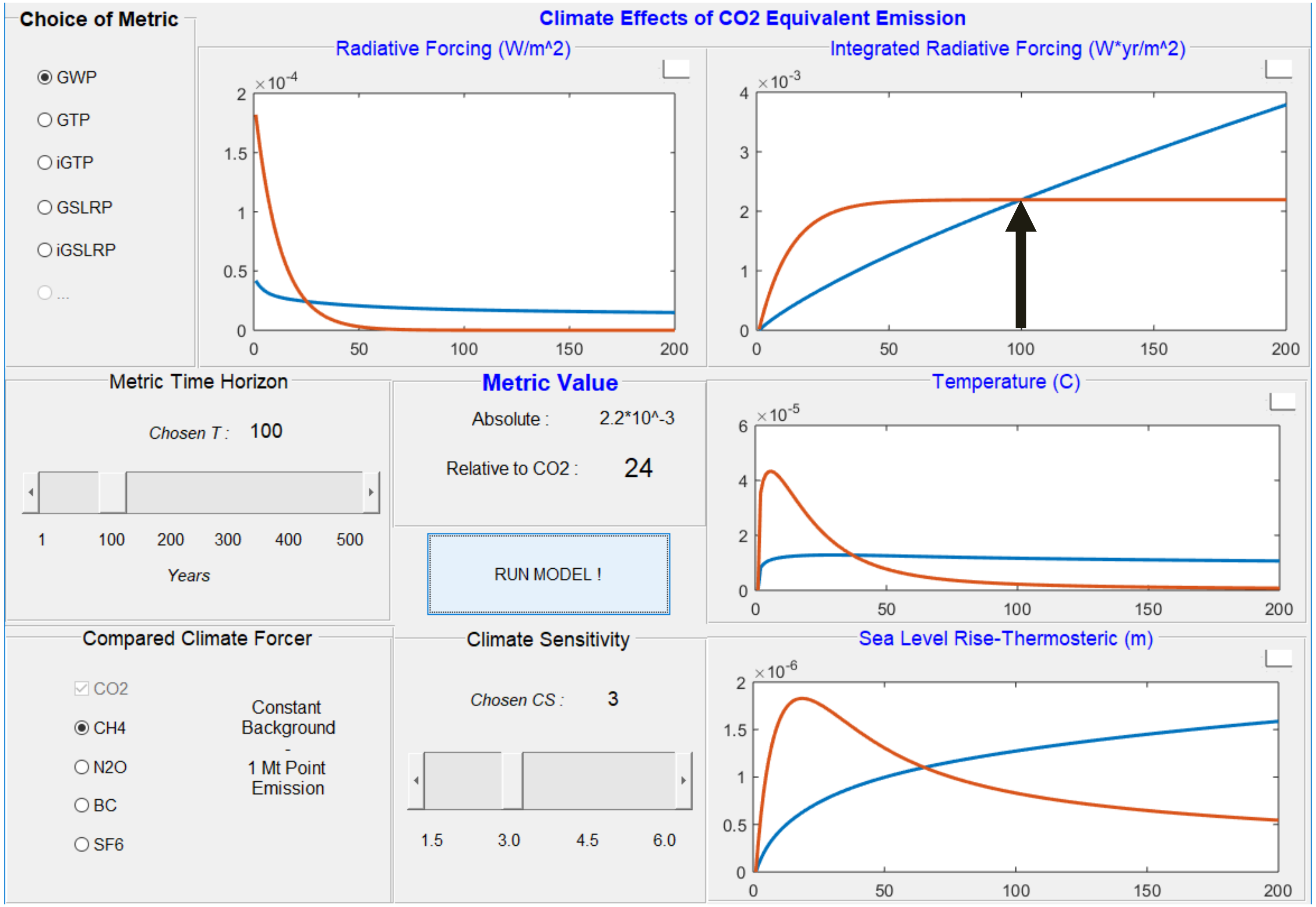

Figure 17. Comparing different climate impacts of CH_4 and CO_2 as a result of using the metric GWP_{100} (excluding CCF). Note how the Climate Metrics Comparison Model (CMCM) helps visualise the trade-off between short- and long term climate impacts that using the metric entails.

7.2 MERITS OF CARRYING OUT A CROSS DISCIPLINARY PHD

Getting to change direction of my PhD work after my licentiate offered an opportunity to engage in research on learning and public perception about climate change. This meant that I got a chance to try to figure out how I could contribute to engaging others in something that I had recently learnt and that felt important to me. In doing so I made room to nurture my interests in both the social and natural world we live in (see Preface). In addition, I also got the opportunity to reflect on my own learning and the relationship *between* the social and natural aspects of reality.

In my opinion, the merits of carrying out a cross disciplinary PhD thesis can be categorized to belong to the following areas:

- Bringing expert knowledge from one discipline into another (both ways). This opens-up for exploring new research questions that are missed out on if not using a combination of perspectives. In using a combination of lenses, there is both the benefit of using more than one lens and the benefit of switching perspective and not always "wearing the same old glasses", but instead moving back and forth between the focuses of the different disciplines (Krefting 1991). Distancing oneself from the "standard" way of conducting research and potentially viewing the meaning of the research differently may provide useful tests to the "normal science" within each discipline (Kuhn 1970; Wagner 1993).
- A greater appreciation for knowledge about knowledge and its acquisition – epistemological insights naturally follow, especially with the addition of the "learning perspective".
- Similarly, it is often the case that different types of research methods make up the standard toolkits of the different disciplines, which provides a cross-disciplinary PhD student with a more versatile set of tools for future inquiries.
- Reflecting on and being accustomed to literature from more than one discipline also makes it easier to appreciate research from yet more fields and prepares the PhD student for collaborations across disciplines. To regularly present and get questions and feedback on your work from people outside your direct field also contributes to a useful training in communicative skills useful for collaborations, utilization of knowledge etc.
- Potentially getting a larger audience and becoming more aware of the need to tailor one's messages depending on the current audience targeted.
- The benefits to the educational role that most researchers have *alongside* the research are major. This point has many facets to it. In my case: an increased appreciation for the complexities surrounding my students' learning processes, more access to competent help to guide me in my educational activities, the possibility to do research on the knowledge and learning of my students, etc.

Of course, there are not only benefits of engaging in cross-disciplinary work. It requires substantial efforts on behalf of the PhD students and his/her supervisors, and there is always a risk that the potential "edge" that is lost from not focusing on one discipline is not replaced by something greater, but instead by something that is not sharp enough for any of the two disciplines. I've knowingly and willingly taken this risk because of my belief that the world needs more bridge-builders to take on the challenges of today and tomorrow that, to me, requires sophisticated collaboration between experts from many schools of thought (e.g. Petrie 1976; Esbjörn-Hargens 2010; O'Brien 2010).

7.3 CLIMATE SCIENCE LITERACY – AN OUTLOOK

Insights from my whole PhD journey have in various ways led me to appreciate how difficult it is for everyone from non-experts, to well-educated adults and even to climate scientists, to grasp the complexities of climate science. I have also come to understand that to become engaging, knowledge of climate change needs to be co-created (Moser and Dilling 2011; McCaffrey & Buhr 2008; Wibeck 2014) and various stakeholders, with various views, need to be involved in the process (O'Brien 2010; Wals & Benavot 2017). In my view, Figure 18 illustrates the situation around CSL and climate science knowledge today and what might need to come about in order to be able to live up to the Paris Agreement. The left-hand side of Figure 18, places *climate science literacy* (CSL) at the centre of a model involving key stakeholders for action on climate change. The-right hand side of Figure 18 emphasizes that, in my opinion (if the world is to live up to the Paris Agreement), all of these stakeholders needs to become co-creators of knowledge, facilitators of learning, and motivators that engage more people in sharing and making sense and meaning of climate science knowledge. This conceptual model is rooted in insights gleaned from different areas: CSL (Wibeck 2014; McCaffrey & Buhr 2008), environmental attitudes and behaviour (Gifford 2011; Ryghaug 2011), active-(e.g. Dewey 1938) and social learning for sustainability (e.g. Arjen Wals 2007), and the trends that the global carbon budget effort point towards (Allen et al. 2009; Le Quéré et al. 2017). Put directly, the model captures my outlook on important aspects of what needs to happen to create the public support and opinion needed to transform policies as well as behaviour related to climate change.

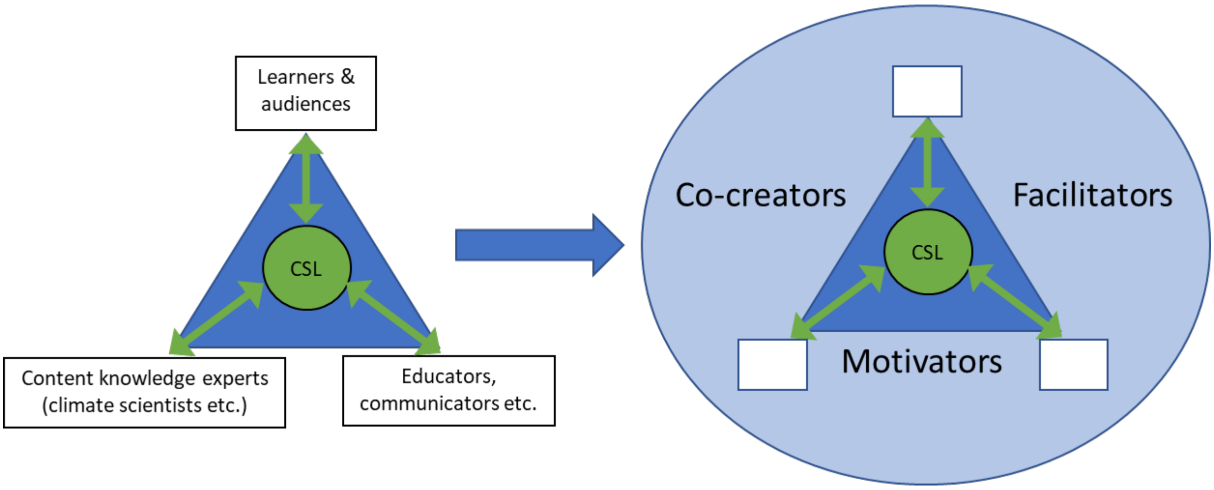

Figure 18. A conceptual model of what I deem necessary for the world to have a chance to live up to the Paris Agreement (Paris Agreement 2015). The model captures how all stakeholders need to collaborate to engage people in climate science literacy (CSL).

Finally to an important question

Does everyone need to know everything about how climate change works, to resolve the knowledge-behaviour gap (McCaffrey & Buhr 2008; Moser & Dilling 2011; Wibeck 2014)?

I believe not. Let me explain why. There are plenty of people who 1) do not eat red meat because it is healthier, 2) recycle because they get money back, 3) reduce their material consumption, 4) vote for parties that suggest high carbon taxes, 5) engage in (or donate to) environmental organisations, 6) invest in "green-tech" or 7) study sustainability oriented educational programs etc., without being knowledgeable in all of the mechanisms of the climate change cause and effect chain (I am for instance one of them). A nation can affect the behaviour of its citizens using different kinds of mechanisms, be it sticks, carrots, education, or calls to do good. To deal with the many ways human activities today cause climate change I believe in a need for a combination of all these mechanisms to assist us in the aspiration of climate change mitigation. It seems that we live in a world today, were science is being questioned or treated like any other sources of biased information with little acknowledgment for the rigorous procedures used in science and their value (Kofman 2018). At the same time, mandatory education is in place for the vast majority of Earth's population. I believe that higher degrees of science literacy can be attained through improved education overall. And when it comes to CSL in particular, I believe that if deep learning is acquired, if only for a subset of the climate cause and effect chain, positive and curious attitudes towards climate science at its whole can be attained (Fabrigar et al 2006). Especially so if a credible access to further knowledge (and tools to acquire that knowledge) on the different aspects of climate change is provided to the learner (to be used at their convenience). Ideally this would involve an appreciation of the science approach to learning including the corner stone of trusting the collective knowledge building through scientific inquiry and science-based academic education.

However, the sense- and meaning-making value of any level of understanding of the climate change cause and effect chain will depend strongly on the starting point of the learner. This is where it becomes crucial to recognize that what and how climate change should be taught and learnt must vary in response to the learner's pre-conditions and there should always be easily accessible material that serves his or her interests in learning about climate change.

Future research should look into how to strike the balance between science literacy in general and CSL in particular, balancing between thorough understanding of aspects of climate change and climate science. Crucial to this quest will be the integral appreciation of how attitudes and behaviour forms in the interconnected space that links our mental and social selves with our behaviour individually and collectively (Esbjörn-Hargens 2010; O'Brien 2010; Gifford 2011; Wibeck 2014; Wals & Benavot). It seems to me that the contributions of the many essential disciplines and non-scientific perspectives (cultural) on climate change will most likely be needed for the collective and social learning needed in the transformation of our societies that a constructive global response to climate change requires.

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IPCC - Appendix A to the Principles Governing IPCC Work

IPCC - Intergovernmental Panel on Climate Change. http://www.ipcc.ch/organization/organization_structure.shtml. Accessed 29 Oct 2018b