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**Uncertainties of low
greenhouse gas emission scenarios**

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Abstract

The scientific discoveries that lay the foundations of our current understanding of the global greenhouse gas (GHG) effect date back almost two centuries. Nowadays, warming of the Earth's climate system is unequivocal and human activities have been identified as the driving force behind it. The study of the potential impacts of climate change also brought to light the dependence of our global society on a hospitable environment. In recent decades, governments have therefore started to look at options to mitigate the imminent risks implied by rising global temperatures; the need for deep GHG emission cuts in order to stabilize the climate is now recognized in the international climate policy debate. However, despite their policy relevance, scenarios that explore how global warming can be kept to very low levels are under-represented in the scientific literature. As a consequence, many uncertainties related to very low GHG emission scenarios remain poorly quantified. This thesis explores and attempts to better quantify the various uncertainties related to very low emission scenarios by focussing on (a) uncertainties in short-term emission trends, (b) uncertainties in pathways to limit global temperature increase to low levels, and (c) the integration of uncertainty assessments across disciplines.

This thesis shows that current emission reduction proposals made by countries do not put the world on a robust path towards limiting global temperature increase to low levels (for example, to below 1.5 or 2 °C). At the same time, however, it shows that also with limited mitigation in the near term, options remain available to limit warming in the long term, albeit at markedly higher cost, with less flexibility for future generations to choose their preferred mitigation technologies, and generally resulting in an overall higher probability of exceeding the specific warming limit. While international climate policy on reducing GHG emissions is stalling, other initiatives are under way that could help achieving climate protection. However, the degree by which these initiatives manage to help limiting long-term climate change varies widely. Global initiatives that foster transitions towards a more sustainable energy system can provide a very good entry point towards stringent climate protection. On the other hand, the contribution of early reductions of air pollutants, that are also radiatively active, is much more limited. Our results show that, despite the multiple uncertainties, the timing of a globally coordinated response to climate change in terms of stringent GHG reductions has the largest impact on the probability to limit warming to very low levels during this century: if mitigation action is delayed, simply spending more money in the future will not compensate for the permanently reduced chances of limiting warming below 1.5 or 2 °C.

Résumé

Les découvertes scientifiques qui ont établi les bases de notre compréhension actuelle de l'influence globale des gaz à effet de serre (GES) remontent à près de deux siècles. De nos jours, le réchauffement du système climatique terrestre est sans équivoque et les activités humaines ont été identifiées comme en étant le moteur principal. L'étude des impacts associés aux changements climatiques a également mis en évidence l'importance d'un environnement hospitalier pour nos sociétés. Par conséquent, au cours des dernières décennies, la politique internationale a commencé à considérer des options qui permettraient d'atténuer les risques imminents liés à l'augmentation globale de la température. La nécessité de réduire les émissions de GES pour stabiliser le climat est actuellement reconnue sur la scène internationale. Par contre, malgré leur importance politique, les scénarios qui explorent comment le réchauffement global peut être maintenu à des niveaux très bas demeurent sous-représentés dans la littérature scientifique. Par conséquent, les incertitudes liées aux scénarios à émissions très basses restent peu étudiées. Cette thèse vise à mieux quantifier les diverses incertitudes associées à ces scénarios à émissions de GES très basses tout en se concentrant sur (a) les incertitudes dans l'évolution en matière d'émissions à court terme, (b) les incertitudes dans les trajectoires qui limitent l'augmentation de la température globale à des niveaux bas et (c) l'intégration du savoir entre les disciplines.

Cette thèse montre que les propositions actuelles faites par les pays pour réduire les émissions de GES échouent à mettre le monde sur une trajectoire qui limite l'augmentation de la température globale à des niveaux bas (par exemple, 1,5 °C ou 2 °C). En même temps, il est démontré que même avec peu d'efforts pour réduire les émissions à court terme, une limitation du réchauffement à long terme reste possible. Par contre, plus on tardera à agir, plus élevé sera le coût, plus réduite sera la flexibilité dans le choix technologique pour les générations futures et plus réduite sera la probabilité de limiter le réchauffement de la planète à des niveaux bas. En vue du manque de résultats effectifs pour réduire les émissions de GES de la part de la politique climatique internationale, de nouvelles initiatives qui pourraient contribuer à la protection du climat se présentent. L'efficacité de ces initiatives pour limiter les changements climatiques à long terme est cependant très variable. Les initiatives globales qui poursuivent la transition vers un système énergétique plus durable constituent un levier important pour la protection du climat. Par contre, la contribution de réductions rapides de polluants atmosphériques, qui sont aussi actifs radiativement, est beaucoup plus limitée. Nos résultats montrent que malgré les diverses incertitudes, c'est le moment d'une réponse globale coordonnée aux changements climatiques en termes de réductions de GES qui a le plus grand impact sur la probabilité de limiter le réchauffement à des niveaux très bas pendant ce siècle : si les actions mises en œuvre

pour réduire les émissions sont reportées, déployer des moyens financiers plus importants dans le futur ne pourra pas compenser les chances réduites de manière permanente de limiter le réchauffement global en dessous de 1.5°C et 2°C.

Contents

Abstract	i
Résumé	iii
I Prologue	1
1 Introduction	3
1.1 Context and motivation	3
1.2 Scenarios, climate objectives, and uncertainty	5
1.2.1 What is a scenario?	5
1.2.2 Integrating scenarios, objectives, and uncertainties	5
1.2.3 Qualifying uncertainty	9
1.3 Objectives and outline	11
1.4 Modelling tools	13
1.4.1 MAGICC	13
1.4.2 MESSAGE	14
II Short-term emission trends and uncertainty	17
2 Analysis of the Copenhagen Accord pledges and its global climatic impacts — a snapshot of dissonant ambitions	19
2.1 Introduction	23
2.2 Methods	24
2.2.1 Reference pathway	24
2.2.2 Emissions assessment	25
2.2.3 Climatic assessment	28
2.3 Results, discussion and conclusion	28
2.3.1 Resulting 2020 emission levels	28
2.3.2 Climatic impacts	32
2.3.3 Conclusion	33
3 Discrepancies in historical emissions point to a wider 2020 gap between 2°C benchmarks and aggregated national mitigation pledges	35
3.1 Introduction	39

3.2	Benchmark definition	41
3.2.1	2020 emission benchmarks	41
3.2.2	Variability in 2000 values	41
3.2.3	Historical emission estimates	43
3.2.4	Officially reported data	43
3.2.5	Composite historical emission estimates	43
3.2.6	Composite official estimates versus other sources	46
3.3	Harmonization methodologies	46
3.4	Results and discussion	47
III	Scenario comparability for climate and impact assessments	51
4	Global warming under old and new scenarios using IPCC climate sensitivity range estimates	53
4.1	Introduction	57
4.2	Results and discussion	58
4.3	Methods	66
IV	Pathways for limiting global temperature increase	69
5	Emission pathways consistent with a 2°C global temperature limit	71
5.1	Introduction	75
5.2	Results and discussion	76
5.3	Methods	81
6	2020 emissions levels required to limit warming to below 2°C	83
6.1	Introduction	87
6.2	Exploring 'feasibility'	87
6.3	Quantified 'feasibility windows'	91
6.4	Pathway characteristics, costs, and risks	94
6.5	Discussion	98
6.6	Methods	99
V	Integration of knowledge across disciplines	101
7	UN's new 'Sustainable Energy For All' initiative compatible with 2°C	103
7.1	Introduction	107
7.2	Energy at the core of development	107
7.3	Energy system transformation and CO ₂ emissions	108
7.4	Our modelling approach	108
7.5	SE4ALL objectives and climate protection	112
7.5.1	Renewable energy indicators	112
7.5.2	Energy intensity improvement indicators	112

7.5.3	Universal energy access and climate action	113
7.6	How to meet multiple targets	114
7.7	Regional contributions to the global objectives	116
7.8	Investing in a sustainable energy future	118
7.9	Conclusion	119
8	Combining short and long-term mitigation efforts to limit global mean warming	121
8.1	Introduction	125
8.2	Results and discussion	126
8.2.1	Emissions in 2020 consistent with 2 °C	126
8.2.2	BC-related sensitivity analysis	128
8.2.3	The temperature impact of methane	130
8.2.4	Rate of temperature change	130
8.2.5	Long term importance of new HFC projections	133
8.3	Conclusions	134
8.4	Methods and materials	135
9	Probabilistic cost estimates for climate change mitigation	137
9.1	Introduction	141
9.2	Results and discussion	143
9.3	Methods summary	149
VI	Epilogue	151
10	Conclusions and outlook	153
10.1	Conclusions	153
10.2	Outlook	155
VII	Appendices	159
A	National GHG emissions reduction pledges and 2 °C: comparison of studies	161
A.1	Introduction	165
A.2	Method	166
A.2.1	Unconditional versus conditional pledges	166
A.2.2	'Lenient' versus 'strict' rules	166
A.2.3	Completed data sets with missing country/sector emissions	168
A.2.4	Harmonized emissions data	168
A.3	Results	169
A.4	Discussion	172
A.4.1	Differences between the four pledge cases	173
A.4.2	Differences between estimates for the same pledge case	176
A.4.3	Other factors that could affect emissions, but that are not reflected in the pledge cases	178

A.5	Conclusions and policy implications	180
A.5.1	Accounting of emissions and targets	180
A.5.2	Ambition level	181
B	Supplementary information: Combining short and long-term mitigation efforts to limit global mean warming	183
B.1	Supplementary tables	187
B.2	Supplementary figures	188
	References	199

Part I
Prologue

Chapter 1

Introduction

The purpose of computing is insight, not numbers

Richard Wesley Hamming (1962)

1.1 Context and motivation

The scientific discoveries that lay the foundations of our current understanding of the global greenhouse gas (GHG) effect date back almost two centuries to the early 19th century (Archer and Pierrehumbert, 2011). Scientific exploration and enquiry has further strengthened and elaborated the insights over time and, based on accumulated evidence from observations, warming of the climate system is nowadays unequivocal (IPCC, 2007c). The improved understanding of climate change also brought to light the dependence of our global society on a hospitable Earth's climate system (IPCC, 2007a) and the role human activities play in causing (IPCC, 2007d) and potentially mitigating these imminent risks (IPCC, 2007b). This has spurred citizens, and governments in their succession, to express their concerns and to demand that action is undertaken to avoid a future with significant higher global average temperatures. These global concerns lead in 1992 to the creation of the United Nations Framework Convention on Climate Change (UNFCCC) whose ultimate objective is to achieve '*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*' (UNFCCC, 1992).

Since then it remains a point of much debate how 'dangerous anthropogenic interference with the climate system' can and/or should be defined (Schellnhuber et al., 2006; Hansen et al., submitted). This will remain so in the foreseeable future, as the risks that are implied when our societies continue to emit large quantities of GHGs into the Earth's atmosphere are not equitably distributed (IPCC, 2007a). Different societies are exposed to different impacts of anthropogenic climate change, which can vary significantly in their local severity. Also the respective capacities to cope with or respond to these environmental changes varies extremely. These multiple realities of how present-day climate change is felt and future climate impacts are anticipated across the globe is reflected in the current state of play of the international climate negotiations under the UNFCCC.

In the 2009 Copenhagen Accord (UNFCCC, 2009b), but even more prominently in the 2010 Cancún Agreements (UNFCCC, 2010a), the 193 nations of the UNFCCC recognize '*that*

deep cuts in global greenhouse gas emissions are required according to science [...] with a view to reducing global greenhouse gas emissions so as to hold the increase in global average temperature below 2 °C above pre-industrial levels'. This formulation explicitly avoids that 'limiting global warming to below 2 °C' would be considered an objective of the UNFCCC. This approach made it acceptable to nations that currently do not consider climate change mitigation a national or global priority. However, a few lines further, the same paragraph also reflects the concerns of more than fifty percent of the world's nations that a global warming of 2 °C might already be excessively high. In particular Small Island Development States (SIDS) and Least-Developed Countries (LDCs) reason that local and regional impacts in a 2 °C warmer world, in particular related to sea-level rise, marine ecosystem services, and droughts, might well exceed the adaptive capacity of their vulnerable societies. Because a 2 °C warmer world would not adequately safeguard these nation's aspirations for poverty eradication and sustainable development, or could, ultimately, not guarantee the long term survival of their cultures and societies, they call for limiting long term global average temperature increase to well below 1.5 °C (UNFCCC, 2009e). To accommodate the concerns of these most vulnerable countries, the text of the Cancún Agreements also recognizes the need to consider strengthening the long term global goal to 1.5 °C on the basis of the best available scientific knowledge in the framework of a review which will start in 2013 and should be concluded by 2015.

Despite the clear policy relevance of scenarios that describe futures for our global society in which we manage to limit global temperature increase to very low levels, the literature on such very low emission scenarios is very meagre. For example, at the time of its latest assessment in 2007, the Intergovernmental Panel on Climate Change (IPCC) had only six detailed scenarios from the entire scientific literature at its disposal for its lowest stabilization category (which aims at limiting CO₂-equivalent concentrations to 445-490 ppm). Such concentration levels still give a large (more than fifty percent) chance that global temperature rise will exceed 2 °C in the long term (Table SPM.5, in IPCC (2007b)). In the past few years, more 2 °C-consistent scenarios have become available in the scientific literature (UNEP, 2012; Rogelj et al., 2011b). However, the very low end of the scenario spectrum, with scenarios aiming at returning warming to below 1.5 °C, remains very scarcely populated despite its extremely high policy-relevance.

This therefore presents the scientific community with a large uncertainty-ridden territory that urges exploration. The fascinating research questions these uncertainties evoke and their high policy and societal relevance, are the core motivation for the work on very low emission scenarios presented in this doctoral thesis.

1.2 Scenarios, climate objectives, and uncertainty

1.2.1 What is a scenario?

The *Oxford English Dictionary*¹ defines a 'scenario' as:

"A sketch, outline, or description of an imagined situation or sequence of events; especially (a) a synopsis of the development of a hypothetical future world war, and hence an outline of any possible sequence of future events; (b) an outline of an intended course of action; (c) a scientific model or description intended to account for observable facts. Hence, in weakened senses (not easily distinguishable from sense 1a transf. and fig.): a circumstance, situation, scene, sequence of events, etc."

It is doubtful that this definition, as complete and nuanced as it attempts to be, will prove to be successful in purveying to a lay person the concept and applicability of scenarios. In that sense, the *Forecasting Dictionary*² (Armstrong and Green, 2012) does a much better job, by providing the following short 'scenario' definition:

"A story about what happened in the future. (note the past tense)"

In particular in relation to climate change, the latter definition communicates the concept of scenarios in an equally simple as conceptually correct way. Emission scenarios are generally forward looking, and they are constructed to explore the implications of a particular story or storyline in the future. Emission scenarios thus describe — under an internally consistent set of assumptions — how the future could potentially unfold, what the impact of specific policies might be, or what costs and benefits they would entail (Rogelj et al., 2013a). They are neither predictions nor forecasts, and do not necessarily have probabilities attached to them.

1.2.2 Integrating scenarios, objectives, and uncertainties

Scenario analysis is always carried out with a given hypothesis in mind. Scenarios can test and illustrate the efficiency or efficacy of policies in achieving a given outcome, show how policies can foster or be simultaneously consistent with multiple objectives like poverty eradication, climate protection, and sustainable development (Rogelj et al., 2013a), or show how the future might look like in the absence of any new policies.

Until recently, most of the climate impact research was conducted through forward modelling starting from a small, illustrative set of marker scenarios (Nakicenovic and Swart, 2000). These scenarios, also known as the 'SRES' scenarios, represent futures in which the driving forces (like population, economy, technology, energy, agriculture, and land-use) are projected into four main directions along two axes (global versus regional, and economic versus environmental), and this in absence of GHG mitigation efforts. Furthermore, in much of the scenario literature, the influence or feedback of climate change impacts on how the future society might

¹<http://www.oed.com/>

²<http://www.forecastingprinciples.com/>

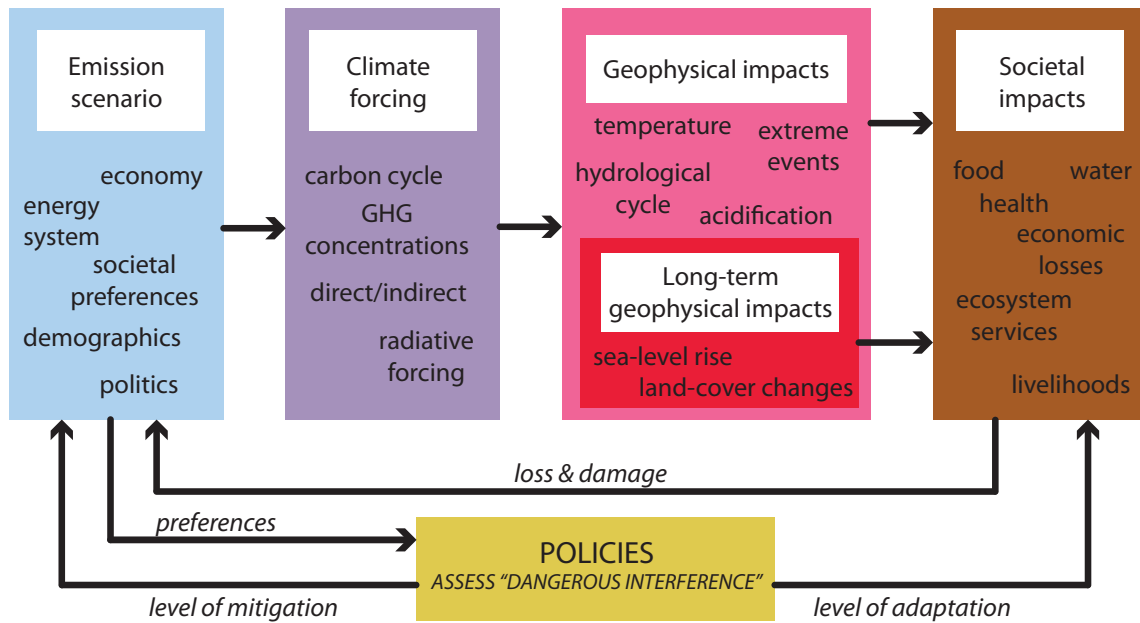


Figure 1.1: Schematic of the web of uncertainties related to climate scenario research, showing the central position of emission scenarios and policies.

develop has been neglected³. Since a few years (IPCC, 2007a), it has become increasingly clear that the societal impacts of climate change could be far from negligible and will have an important influence on the development of future society (The World Bank, 2012).

Figure 1.1 provides a schematic overview of how emission scenarios and societal impacts of climate change are bidirectionally connected. Policies can limit GHG emissions and therewith temper future climate change. At the same time, other policies can promote adaptation measures to prepare societies to cope with projected climate impacts.

However, not all connections between emissions and climate impacts in this scheme run over policies. For example, climate impacts related to global temperature increase are to a very large degree defined by the cumulative amount of carbon emissions into the atmosphere. Once these GHGs are emitted, policies will have very little effect on the committed warming (Allen et al., 2009; Meinshausen et al., 2009) — except in the case carbon is actively extracted from the atmosphere at a globally massive scale. On the other hand, once significant climate impacts occur, this can entail specific societal damages or unavoidable losses that will influence the economic activity of the global system and therewith emissions, irrespective of the adaptation policies in place (Hof et al., 2010). Whereas policy connections are often well-recognized and well-explored in scenario analyses, non-policy-related connections aren't.

Historically, assessment of climate impacts has always been in a forward direction (Figure 1.2, panel a), from emissions to impacts (Nakicenovic and Swart, 2000; IPCC, 2007a). More recently, concentration pathways — the '*Representative Concentration Pathways*', or

³Some very simplified examples of such integration have been attempted at very aggregated scales (Stern, 2006; Nordhaus, 1992)

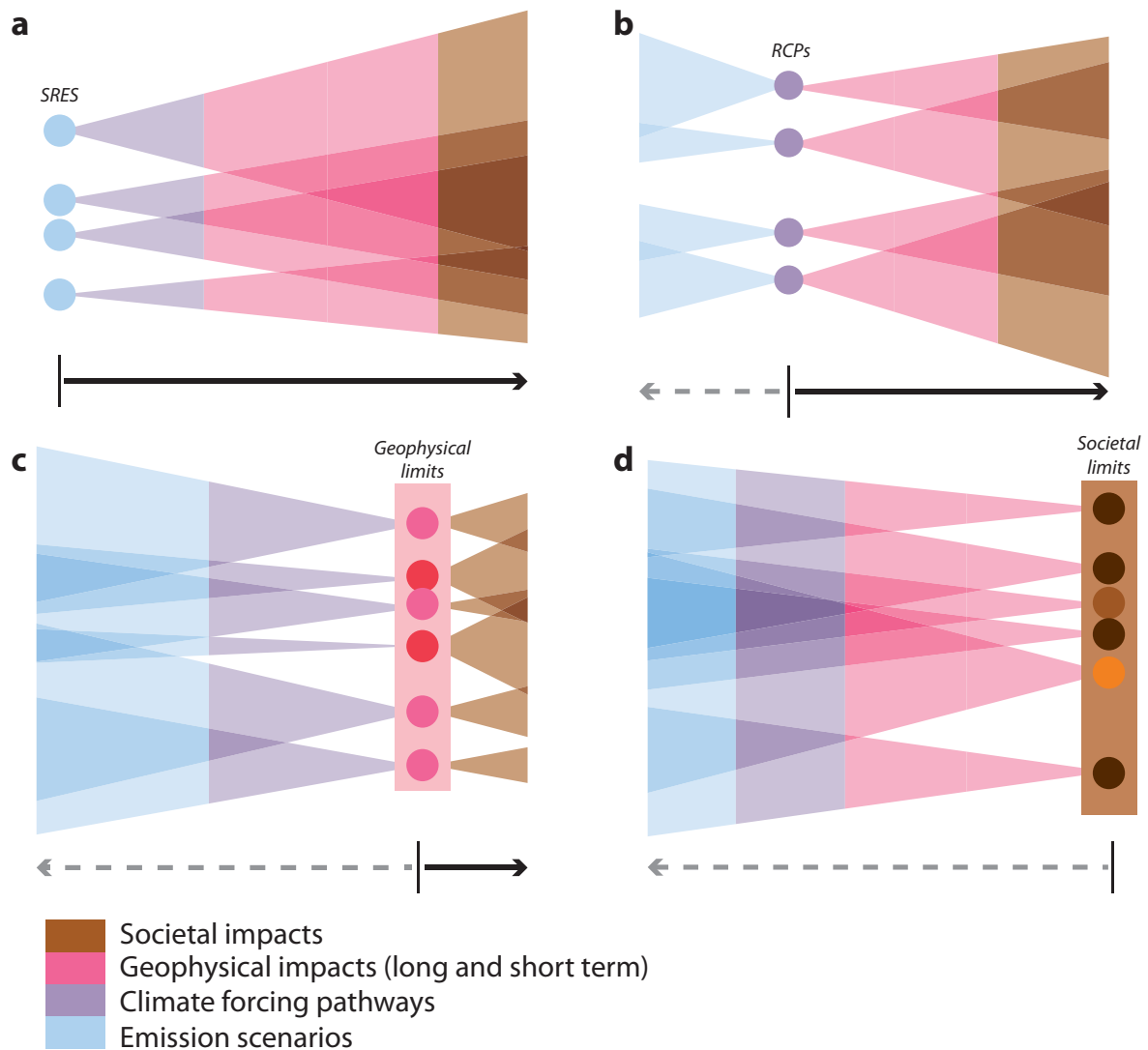


Figure 1.2: Four different simplified analytical approaches to assess the link and implied uncertainties between emissions and their societal impacts. Panels **a-d** have emissions, forcing, geophysical limits, and societal limits at the center, respectively. Solid arrows denote forward modelling steps; dashed arrows denote backward or inverse modelling steps. Note that none of the simplified approaches incorporates the 'loss & damage' link shown in Figure 1.1.

RCPs (Moss et al., 2010) — have been defined as a point of departure of a large-scale exercise to assess climate impacts resulting from this forcing, as well as inversely and recursively attempt to define consistent emission scenarios (Figure 1.2, panel b). This approach has the advantage that it will yield groups of multiple future scenarios with alternative narratives that each would result in the same climatic impacts.

Although both above-mentioned approaches have their merits — if not only because at that time they were initiated they were the only feasible option due to computational constraints — they are fundamentally impractical and confusing for policy makers. As much as scientist might hope, policy makers are no physicists who easily capture how joint distributions of uncertainties can influence emission budgets. Policy makers are used to act in real-world situations. How much the actual rise in temperatures or sea-level from a given emission scenario will be is probably only fascinating to a select group of geoscience geeks if no connection to the implied societal impacts is provided. This understanding is quintessential in science-policy communication. Figure 1.2, panel c and d, show two logical alternative approaches that put the policy-relevance of the exercise more at the center. The conclusions and outlook section of this thesis (Chapter 10) will elaborate this issue in more detail.

1.2.3 Qualifying uncertainty

'Uncertainty' is a common word that is used to describe aspects of our knowledge we are not sure of or which we cannot determine precisely. However, if used incautiously in science communication with policy makers, it is bound to produce confusion and misunderstandings about its true meaning. This can result in either overconfidence about the precision or correctness of results, in misrepresentation of the assessment, or in the errancy that because uncertainties are large, risks are small (Smith and Stern, 2011). Because the policy relevance of very low emissions scenarios is a key motivation for the research presented in this thesis, this section shortly contemplates on the difficulties and pitfalls in communicating scientific results, together with their related uncertainties, to the wider public and policy makers in particular.

Describing the wide variety of kinds of uncertainties that exist in the real world requisites a well-calibrated and precise language. In their discussion of uncertainty in science and its role in climate policy, Smith and Stern (2011) propose four varieties of uncertainty: imprecision, ambiguity, intractability, and indeterminacy. While not being mutually exclusive, these concepts all emphasize a different aspect of the limitations in our ability to quantify or understand outcomes in the future.

Smith and Stern (2011) define their four varieties of uncertainty as:

- **Imprecision:** *uncertainty related to not precisely known outcomes, but for which it is believed robust probability statements can be provided. In other literature, this variety of uncertainty is also called 'statistical uncertainty' (Walker et al., 2003; van der Sluijs et al., 2003)*
- **Ambiguity:** *relates to outcomes, which can be either known or disputed, for which no probability statements can be made. In other literature, this variety is also called 'recognized ignorance'⁴ (van der Sluijs et al., 2003) or 'scenario uncertainty' (Walker et al., 2003).*
- **Intractability:** *denotes the uncertainty related to computations or analysis known to be relevant to an outcome, but lying beyond the current mathematical, computational, or abstractive capacity to formulate or to execute.*
- **Indeterminacy:** *is used for communicating the uncertainty of quantities for which, despite their importance and relevance, no precise value exist. This can arise either when a model parameter does not correspond to an actual physical quantity, or as a result of the unavoidable existence of a diversity of views among people about the desirability of obtaining or avoiding a given outcome.*

The relevance and applicability of this calibrated language for uncertainties related to very low emission scenarios can easily be illustrated. For example, because of measure and/or systematic errors, any observational dataset — emissions, temperatures, or ocean heat uptake alike — will have an *imprecision* attached to it which is projected into the future when assessing the climatic outcomes of emission scenarios. Furthermore, the evolution of the global society and its associated GHG emissions are driving forces in long term projections of the Earth's climate into the future. The inability to simulate how society *will* (in contrast to a hypothetically

⁴Note that van der Sluijs et al. (2003) use both the terms 'recognized ignorance' and 'scenario uncertainty' in their paper but refer to two distinct classes of uncertainty.

could) develop in the future adds *ambiguity* into the picture. *Intractability* is also well-known in climate modelling, where simplified versions of climate models, on a coarser grid and/or not explicitly including all small scale processes, are run in order to reduce the computational cost in terms of time and resources. *Indeterminacy*, finally, has already been alluded to in the first section of this chapter. Differences in actual and perceived vulnerability showed to result in differing positions about which climate objective is to be pursued (for example, either a 1.5 or 2 °C limit) and with which probability one ought to aim at achieving this objective. In addition, *indeterminacy* is also the uncertainty arising when certain model parameters do not have a real-world, empirically definable counterpart, for example, the discount rate and time preference in economic models (Smith and Stern, 2011).

However, while providing an excellent semantic framework to reflect the nature of the various uncertainties scientists are exposed to in their assessments, these four varieties of uncertainty also show some drawbacks for their use in an effective science-policy dialogue. Science and scientists approach the world in a fundamental different way than policy makers. By applying the scientific method, which consists in systematic observation, measurement, experiment, and the formulation, test, and modification of hypothesis⁵, scientists are expected to act as observers: impartial interpreters and reporters of the perceived reality that surrounds us. Policy and decision makers, which can be either part of the public or private sphere, occupy an entirely different position in society and in our world. They are actors in the above-mentioned reality whose main and arguably sole purpose is to interact with the world and shape the course of society into a direction which is in closest accordance with what they perceive to be ultimately the most beneficial path — 'beneficial' can here be measured against a large variety of benchmarks, ranging from personal, monetary, egoistic, or survival interests, to social, sustainability, altruistic, moral or humanitarian interests in both the short and longer term.

With this apparent fundamental distinction between the science and policy perspectives on the world surrounding us, the question arises as to which degree each of the uncertainties characterized by scientists are equally an uncertainty in the world of policy and decision makers. In some cases this is more the case than in others. For example, current *imprecision* and *intractability* might appear to be beyond the influence of policy makers. However, when looking into the future, policy makers can choose to steer funds towards targeted research that could help reducing these uncertainties. The reduction of these uncertainties is thus closely related to their actions. Furthermore, *indeterminacy* is a variety of uncertainty in which value judgements of policy and decision makers (and in extension of each individual member of the global society) are main determinants. This variety of uncertainty can therefore be much smaller for policy makers than for the idealized passive and objective scientist. Lastly, policy makers can actively decide to pursue a particular long term outcome, even if we cannot assign a probability to this outcome. *Ambiguity* can therefore in many cases be translated into policy *choices*, *preferences*, or *options* instead of uncertainties. Being aware of these radical different view points between scientists and policy makers, can help to effectively translate insights of scientific uncertainty assessments into messages targeted to policy and decision makers.

Finally, besides the above-mentioned four varieties of uncertainty proposed by Smith & Stern, any thorough scientific assessment of uncertainties should adopt an appropriate amount

⁵Based on the definition of 'scientific method' in the *Oxford English Dictionary*, <http://www.oed.com/>

of caution and also include the possibility of us being unaware to certain aspects of the reality that surrounds us. *Unawareness* would therefore be a necessary, yet hardly quantifiable, fifth variety of uncertainty that should accompany any scientist's thoughts when contemplating the robustness of his or her analysis and insights.

These multiple varieties of uncertainty, their omnipresence in assessments of very low emission scenarios, and their importance for an effective science-policy dialogue lead us to the objectives of this doctoral thesis.

1.3 Objectives and outline

The primary objective of this doctoral thesis is to explore and quantify uncertainties related to the very low end of emission scenarios. By doing so, it tries to advance our understanding about the nature, degree, and relative importance of various kinds of uncertainty.

Specific topics that have been studied include:

- I – Imprecision and ambiguity in short-term emission trends
- II – Imprecision and intractability in scenario comparability
- III – Uncertainties related to emission pathways to limit warming to low levels
- IV – Cross-disciplinary integration of insights and assessments

The policy relevance of these questions was a central criterion in selecting and prioritizing particular analyses. However, the complexities of determining what 'dangerous anthropogenic interference' would imply — and hence what an adequate global climate objective would be — are outside the scope of the research described in this doctoral thesis and were therefore not touched upon. Also, it should be noted that the papers published over the years in the framework of this doctoral thesis do not yet consistently make use of the calibrated uncertainty language described above. The body of this doctoral thesis is structured in four main parts, in line with the four broad topics described above. Each part contains one or more chapters as shortly outlined below.

I — Short-term emission trends and uncertainty: Short-term emission trends are strongly influenced by either already implemented or anticipated policies. The first chapter in this part (Chapter 2) therefore investigates the possible climatic impact pledges made by countries under the Copenhagen Accord can have on global temperature rise (Rogelj et al., 2010a). To do so, a detailed analysis and quantification of the outcome of the emission reduction and limitation pledges in terms of global GHG emissions in the short and medium term is carried out. Then, with a simple scenario approach, the consistency of these pledges with the objective of limiting global temperature increase to below 2 °C during the entire 21st century is verified. Subsequently, the second chapter in this part (Chapter 3) explores how uncertainties in estimates of historical global emissions can influence the assessment of the adequacy of a set of pledges with regard to a particular temperature limit (Rogelj et al., 2011a). A study related to this part (available in the Appendix to this manuscript) is a comparison of a large number of studies that all quantify the effect of national GHG reduction pledges (Höhne et al., 2011b). I contributed to this study as a co-author, in particular for the assessment of the possible influence of surplus emissions credits.

II — Scenario comparability for climate and impact assessments: Much of the scientific insights in terms of climate impacts available in the literature are based on a limited set of scenarios. Climate projections for the Fourth Assessment Report (IPCC, 2007d) (AR4) of the IPCC were based on a different set of scenarios and a different set of models than those developed in preparation of the IPCC Fifth Assessment Report (AR5). This implies that by AR5 both models and scenarios will have changed, making a comparison with earlier literature challenging. To facilitate this comparison, Chapter 4 (Rogelj et al., 2012b) provides climate projections of both the SRES scenarios and the RCPs in a single consistent framework. These estimates are based on a model setup (see Section 1.4.1 for an introduction to the model) that probabilistically takes into account the overall consensus understanding of climate sensitivity uncertainty, synthesizes the understanding of climate system and carbon-cycle behaviour, and is at the same time constrained by the observed historical warming.

III — Pathways for limiting global temperature increase: Because global average peak warming is largely defined by the cumulative amount of GHGs emitted into the atmosphere, multiple evolutions of emissions over time can achieve virtually the same long term climatic outcome. A first chapter in this part (Chapter 5) (Rogelj et al., 2011b) therefore explores if general characteristics can be found in pathways available in the literature that limit global temperature to below a given limit with a certain probability. Such pathways describe technologically and economically feasible ways to limit GHG emissions over time, but mostly assume that efforts to reduce emissions start immediately. Because the state of international climate policy indicates that this currently is not necessarily the case, Chapter 6 investigates the available short-term flexibility in scenarios that limit warming to below 2 °C with a high probability (Rogelj et al., 2012a).

IV — Integration of knowledge across disciplines: Because uncertainties can arise from a multitude of sources (see Figures 1.1 and 1.2) the interaction between some of these uncertainties has been explored in this part. Chapter 7 assesses whether global energy objectives, principally developed to foster sustainable development and poverty eradication, can provide a good entry point to climate protection (Rogelj et al., 2013a). Then, Chapter 8 assesses how initiatives that target mitigation of short-lived climate forcers and air pollutants can influence global warming, and what their relative importance is with regard to mitigation of long-lived GHG mitigation. Finally, Chapter 9 explores the implications and relative importance of uncertainties surrounding climate protection in four different dimensions: uncertainties in the geophysical response of the climate system to anthropogenic GHG emissions, uncertainties about the availability of future technologies, uncertainties about future societal preferences influencing energy demand, and political choices related to the timing and level of stringency of global climate action (Rogelj et al., 2013b).

1.4 Modelling tools

This thesis aims at achieving its objectives through a modelling approach rooted in scenario analysis. The work described here makes extensive use of the MAGICC reduced-complexity carbon cycle and climate model and the MESSAGE integrated assessment modelling framework. Both modelling tools are shortly described below.

1.4.1 MAGICC

The 'Model for the Assessment of Greenhouse Gas Induced Climate Change' (MAGICC) (Meinshausen et al., 2011a,b) is a reduced complexity carbon cycle and climate model developed, used and validated over more than two decades (Wigley and Raper, 1987, 1992, 2001; Raper et al., 1996; Wigley et al., 2009). It lies at the basis of many high-impact publications (see earlier references as well as Wigley (2005); Meinshausen et al. (2009)) and is one of the most widely used climate models of reduced-complexity in past IPCC Assessment Reports (Meehl et al., 2007).

At the basis of MAGICC's climate component lies the global energy balance equation for the perturbed climate system, which describes how the flux of incoming energy is partitioned into an outgoing energy flux and changes in the heat content of the ocean:

$$\Delta Q_G = \lambda_G \Delta T_G + \frac{dH}{dt} \quad (1.1)$$

in which ΔQ_G is the global-mean radiative forcing at the top of the troposphere, ΔT_G the global-mean surface temperature perturbation, λ_G the global-mean feedback factor, and $\frac{dH}{dt}$ the heat content change of the ocean⁶.

MAGICC consists of a hemispherically averaged upwelling-diffusion ocean model coupled to a single atmosphere layer (see Figure 1.3) in combination with globally averaged terrestrial and ocean carbon cycles that include the CO₂ fertilisation effect and the temperature effect on respiration and decomposition, amongst other effects.

While MAGICC can emulate global mean features of the climate system in close agreement with the behaviour observed in single, much more complex, atmosphere-ocean general circulation models (AOGCMs) (Meinshausen et al., 2011a,b), the studies presented in this doctoral thesis use a probabilistic setup of the model based on a 600-member ensemble. Together, these 600 members closely reflect the carbon cycle and climate uncertainties assessed in the IPCC Fourth Assessment Report (IPCC, 2007d). Furthermore, the temperature projections in this setup are also constrained by observed and estimated hemispheric temperatures and ocean heat uptake. A detailed description of this setup is found in Meinshausen et al. (2009).

An important recent addition to the model is the inclusion of the near-permafrost carbon feedback (Schneider von Deimling et al., 2012) which models the release of carbon and methane from aerobic and anaerobic decomposition in thawing permafrost. However, in the studies presented here, the model was still used in a version that did not include this feedback.

⁶Note that $\lambda_G \Delta T_G$ is the Taylor series linearisation ($\sum_{n=0}^1 \frac{f^n(a)}{n!} (x - a)^n$) around the global-mean temperature during pre-industrial times ($a = T_{pre-ind}$) of the Stefan-Boltzmann law which describes that the radiant exitance (M_e) of an object is proportional to the fourth power of the temperature (T) of that object.

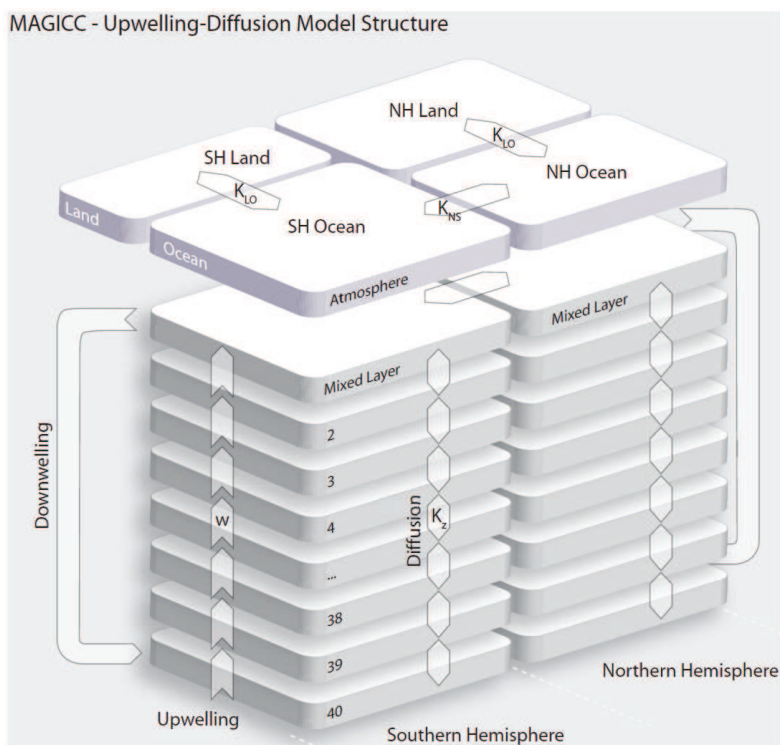


Figure 1.3: Schematic overview of the climatic component of the MAGICC model, from Meinshausen et al. (2011a), showing the partitioning of the atmosphere in four boxes (Northern-hemisphere land and ocean, and Southern-hemisphere land and ocean), and the upwelling-diffusion of the ocean layers. The depth-dependency of the ocean layer area and the entrainment during downwelling is not shown here.

Finally, the MAGICC carbon cycle and climate model is the main part of the climate module of the 'Potsdam Real-time Integrated Model for the Probabilistic Assessment of Emission Paths'⁷ (PRIMAP), a modelling framework used extensively for the detailed, real-time assessment of climate policy and its impacts (Nabel et al., 2011; Rogelj et al., 2010a,b; den Elzen et al., 2012).

1.4.2 MESSAGE

MESSAGE (the 'Model for Energy Supply Strategy Alternatives and their General Environmental impact') is an integrated assessment modelling (IAM) framework developed at the International Institute of Applied Systems Analysis (IIASA) (Messner and Strubegger, 1995; Messner and Schrattenholzer, 2000; Rao and Riahi, 2006; Riahi et al., 2007, 2012). IAM combines insights from various fields — such as economics and the geophysical, biological, social, and engineering sciences — for the systematic analysis of possible future development pathways. Scenarios developed by IAM thus describe — under an internally consistent set of assumptions — how the future could potentially unfold, what the impact of specific policies might be, or what costs and benefits they would entail. The MESSAGE IAM framework is used in three of the studies presented in this thesis to create detailed energy-environment-economy-engineering (E4) scenarios (Rogelj et al., 2012a, 2013a,b).

⁷<http://www.primap.org/>

MESSAGE evolved from a linear programming (LP) systems engineering optimization model that minimizes total discounted energy system costs for a given set of constraints. In doing so it can provide information on the optimal technology mix, required investments and their timing, or temporal trajectories for various forms of energy, amongst other things. This optimization model configuration is fundamentally different from the forward modelling approach of climate models. Climate models will compute the state of the climate system in the next time step based on the model's current state and a set of physical equations that determine the evolution of the system. In contrast, MESSAGE requires the current state of the energy system, a set of driving constraints, and a metric for optimization to find the 'optimal' solution for the following time step.

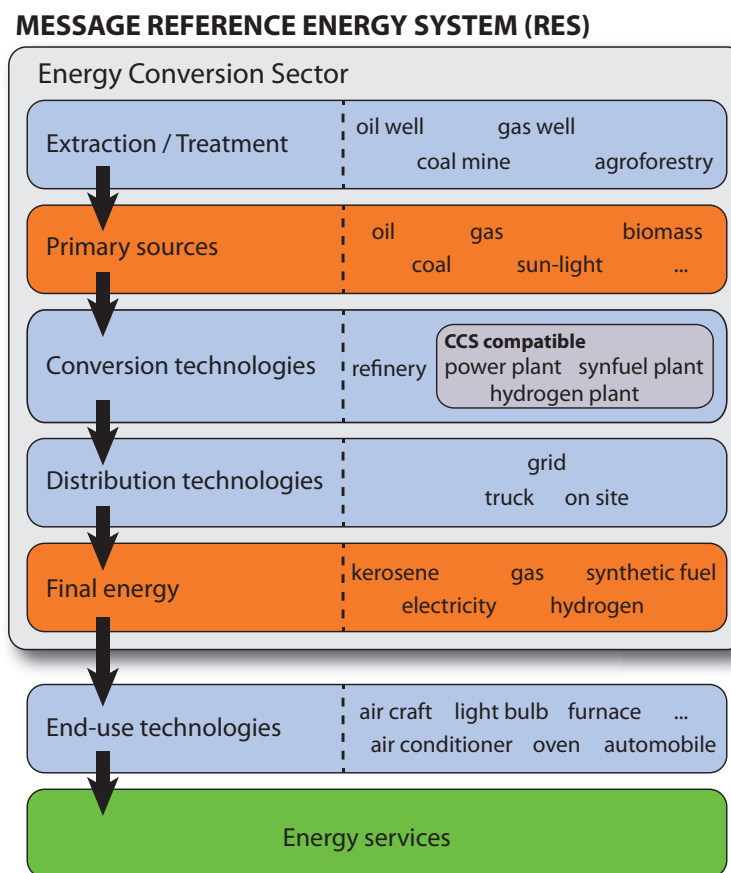


Figure 1.4: Schematic representation of the MESSAGE Reference Energy System (RES) from Rogelj et al. (2012a). Blue fields indicate energy technologies, orange fields energy carriers, and green fields energy services.

As described more in detail by O'Neill et al. (2009), the representation of the energy system in MESSAGE includes the vintaging of the long-lived energy infrastructure, the inertia of the system for replacing existing facilities with new generation systems, the interdependence of various technologies, and possible phenomena that are linked to the scale at which a technology is deployed (for example, the learning effect in making a technology more efficient or producing it at lower costs). Together, these factors can represent the path-dependency of the energy system with respect to choices that are made now (also known as 'lock-in' into a par-

ticular path). MESSAGE includes a detailed representation of all GHG emitting sectors at the level of its eleven world regions (see Rogelj et al. (2012a) for a detailed overview).

A typical application of the model is, for example, to compute a scenario that attempts to limit the cumulative amount of GHG emissions over the 21st century to a specified maximum budget. MESSAGE will start its optimization from the current state of the energy system and disposes of a pre-defined Reference Energy System (RES) that includes all the possible energy chains that MESSAGE can make use of, as well as a specified set of performance characteristics of all technologies. Figure 1.4 shows a simplified illustration of the MESSAGE reference energy system. During its LP optimization MESSAGE will then determine time-evolving contributions of all available technologies required to deliver a specified demand in energy services.

Importantly, MESSAGE also tracks emissions of a full basket of air pollutant species that have an important influence on the climate, albeit at much shorter time scales than CO₂. These air pollutant species include particulate matter (PM_{2.5}), sulphur dioxide (SO₂), nitrogen oxides (NO_x), volatile organic compounds (VOC), carbon monoxide (CO), black carbon (BC), organic carbon (OC), and ammonia (NH₃).

Finally, besides questions related to GHG emissions, MESSAGE can also be used, for example, to study questions of energy security, public health, or energy access and sustainable development (e.g., see McCollum et al. (2011); Ekholm et al. (2010)).

Part II

Short-term emission trends and uncertainty

Chapter 2

Analysis of the Copenhagen Accord pledges and its global climatic impacts — a snapshot of dissonant ambitions

Analysis of the Copenhagen Accord pledges and its global climatic impacts — a snapshot of dissonant ambitions

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Abstract

This analysis of the Copenhagen Accord evaluates emission reduction pledges by individual countries against the Accord's climate-related objectives. Probabilistic estimates of the climatic consequences for a set of resulting multi-gas scenarios over the 21st century are calculated with a reduced complexity climate model, yielding global temperature increase and atmospheric CO₂ and CO₂-equivalent concentrations. Provisions for banked surplus emission allowances and credits from land use, land-use change and forestry are assessed and are shown to have the potential to lead to significant deterioration of the ambition levels implied by the pledges in 2020. This analysis demonstrates that the Copenhagen Accord and the pledges made under it represent a set of dissonant ambitions. The ambition level of the current pledges for 2020 and the lack of commonly agreed goals for 2050 place in peril the Accord's own ambition: to limit global warming to below 2 °C, and even more so for 1.5 °C, which is referenced in the Accord in association with potentially strengthening the long-term temperature goal in 2150. Due to the limited level of ambition by 2020, the ability to limit emissions afterwards to pathways consistent with either the 2 or 1.5 °C goal is likely to become less feasible.

2.1 Introduction

In Copenhagen, December 2009, representatives of 193 governments gathered at the 15th session of the Conference of the Parties (COP15) of the United Nations Framework Convention on Climate Change (UNFCCC, henceforth also called 'the Convention') and the 5th session of the Conference of the Parties serving as the Meeting of the Parties to the Kyoto Protocol (CMP5); about 120 of them were represented by Heads of State. Work initiated in Bali in 2007, with the aim to urgently enhance the implementation of the Convention in order to prevent dangerous anthropogenic interference with the climate system (UNFCCC, 2007), was to be completed at COP15. In the end, the conference resulted in the 'Copenhagen Accord' (henceforth called 'the Accord') (UNFCCC, 2009b), which was negotiated as part of a closed negotiating segment by 26 nations. Not reflecting the ambitions of, or involving, many of the Parties, it was only 'taken note of' by the Conference of the Parties. The total number of Parties that have expressed their intention to be associated with the Accord is 138 (information as of 19 August 2010). Additionally, decisions were made to continue negotiations under both the Convention (UNFCCC, 2009d) and the Kyoto Protocol (KP, henceforth also called 'the Protocol') (UNFCCC, 2009c) tracks until the end of 2010. The UNFCCC Secretariat clarified that the provisions of the Accord do not have any legal standing within the UNFCCC process (UNFCCC, 2010h). Although its significance as a political agreement is disputed among Parties, it cannot be neglected as it is framing the ongoing negotiations towards a global agreement.

In the Accord, Parties '[...] agree that deep cuts in global emissions are required according to science, [...] with a view to reduce global emissions so as to hold the increase in global temperature below 2 °C' and hereby preventing 'dangerous anthropogenic interference with the climate system'. 1.5 °C is referenced in the Accord in association with potentially strengthening the long-term temperature goal based on 'various matters presented by the science' in 2015. Tables for individual country mitigation pledges were left empty in the Accord. By the end of August 2010, 85 countries from both developed and developing countries had submitted pledges. The final version of the Accord does not include long-term reduction goals, such as a global reduction target for 2050. Global targets of -50% from 1990 levels by 2050 and an aggregate developed country target of at least -80% by 2050 were present in informal drafts that circulated until a few hours before the conclusion of the negotiations, and are also part of current negotiation texts in preparation for COP16 (as of August 2010) (UNFCCC, 2010d).

Relation to earlier literature

Here, we analyse the Accord with the pledges as they were communicated to the UNFCCC by mid-April 2010 (UNFCCC, 2010f,g). The focus of our analysis is the extent to which these pledges bridge the gap from current policy to what is needed to achieve the Accord's climate-related objectives. Many groups have already carried out analyses to assess the emission levels resulting from the Accord (Ecofys and ClimateAnalytics, 2010; Climate Interactive, 2010; den Elzen et al., 2010c; European Commission, 2010b; Levin and Bradley, 2010; Macintosh, 2010; Stern, 2009; UNEP, 2010a), but the analysis presented here is one of the few — besides the analysis of Ecofys and ClimateAnalytics (2010) and den Elzen et al. (2010c) — that considers specific provisions, such as the banking of surplus emission allowances, and debits and credits

resulting from land use, land-use change and forestry (LULUCF) accounting, that can deteriorate the level of ambition for emission reductions in 2020. Additionally, we perform individual probabilistic multi-gas climate runs for each emission pathway, not present in other analyses in the literature. This analysis builds on and provides an extension of our earlier work (Rogelj et al., 2010b).

2.2 Methods

The global climatic consequences of the Accord are assessed against a set of scenarios. Two options for 2020 (case 1 and case 2) are constructed based on the range of pledges and actions submitted to the Accord. To calculate emission levels in 2020, a bottom-up approach is applied with the emission module of the Potsdam Integrated Model for Probabilistic Assessment of Emission Paths (PRIMAP) (Nabel et al., 2011). Emissions are reduced (see tables S1 and S3 in the supplementary data available at stacks.iop.org/ERL/5/034013/mmedia for an overview of the considered mitigation actions) from a composite reference pathway which incorporates policy in place¹ before COP15/CMP5. When no targets or actions are available for a country, the pre-defined reference pathway is assumed. Emissions are extended beyond 2020 assuming either further growth or a 2050 global reduction target. For calculations of the climatic consequences, a probabilistic approach with the reduced complexity climate model MAGICC (Meinshausen et al., 2008) is used, with model parameters closely representing estimates of the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007d).

2.2.1 Reference pathway

A reference pathway which accurately represents past emission levels as reported by Parties is paramount to calculate target levels that are defined as a percentage below a particular base year level. Analogously, target levels which are defined as a deviation from a certain baseline require country projections. Therefore, a comprehensive composite reference scenario (further referred to as the PRIMAP4 scenario) was constructed for all parties. Targets are often defined on the so-called Kyoto greenhouse gas (GHG) basket and not on single GHGs. The Kyoto-GHG basket includes carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF₆). To construct the CO₂-equivalent (CO₂eq) Kyoto-GHG basket, the global warming potentials (GWP) that are used under the Protocol for reporting purposes (UNFCCC, 1997b) as well as under the Convention (UNFCCC, 2002) are used. These GWPs are those specified in the Second Assessment Report of the IPCC (IPCC, 1996).

This PRIMAP4 reference scenario with annual country resolution is constructed as a composite pathway. A detailed description of the methodology can be found in Nabel et al. (2011). The PRIMAP4 scenario is based on the following emission data sources in descending or-

¹In accordance with the assumptions made in the International Energy Agency's (IEA) World Energy Outlook (IEA, 2009). For example the 20% pledge of the European Union (EU) was already in place before COP15/CMP5 as part of the European Climate and Energy Package and is therefore included in the reference pathway.

der of prioritization: (1) National Inventory Submissions to the UNFCCC (UNFCCC, 2009a) as submitted by Parties. Only Annex I countries² have the obligation to provide these annual submissions. For Non-Annex I countries, data from (2) National Communications to the UNFCCC (UNFCCC, 2009f) are considered. These two reported historical data sources are complemented with (3) historical data from the Carbon Dioxide Information Analysis Centre (CDIAC) for CO₂ from fossil fuel and cement (Boden et al., 2009) and (4) historical data from the Emission Database for Global Atmospheric Research (EDGAR) for CH₄ and N₂O (JRC and PBL, 2009). For future projections, emissions from (5) the International Energy Agency's (IEA) World Energy Outlook (IEA, 2009), (6) the Prospective Outlook on Long-term Energy Systems (POLES) model (ENERDATA, 2009) and (7) the downscaled composite scenario based on the SRESA1B pathway developed in the framework of the ad hoc group for the Modelling and Assessment of Contributions of Climate Change (MATCH) are used (Höhne et al., 2011a). To complement the MATCH pathways for fluorinated gases (HFCs, PFCs and SF₆), (8) the downscaled SRESA1B pathway of the Netherlands Environmental Assessment Agency was used (van Vuuren et al., 2006).

For international shipping, historical data provided by the International Maritime Organization (IMO) (Buhaug et al., 2009) is combined with IMO's best estimate of the SRESA1B scenario. For international aviation, historical emission and projection data (Owen et al., 2010) is completed with future trend data from the OMEGA project (Meinshausen and Raper, 2009).

The data underlying the calculations on LULUCF accounting are based on the KP LULUCF activities calculated by using proxies developed from the LULUCF sectoral data reported in national inventories to the UNFCCC. A detailed description of the LULUCF activity reference data is provided online (Nabel et al., 2010).

2.2.2 Emissions assessment

The PRIMAP4 scenario described above is the starting point for a bottom-up assessment of the emission implications of the Accord. Many Parties provided a range of emission targets with the more ambitious end being conditional, for example, upon a global comprehensive agreement or access to financing. The two ends of the ambition range lead to our cases for 2020: 'case 1' applies the low ambition and 'case 2' the high ambition options. Our assessment is based on the international pledges of Parties in the framework of the Accord only, although in some cases (e.g. China) some interpretations of national climate plans could be more ambitious than the international pledge of a Party.

Developed countries

The emission levels in 2020 for developed countries are calculated by applying the emission reduction percentages of their pledges to their respective base year emissions. On top of these reduction pledges, various provisions from the Protocol are considered. Developed countries, for which land-use change and forestry was a net source in 1990, fall under the provisions of article 3.7 of the Protocol (UNFCCC, 1997a). This paragraph states that countries shall

²So-called Annex I countries are listed in Annex I of the UNFCCC (UNFCCC, 1992), see the supplementary data (available at stacks.iop.org/ERL/5/034013/mmedia).

add their emissions from land-use change to their base year emissions from which the allowed emissions in the respective commitment period are calculated. Specifically, this provision is assumed for the 2000 reference year for Australia's 2020 pledge under the Accord. Once emission levels based on the pledges are calculated, credits from LULUCF accounting and surplus allowances are added.

LULUCF accounting in developed countries can generate emission credits or debits which influence the final allowances of countries for their industrial, fossil and agricultural emissions. The Accord did not address this issue. The rules for the first KP commitment period (CP1) are described in the Protocol and the Marrakesh Accords (UNFCCC, 2001). Under article 3.3 of the Protocol, individual countries must account for GHG fluxes from afforestation, reforestation, and deforestation, and under article 3.4 they can choose additional activities to account for. Those additional activities are forest management, cropland management, grazing-land management and revegetation. Debits or credits from forest management activities are subject to a country-specific cap, listed in the appendix to the Annex of Decision 16/CMP.1 (UNFCCC, 2005). Setting the size of the cap for each country was informed by 3% of the base year emissions and 15% of the forest management sector. Continuation of the same rules but with forest management accounting made mandatory would likely result in net credits of 0.3 gigatonnes CO₂eq (GtCO₂eq) per year from 2013 to 2020. For illustration, we assume that the cap on forest management is increased to 4% of 1990 emissions as a proxy for the lower ambition options currently discussed, for example introducing exception clauses for not having to account for so-called natural disturbances (UNFCCC, 2010c). Our LULUCF accounting assumption leads to yearly allowances of 0.5 GtCO₂eq for the group of developed countries which specified to use LULUCF accounting to achieve their target in communications prior to the Accord (UNFCCC, 2010c). As no post-2012 LULUCF accounting rules have been agreed, there is clearly some uncertainty in regard to the final net effect. These LULUCF allowances are included in case 1, while in case 2 we assume LULUCF accounting to result in a net zero effect. For case 1, target emissions of a country pledge 'including LULUCF' will be increased by credits from LULUCF accounting and vice versa for debits.

Furthermore, if a developed country reaches emission levels which are below its initially attributed assigned amount units (AAUs) in CP1, the difference between the real emission and their allowances can be banked as surplus AAUs to be used in subsequent commitment periods under the provisions specified in article 3.13 of the Protocol. Because of weak CP1 targets and due to the economic slowdown after the collapse of the Soviet Union, the emissions of some countries with economies in transition are well below their AAUs. This is particularly the case for Russia (5.6 GtCO₂eq), Ukraine (2.5 GtCO₂eq) and other countries in Eastern Europe which are now part of the European Union (2.8 GtCO₂eq) (see figure 2.1). The Accord does not address these estimated 11 GtCO₂eq of surplus AAUs. Credits from LULUCF accounting (RMUs) cannot be banked (UNFCCC, 2001). RMUs, however, can be used domestically or traded in CP1 by countries already having surplus AAUs and therefore still result in 1.0 GtCO₂eq of additional surplus allowances. This yields a total of 12 GtCO₂eq surplus AAUs banked from CP1 to subsequent commitment periods. Depending on the quantitative emission reduction or limitation commitments (UNFCCC, 2010e) Parties negotiate for after 2012, additional surplus AAUs are estimated in the range of 2-12 GtCO₂eq. In our case 1, the banked AAUs from CP1 are added on top of the pledged pathways as a linearly increasing wedge,

shown in figure 2.2(a), while surplus generated after 2012 is used after 2020. Case 2 assumes that Parties agree to not purchase banked AAUs from CP1 but at the same time allows for the generation and use of about 2 GtCO₂eq of new surplus AAUs after 2012.

Developing countries

In contrast to the relatively precise pledges of developed countries, developing countries specify their mitigation actions, labelled as Nationally Appropriate Mitigation Actions (NAMAs), in a plethora of ways. A common method to specify developing countries' actions is in terms of reductions from an implied, but often unspecified, future 'business-as-usual' scenario. Also, some proposed actions are framed in terms of emission intensity improvements, i.e. a decrease of emissions per gross domestic product (GDP). For example, China proposed a decrease of 40-45% in their CO₂ emission intensity from 2005 to 2020. This could amount to slightly higher or lower intensity improvements than projected in the reference scenario, e.g. 40% is projected as emission intensity improvement in the reference case by IEA based on World Bank GDP-Purchasing Power Parity projections (IEA, 2009). For China, we quantified the most encompassing of the stated pledges, i.e. the CO₂ intensity improvement target, but not the partially overlapping renewable energy and reforestation pledges. Only countries with quantitative descriptions in their NAMAs are included in this analysis. Emission reductions occurring in the land-use sector are treated separately (see also below).

International shipping and aviation

Besides national emissions, the emission contribution from international bunkers is also calculated to obtain the global total. Emissions from international shipping and aviation are not addressed by the Accord. Therefore we apply the announcements by the respective industry association (ICS, 2009) and the specialized agency of the United Nations (ICAO, 2009), recognizing that at this stage there is no clear indication of if or how these are to be achieved in practice.

Global land-use emissions

Because of the large uncertainties in the data for land use and land-use change emissions provided in the National Communications of developing countries, global pathways of deforestation are based on those developed in the framework of the representative concentration pathways (RCP) for the IPCC Fifth Assessment Report process. As reference pathway, we assume the global harmonized RCP8.5 pathway (Riahi et al., 2007). From this global pathway the announced deforestation reduction ranges from Brazil, Indonesia and other countries are subtracted such that case 1 and case 2 global deforestation pathways are created.

Emission extensions beyond 2020

The Accord only specifies pledges for 2020. As the global climatic assessment strongly depends on what happens after 2020, two different extensions of the emission pathway beyond

2020 were developed. The 'reference growth' case allows emissions to grow further according to the growth rates found in the PRIMAP4 scenario if no 2050 targets from before the Accord were available. The 'global 2050 target' variants halve the global Kyoto-GHG basket of emissions by 2050 from 1990 levels, and emissions continue to decrease after 2050 with an exponential decrease at a rate equal to the average reduction rate in the last decade before 2050. The pathways resulting from these two variants are depicted in figure 2.2(a).

2.2.3 Climatic assessment

Global climatic consequences (temperature, CO₂ and CO₂eq concentrations) are calculated with the PRIMAP climate module. To calculate the climatic consequences of each global scenario, emissions of GHGs, tropospheric ozone precursors and aerosols are generated by building on the multi-gas characteristics within a large set of IPCC scenarios (Nakicenovic and Swart, 2000), using the Equal Quantile Walk method (Meinshausen et al., 2006). Subsequently, these emissions are run through the reduced complexity coupled carbon cycle climate model MAGICC6.3 (Meinshausen et al., 2008) to obtain future concentrations and temperature probability distributions. Each resulting emission pathway is run with 600 different sets of climate model parameters as in the 'illustrative default' case in (Meinshausen et al., 2009) and with a distribution of the climate sensitivity closely representing IPCC AR4 estimates (IPCC, 2007d). Before being used as input to the climate model, the global bottom-up pathway is harmonized to historical emission levels in 2000 in accordance with the IPCC scenarios of the Special Report on Emission Scenarios (SRES) (Nakicenovic and Swart, 2000).

2.3 Results, discussion and conclusion

2.3.1 Resulting 2020 emission levels

Global aggregate emission levels for the case 1 and case 2 interpretation of the Accord are 53.2 and 47.4 GtCO₂eq in 2020, respectively, as summarized with other results in table 2.1. Furthermore, case 1 yields emissions in 2020 which are virtually equal to the emissions of the PRIMAP4 scenario. This illustrates that the net effect of current Accord pledges in case 1 would globally not stimulate any actions beyond those which were already in place before COP15/CMP5, if countries would pool or freely exchange their emission allowances. Figure 2.2(a) shows the calculated pathways.

Aggregate emission allowances of developed countries in 2020 are 19.9 and 15.7 GtCO₂eq, or 6.5% above and 15.7% below 1990 levels in case 1 and 2, respectively. Other analyses, for example by the European Commission (2010b), yield deeper aggregate reduction percentages for developed countries in their most ambitious cases. The main reason for this is that — for comparison with IPCC ranges — we consider the developed countries' group to consist of all countries listed in Annex I of the UNFCCC (UNFCCC, 1992), i.e. including Turkey³.

³Turkey is listed in Annex I of the Convention, but did not take up commitments under the KP and thus is not listed in Annex B of the Protocol. Moreover, Turkey so far did not submit a pledge to the Copenhagen Accord and thus its reference path is used. We choose to include Turkey in the Annex I aggregate to assure consistency with IPCC ranges for Annex I.

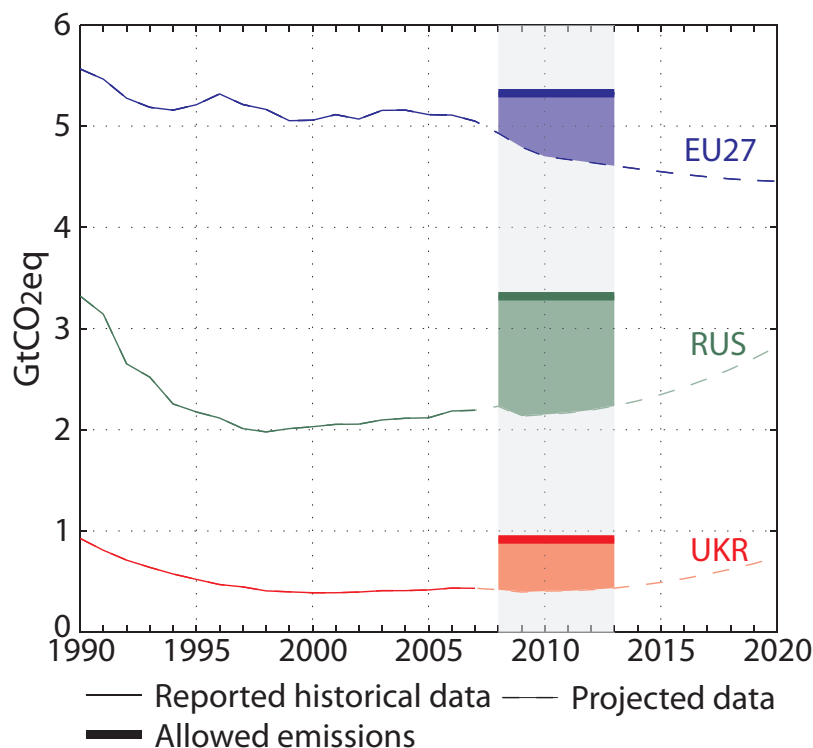


Figure 2.1: Illustration of estimation of surplus assigned amount units (AAUs) for Ukraine (UKR), the Russian Federation (RUS) and the European Union (EU27). Reported data to the UNFCCC is plotted as thin solid lines up to 2007. The dashed line shows the projections of the PRIMAP4 reference scenario and case 1 targets without provisions for 2020. The thick solid line segments between 2008 and 2012 show the emission allowances under the Kyoto Protocol for each respective country. The coloured area under the thick line segments hence represents the estimated surplus emissions allowances for the first commitment period of the Kyoto Protocol for each country.

Looking at the individual developed countries' results reveals weak ambition levels. The European Union's target is a reduction of 20 or 30% below 1990 levels. Smaller annual reductions from now to 2020 would be required to achieve the 20% target, than the average reductions from 1980 to 2010 (-0.51% and -0.65% p.a. relative to 2000 levels, respectively). The United States' target is 17% below 2005, equivalent to only 3% below 1990 levels. Canada aligned itself with the USA target which results in an effective target of 3% above 1990 levels. Canada's proposed 2020 emission allowances would be above its current KP target (6% below 1990 levels), making Canada the only country weakening its ambition level following the Accord. Targets for Russia, Ukraine and Belarus still imply emission levels above projected PRIMAP4 levels, generating additional so-called 'hot air'. Pledges of two developed countries have significantly higher ambitions: Japan and Norway with 25%, and 30%-40% below 1990, respectively. Ultimately, even the optimistic interpretation of the Accord's pledges results in effective reductions by 2020 far outside the 25-40% range of aggregated emission reductions for developed countries specified in Box 13.7 of IPCC AR4 (IPCC, 2007b). That box provided data for the lowest category of analysed mitigation scenarios which stabilize at-

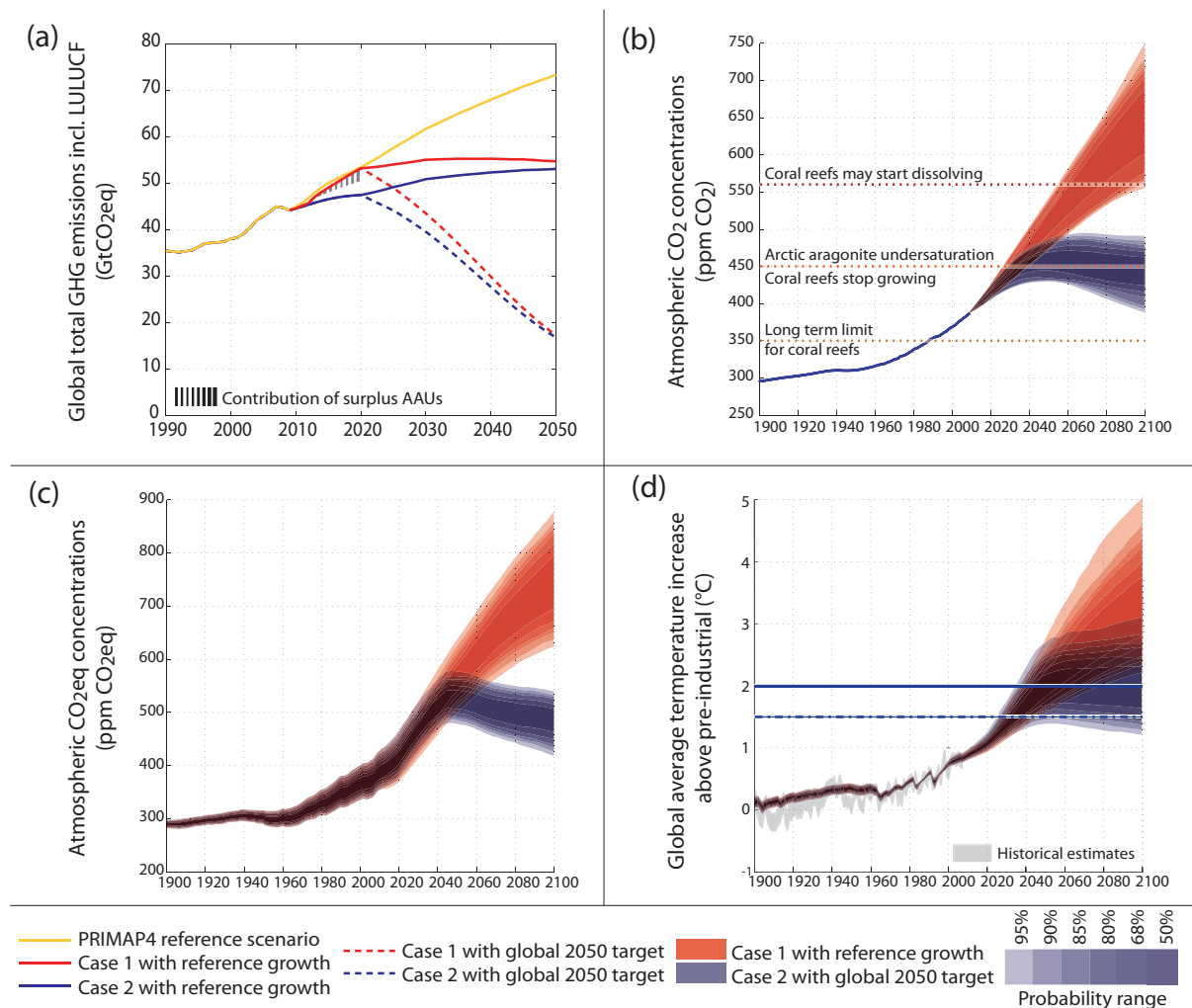


Figure 2.2: Overview of emission pathways and their climatic consequences. (a) Global emission pathways of the PRIMAP4 reference scenario (yellow line), the case 1 (blue line) and case 2 (red line) interpretation of Copenhagen Accord pledges for 2020. The shaded area shows the contribution of banked surplus emission allowances. The dashed lines show the emission pathways with a global 2050 target being halving global emissions by 2050 from 1990 levels. Climatic consequences are shown for case 1 with reference growth (solid red line) and case 2 with a long-term target (dashed blue line). (b) Probability ranges for atmospheric CO₂ concentrations with thresholds due to ocean acidification (McNeil and Matear, 2008; Silverman et al., 2009; Steinacher et al., 2009; Veron et al., 2009). (c) Atmospheric CO₂eq concentrations. (d) Probability ranges for global temperature increase above pre-industrial with 1.5 and 2°C thresholds. Historical temperature data estimates from Brohan et al. (2006).

atmospheric CO₂eq concentrations between 445 and 490 ppm CO₂eq and have a best estimate global temperature increase of 2.0-2.4 °C at equilibrium.

Our assessment of developing countries' actions in 2020 results in aggregate emissions of 29.0 and 28.2 GtCO₂eq, for case 1 and 2, respectively. These emission levels are excluding deforestation-related emissions, as they are treated separately (see below). The quantified reductions reflect deviations below the PRIMAP4 reference scenario of 5 and 7% respectively. These percentages are not directly comparable with the IPCC AR4, as only a 'substantial deviation' was specified in Box 13.7 of the AR4 (IPCC, 2007b). A quantification of this 'substantial deviation from baseline' has been attempted by den Elzen and Höhne (2008, 2010) and resulted in a rough range of 15-30% deviation below 'the baseline' in 2020. A strict comparison with the latter range is not possible due to the lack of absolute emission levels to compare with. As the NAMAs analysed here represent about 68% of total projected developing country emissions in 2020, they appear to be a good proxy for estimating the overall aggregate level of ambition for developing countries. Whilst there are uncertainties in the projections of developing country emissions, by building on data which is officially reported by Parties, this analysis has tried to be closely aligned with actual Party intentions as expressed under the Accord.

The international transport sector's contribution to the global 2020 emission level is 1.9 GtCO₂eq in case 1, with 1.1 GtCO₂eq from international shipping and 0.7 GtCO₂eq from international aviation. In case 2, lower shipping emissions reduce the contribution of the international transport sector to 1.8 GtCO₂eq.

The influence of the Accord's pledges on land-use-related emissions in 2020 is assessed globally. Case 1 yields global land-use emissions of 2.5 GtCO₂eq. This results from our reference level emissions in 2020 of 3.3 GtCO₂eq lowered by the less ambitious end of the REDD-related (reducing emissions from deforestation and forest degradation) pledges. In case 2, net emissions are 1.8 GtCO₂eq. The latter level might actually be too optimistic, as discussed below.

If nations would agree to a 50% reduction by 2050 from 1990 levels, then global industrial emissions will need to decline on average 3.0-3.5% (compared to 2000 levels) in each year between 2020 and 2050 for case 1 and 2 respectively. Such reductions would require unprecedented political will to incentivize the necessary technological and economic innovation and can be regarded as extreme based on current scenario literature (den Elzen et al., 2010b). It should also be pointed out, that a 50% reduction from 1990 levels by 2050 is considerably more ambitious than the same reduction relative to e.g. 2005 levels, as global emissions rose by 21% between 1990 and 2005.

Uncertainties are an inherent part of global emission assessments. For example, even inventories for historical emissions (Boden et al., 2009; IEA, 2009; IPCC, 2007b; JRC and PBL, 2009) have uncertainty ranges of $\pm 10\%$ for fossil and industrial CO₂ emissions and up to $\pm 75\%$ for CO₂ emissions from land-use. The latter uncertainty range is still without taking into account recent re-estimates for peat-fire (van der Werf et al., 2010) and peat-degradation (Hooijer et al., 2010) emissions. The uncertainty range for the results of this analysis is at least as large as the uncertainties in historical emissions, and is further increased by the uncertainties in the quantification of future action and compliance.

2.3.2 Climatic impacts

Case 1 with reference growth after 2020 results in a likely global temperature increase of 2.5-4.2 °C above pre-industrial in 2100 and is still increasing afterwards. For the 'likely' range we assume an 80% range around the median, corresponding to the IPCC's 'likely' definition of 66%-90% (IPCC, 2005a). Using the same IPCC uncertainty definitions, 2 °C is exceeded with virtual certainty (>99% chance) as illustrated in figure 2.2(d). Therefore this scenario is not in line with the Accord's aim to limit the global temperature increase to 2 °C. Case 2 with reference growth yields very similar results because of the high cumulative emissions between 2000 and 2050 implied by the emission trajectory (Meinshausen et al., 2009). A scenario with case 2 emission levels in 2020 and a global 2050 target of 50% below 1990 levels results in a likely range of 1.5-2.6 °C of maximal 21st century global temperature increase and a 49% chance to stay below 2 °C. Probability plots of the climatic results for case 1 with reference growth and case 2 with a global 2050 target are shown in figures 2.2(b)(d).

Rising global average temperature levels are not the only possible 'dangerous anthropogenic interference with the climate system'. For example, increasing atmospheric CO₂ levels cause increasing ocean acidification and will adversely impact marine ecosystems (Doney et al., 2009; Hoegh-Guldberg and Bruno, 2010). A recent study (Veron et al., 2009) defines an atmospheric CO₂ concentration of below 350 ppm CO₂ as a long-term safe limit needed for coral reefs, while a CO₂ concentration of 450 ppm CO₂ would cause reefs to be in rapid and terminal decline. Silverman et al. (2009) indicate furthermore that coral reefs cease to grow and start dissolving at 560 ppm CO₂. Both in Arctic (Steinacher et al., 2009) and Antarctic (McNeil and Matear, 2008) oceans, aragonite undersaturation — causing calcium carbonate shells beginning to dissolve — is projected to occur at atmospheric concentration levels of 450 ppm CO₂. For case 1 and without a 2050 target, median estimates would exceed the 450 ppm CO₂ threshold in approximately 2030. The 560 ppm CO₂ threshold is very likely exceeded by the end of this century. Even for case 2 (with a global 2050 target and exponential decline afterwards), estimated likely CO₂ levels (408-475 ppm CO₂) would imply a rapid decline of coral reefs and arctic aragonite undersaturation during the 21st century. Continuous mitigation effort through the entire century and beyond will be necessary to return atmospheric CO₂ concentrations to a level considered safe for marine ecosystems.

When looking at the range of analyses of the Accord (see above), estimated 2020 emission levels are in broad agreement. However, in some cases, emissions of 48 GtCO₂eq or higher in 2020 are interpreted as congruent with being '2 °C compliant' (Bowen and Ranger, 2009; Stern, 2009; UNEP, 2010a). Such pathways often rely on ambitious global emission reduction rates e.g. 5% yearly from 2021 to 2030. Although not impossible nor strictly infeasible, global annual reduction rates of 5% in the decade after 2020 would require far reaching policy interventions in the coming years to motivate key investments.

Thus, we investigate a fourth illustrative scenario (see table 2.1), which we label '2 °C compliant'. Following the assessment of Box 13.7 of the AR4 (IPCC, 2007b), we apply an aggregate developed country reduction of 30% below 1990 levels and a 'substantial deviation from baseline' of 20% for developing countries to the PRIMAP4 scenario. Global land-use CO₂ emissions are taken from RCP4.5 (Clarke et al., 2007; Smith and Wigley, 2006; Wise et al., 2009). This results in global emission levels of 40-44 GtCO₂eq in 2020, depending on

the baseline (the global PRIMAP4 reference scenario is rather low). These 2020 emission levels would limit the decline of global industrial emissions on average to below 2.3% (compared to 2000 levels) in each year between 2020 and 2050 — if keeping the goal of halving global emissions from 1990 to 2050. In order to reach this 2050 milestone, starting from 2020 emission levels of 44 GtCO₂eq or higher would imply reduction rates that are sometimes considered extreme based on the current scenario literature (den Elzen et al., 2010b).

As the Accord has no legally binding character, parties can add, modify or withdraw their submitted pledges or actions without any restriction. Since mid-April — the moment the snapshot of mitigation actions for this study was taken — several parties have done so. As a positive example, additional actions were submitted by Papua New Guinea, Moldova, Mauritania and others. Most of these actions are unfortunately not quantifiable because of a lack of quantitative details in the submissions. A clear assessment with respect to the global PRIMAP4 pathway is therefore not possible. For Indonesia, an increased reduction in deforestation was assumed for case 2. As this reduction, which is conditional on international support, was not part of their submission, the current deforestation pathway might show an overly optimistic picture for the Accord's outcome. For our analysis, these changes in the pledges will slightly change the aggregate emission numbers, but not the key results of our analysis.

2.3.3 Conclusion

If the average national ambition level for 2020 is not substantially improved and loopholes closed in the continued negotiations, only low probability options remain for reaching the 2 °C (and possible 1.5 °C) ambition of the Accord. Most developed country submissions to the Accord indicate that only with a global and comprehensive agreement countries are inclined to commit to more, and likewise for developing countries the required level of support through financing, technology and capacity building is needed. With the negotiation mandates having been extended to the end of 2010, committing to higher ambitions and agreement by all Parties still remains possible. It is clear from this analysis that higher ambitions for 2020 are necessary to keep the options for 2 and 1.5 °C open without relying on potentially infeasible reduction rates after 2020. In addition, the absence of a mid-century emission goal — towards which Parties as a whole can work and which can serve as a yardstick of whether interim reductions by 2020 and 2030 are on the right track — is a critical deficit in the overall ambition level of the Copenhagen Accord.

Table 2.1: Characteristics of four analysed pathways.

	Case 1 Post-2020 ref. growth	Case 2 Post-2020 ref. growth	Case 2 Global 2050 target	Illustr. 2 °C compliant
<i>2020 emissions [GtCO₂eq]</i>				
Global	53.2	47.4	47.4	40.3
Annex I	19.9	15.7	15.7	13.1
Non-Annex I	29.0	28.2	28.2	24.4
Land-use CO ₂	2.5	1.8	1.8	1.2
Internat. transport	1.9	1.8	1.8	1.6
<i>2050 emissions [GtCO₂eq]</i>				
Global	54.7	53.1	17	17
Annex I	6.4 ^a	6.4 ^a	N/A ^b	N/A ^b
Non-Annex I	45.3	44.2	N/A ^b	N/A ^b
Land-use CO ₂	1.6	1.1	1.1	0.9
Int. transport	1.4	1.4	0.6	0.6
<i>2100 emissions [GtCO₂eq]</i>				
Global	43	42	1	3
<i>Cumulative emissions from 2000 to 2050 (total emissions)[GtCO₂eq]</i>				
Global	2776	2638	2080	1792
<i>Average 2020-2050 reduction rate (emissions excl. LULUCF)</i>				
Global	No reduction	No reduction	3.0%	2.3%
<i>2100 CO₂ concentrations [ppm CO₂]</i>				
Median estimate	650	636	448	431
Likely (80%) range	568-714	558-697	408-475	395-456
<i>2100 CO₂eq concentrations [ppm CO₂eq]</i>				
Median estimate	748	730	484	465
Likely (80%) range	659-838	644-813	439-525	425-501
<i>Maximal 21st century temperature increase above pre-industrial</i>				
Median estimate [°C]	3.3	3.2	2.0	1.8
Likely (80%) range [°C]	2.5-4.2	2.4-4.1	1.5-2.6	1.4-2.4
Probability > 1.5 °C	100%	100%	93%	84%
Probability > 2 °C	>99%	>99%	49%	37%
Probability > 3 °C	64%	60%	3%	2%

^a 2050 targets by Annex I Parties communicated prior to the Copenhagen Accord are taken into account (see the supplementary data available at stacks.iop.org/ERL/5/034013/mmedia).

^b Because for this pathway no assumptions are made about the share of emission reductions by either Annex I or Non-Annex I Parties in 2050, only the global value is relevant for this exercise.

Chapter 3

Discrepancies in historical emissions point to a wider 2020 gap between 2 °C benchmarks and aggregated national mitigation pledges

Discrepancies in historical emissions point to a wider 2020 gap between 2 °C benchmarks and aggregated national mitigation pledges

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Abstract

Aggregations of greenhouse gas mitigation pledges by countries are frequently used to indicate whether resulting global emissions in 2020 will be 'on track' to limit global temperature increase to below specific warming levels such as 1.5 or 2 °C. We find that historical emission levels aggregated from data that are officially reported by countries to the UNFCCC are lower than independent global emission estimates, such as the IPCC SRES scenarios. This discrepancy in historical emissions could substantially widen the gap between 2020 pledges and 2020 benchmarks, as the latter tend to be derived from scenarios that share similar historical emission levels to IPCC SRES scenarios. Three methods for resolving this discrepancy, here called 'harmonization', are presented and their influence on 'gap' estimates is discussed. Instead of a 3.4-9.2 GtCO₂eq shortfall in emission reductions by 2020 compared with the 44 GtCO₂eq benchmark, the actual gap might be as high as 5.4-12.5 GtCO₂eq (a 22-88% increase of the gap) if this historical discrepancy is accounted for. Not applying this harmonization step when using 2020 emission benchmarks could lead to an underestimation of the insufficiency of current mitigation pledges.

3.1 Introduction

Following the Climate Summit of the United Nations Framework Convention on Climate Change (UNFCCC) in December 2009 in Copenhagen, several studies have been published which intend to track, assess and communicate the levels of mitigation action which can be expected from the pledges put forth. Analysts from research institutes, government agencies, non-governmental organizations and from the private sector alike (Ecofys and ClimateAnalytics, 2010; Climate Interactive, 2010; den Elzen et al., 2010c; European Commission, 2010b; Levin and Bradley, 2010; Lowe et al., 2010; Macintosh, 2010; PIIE, 2010; Project Catalyst, 2010; PwC, 2010; Risø Center UNEP, 2010; Rogelj et al., 2010a,b; Stern, 2009; Stern and Taylor, 2010; UNEP, 2010a) project emission levels in 2020 based on international pledges made in the framework of the Copenhagen Accord (UNFCCC, 2009b) and the UNFCCC (UNFCCC, 2010f,g), on government reports addressing mitigation action (NCCC Indonesia, 2009) or on national policy plans (NDRC China, 2007; PMCCC India, 2008). Most analyses (Ecofys and ClimateAnalytics, 2010; Climate Interactive, 2010; den Elzen et al., 2010c; European Commission, 2010b; Lowe et al., 2010; Macintosh, 2010; Project Catalyst, 2010; Risø Center UNEP, 2010; Rogelj et al., 2010a,b; Stern, 2009; Stern and Taylor, 2010; UNEP, 2010a) attempt to evaluate whether the world is on track to limit global temperature increase to 2 °C above pre-industrial or not. Some studies (Rogelj et al., 2010a,b) also look at limiting warming to below 1.5 °C by 2100, a temperature level which was included in the Copenhagen Accord in relation to the strengthening of the long-term emission reduction goal after a review in 2015.

Deciding whether assessed 2020 greenhouse gas (GHG) emission levels are likely to be consistent with emission paths that can limit global warming to 2 °C can be done in several ways. Two main approaches are found in the literature: (a) the 'benchmark approach', which compares estimated emissions to a benchmark emission level considered as a test of consistency with the temperature goal or (b) the 'full century approach', which involves running a reduced complexity climate model with explicit post-2020 emission pathway assumptions. The benchmark approach compares the assessment of emission levels in 2020 to a predefined level or range (hitherto called 'the benchmark'), which is assessed to be in line with 2 °C. The path followed by global emissions after 2020 is not explicitly modelled, but derived from the assumptions of the studies providing the benchmark. The 'full century approach', which runs an entire emission pathway, or set of pathways, through a climate model, is used less often but has the advantage that post-2020 assumptions are made explicit. In this analysis we show that unconsidered application of the benchmark approach can lead to imprecise conclusions of emission assessments concerning the 2 °C compliance of a 2020 emission level (see figure 3.1). In this paper, we quantify the mismatch in emission levels which are officially reported by countries, and the emissions levels initially used by different groups to construct the 2020 emission benchmarks. Three illustrative methodologies for approaching this issue are suggested and their influence quantified.

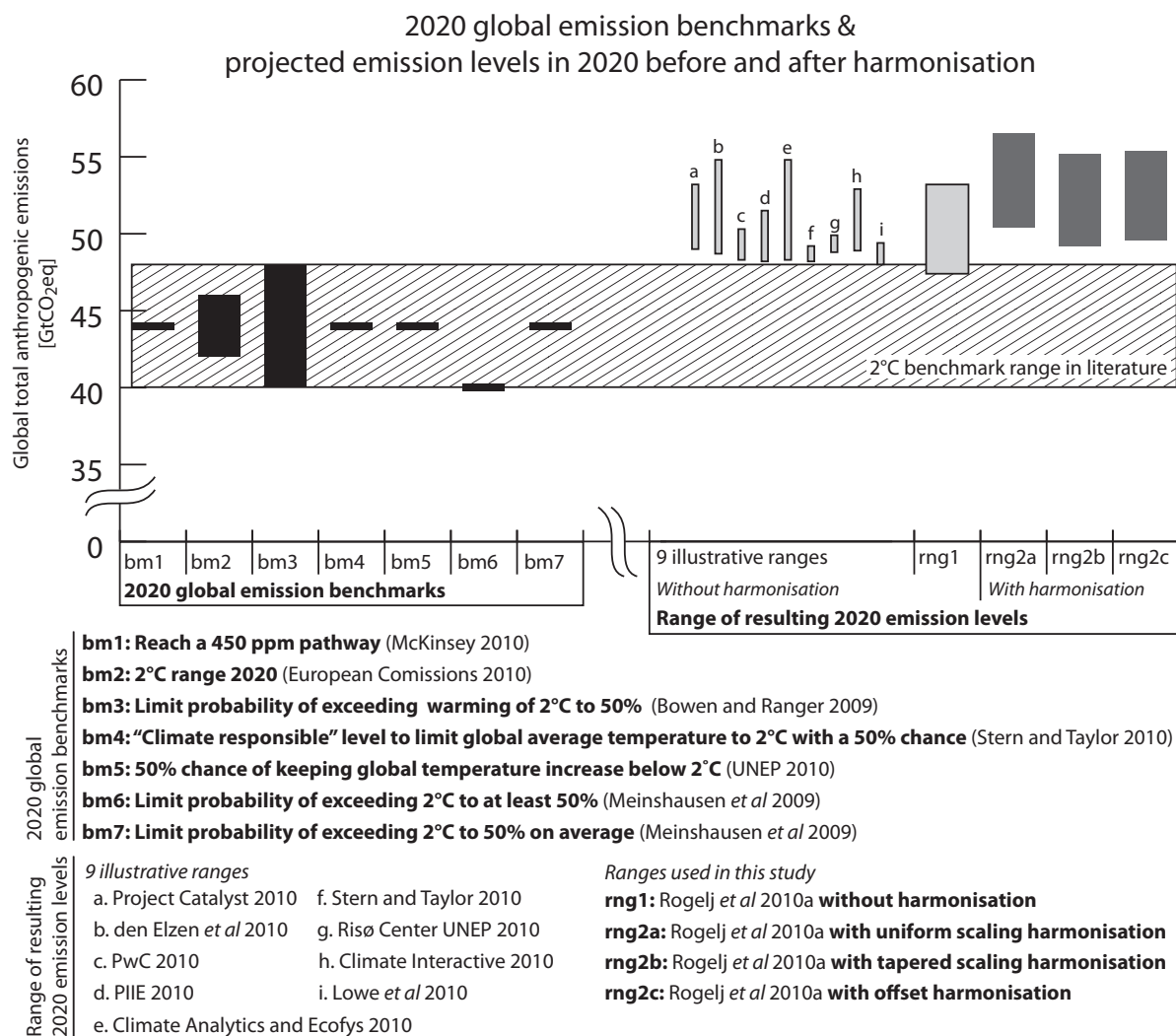


Figure 3.1: Overview of global emission benchmarks for 2020 as found in the literature in terms of global total anthropogenic emissions in $GtCO_2eq$ (black ranges at the left), the range of resulting emissions based on pledges under the Copenhagen Accord for nine illustrative studies (narrow bounded light grey ranges), and the range used for this study before harmonization (wide bounded light grey shaded range) and after harmonization (wide dark grey shaded ranges). The x-axis indicates the studies as well as the climate goals the respective benchmarks were developed for in the case of 2020 benchmarks, and the harmonization methods for the projected 2020 emission ranges under the Copenhagen Accord, respectively.

3.2 Benchmark definition

All the studies in the literature that apply the benchmark approach use 2020 as the year in which estimated emission levels are compared to the benchmark. The fact that this provides a link to the Copenhagen Accord (UNFCCC, 2009b) and ongoing climate negotiations (UNFCCC, 2010d) supports this approach.

3.2.1 2020 emission benchmarks

Several studies have estimated what global 2020 emission levels in gigatonnes carbon dioxide equivalence (GtCO₂eq) could be considered as an appropriate 2 °C benchmark level (Bowen and Ranger, 2009; European Commission, 2010a; Meinshausen et al., 2009; Project Catalyst, 2010) (see figure 3.1). An analysis of the methodologies used by these assessments reveals that they all use harmonized historical emissions drawn from the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emission Scenarios (SRES) (Nakicenovic and Swart, 2000) to determine their climate-related benchmarks. These harmonized historical emissions are defined for the so-called Kyoto greenhouse gas (Kyoto-GHG) basket which consists of carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorinated compounds (PFCs) and sulfur hexafluoride (SF₆) and takes into account contributions of fossil fuels, industry, land use and land-use change and forestry, international shipping and international aviation.

When comparing temperature benchmarks to 2020 emissions levels resulting from the assessments of mitigation action compilations (for example the Copenhagen Accord), it is paramount that the assumptions used in framing the studies providing the benchmarks are taken into account and, if necessary, adjusted for, so there is consistency in the temperature comparison. An aggregated indicator of whether a consistent set of assumptions is applied in both the studies providing the benchmarks and the pledge assessments is global historical emission levels. As explained above, all studies which provide temperature benchmarks are assuming historical emission from the IPCC SRES scenarios. In the remainder of this analysis, all examples therefore focus on a harmonization to these historical emission values.

3.2.2 Variability in 2000 values

The issue that arises is that historical estimates based on other methodologies or data sets can differ from the estimates of the SRES data set (see figure 3.2). Looking at the literature, global fossil fuel emission estimates for 2000 differ by up to 5%, which is comparable to the ±6% uncertainty assessed by Prather et al. (2009) for reported emissions, and the variation increase for other sources, where either the underlying emission and activity estimates are uncertain or different methodologies are used to account and report for emissions from activities. Additionally, each emission estimate methodology has its own intrinsic uncertainty range (Bun et al., 2010; Jonas et al., 2010; Winiwarter and Muik, 2010). Figure 3.2 provides an overview of historical 2000 emission levels from various sources and their uncertainty ranges.

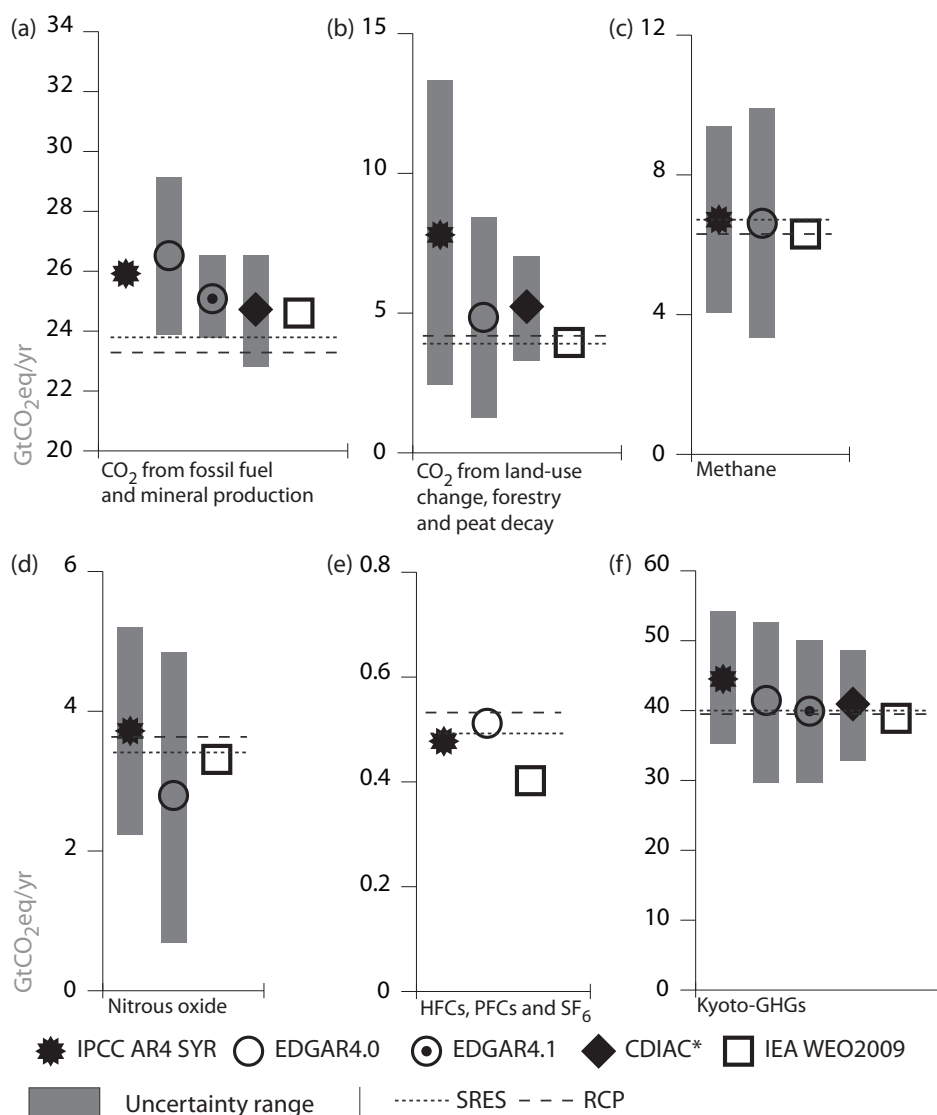


Figure 3.2: Comparison between scenario and inventory data for global anthropogenic GHGs in 2000. (a) CO₂ emissions from fossil fuel and mineral production; (b) CO₂ emissions from land-use change, forestry and peat decay; (c) methane emissions; (d) nitrous oxide emissions; (e) HFCs, PFCs and SF₆; (f) GWP-weighted (IPCC, 1996) aggregate emissions of all greenhouse gas emissions controlled under the Kyoto Protocol (sum of emissions shown in panels (a)-(e)). The dashed lines show harmonized RCP values (Meinshausen et al., 2011c; Vuuren et al., 2011), and the dotted lines SRES values (Nakicenovic and Swart, 2000). Values are shown for the Synthesis Report of the IPCC Fourth Assessment Report (IPCC, 2007c), the Emission Database for Global Atmospheric Research (EDGAR), release 4.0 (JRC and PBL, 2009) and release 4.1 (Olivier and Peters, 2010), the Carbon Dioxide Information Analysis Center (CDIAC) (Boden et al., 2009; Houghton, 2008) and the World Energy Outlook 2009 (WEO2009) from the International Energy Agency (IEA, 2009). Values of WEO2009 were extrapolated linearly from the first reported global values in 2005. In panel (f), contributions of missing GHGs were taken from EDGAR4.0 and IPCC AR4 SYR for the completion of EDGAR4.1 and CDIAC data, respectively. Specific uncertainty ranges are calculated for EDGAR4.0 (derived from Olivier et al. (1999)) and CDIAC (derived from Houghton (2003); Marland and Rotty (1984)). When not explicitly referenced, the uncertainty ranges are derived from the respective source publications. For each study cited, sources of uncertainty are different, because their methodologies are different. This figure only shows the aggregated uncertainty ranges for all sources of uncertainty.

3.2.3 Historical emission estimates

Various studies have made historical emission inventories and have estimated historical anthropogenic emission levels, e.g. for the year 2000 (Boden et al., 2009; Houghton, 2008; IEA, 2009; IPCC, 2007c; JRC and PBL, 2009; Meinshausen et al., 2011c; Nakicenovic and Swart, 2000). Important uncertainties exist for those historical levels and for virtually every gas in the Kyoto-GHG basket (see figure 3.2). These uncertainties result in a range of estimates for the final total global anthropogenic GHG emission basket from the same set of global activities. As the SRES estimates result from a coordinated effort among various research groups, they provide a good reference point. Figure 3.3 illustrates that the IPCC SRES levels are within the uncertainty ranges of other estimates.

3.2.4 Officially reported data

Emission assessments relating to international climate policy negotiations rely on data which are officially reported by countries according to agreed methodologies and reviewed by expert review teams. Under articles 4.1 and 12 of the UNFCCC, all parties to the convention must *'develop, periodically update, publish and make available (...) national inventories of anthropogenic emissions (...)'* as well as submit periodically national communications (UNFCCC, 2009f). Non-Annex I countries submit national inventories as part of their national communications. Those Annex I countries that have ratified the Kyoto Protocol must also provide additional information in both their national communications and their annual national inventory submissions (UNFCCC, 2009a) to show compliance with the Kyoto Protocol.

Annex I inventory reporting rules, guidelines and methodologies are quite complex and involve important and agreed assumptions about when and how emissions from activities with latent release potential are accounted for (e.g. release of HFCs from in use applications, deforestation with slow release of carbon from oxidizing soils, etc). Furthermore, estimates made of the release of CO₂ from fossil fuel combustion within a country have an uncertainty of $\pm 6\%$ (Prather et al., 2009). Therefore, for different data sources, emissions from national estimates and global estimates will not match perfectly. For example, the USA officially reported to the UNFCCC that CO₂ emissions from fossil fuel and mineral production in 2000 were 5.95 GtCO₂ (UNFCCC, 2009a). The US Energy Information Administration reported 5.89 GtCO₂ (EIA, 2010) for the same emission sectors. A lower estimate of 5.74 GtCO₂ is reported in the CDIAC database (Boden et al., 2009), and the International Energy Agency estimates 5.66 GtCO₂ (IEA, 2009). For this specific case the standard deviation across the different estimates is 2.5% around a mean. This does not take into account the uncertainties of the respective estimates and the fact that some data sources do not use the exact same emission sector definitions.

3.2.5 Composite historical emission estimates

While the data in the Annex I national inventory submissions are reported annually, national communications of non-Annex I countries only contain emissions for certain years, sometimes only up to 1994. To define 2000 global emission levels, the latter values thus have to be projected from their last reported year up to the year 2000. To quantify the sensitivity of estimated 2000 values to assumptions, a set of three different composite emissions pathways

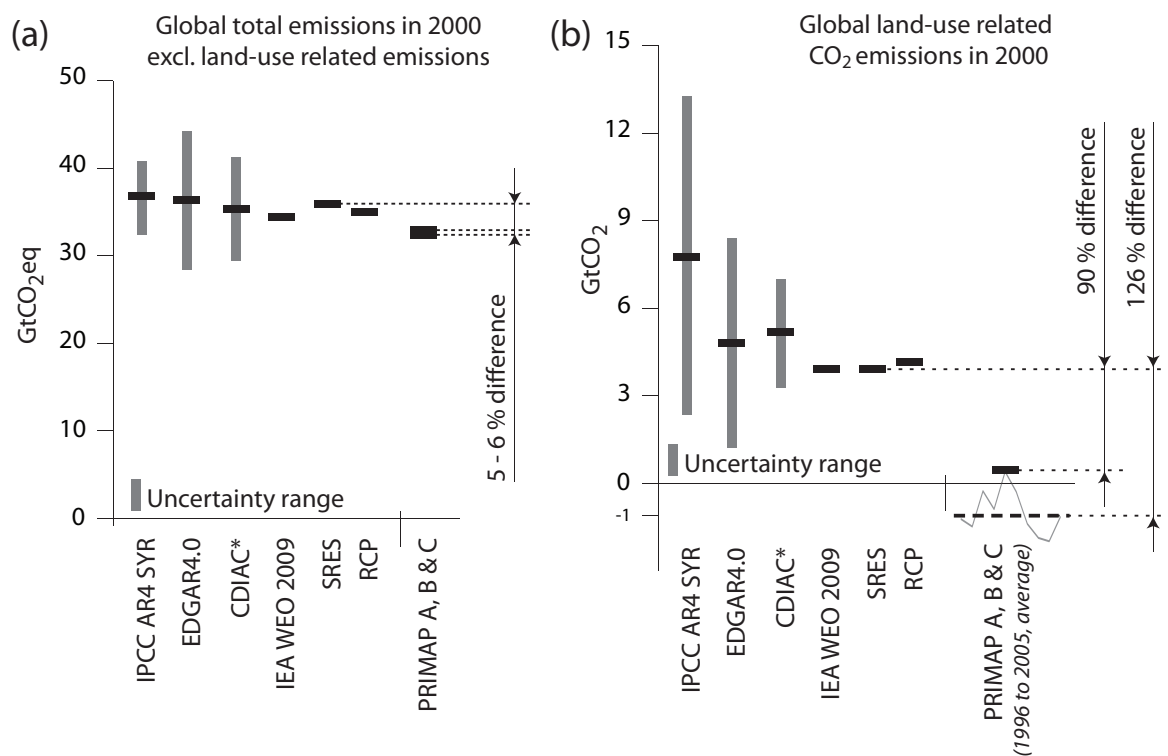


Figure 3.3: Overview of historical emission levels in 2000 derived from various global studies for both (a) global total anthropogenic emissions excluding land-use related emissions for the Kyoto-GHG basket (CO_2 , CH_4 , N_2O , HFCs, PFCs and SF_6) and (b) global anthropogenic land-use related CO_2 emissions, compared to the values from composite PRIMAP baselines based on data officially reported by countries to the UNFCCC. Black bars indicate the inventory estimates, grey bars indicate uncertainties as reported by the studies. CDIAC only provides values for CO_2 from fossil fuel and cement, and from land-use change. To allow comparability, CDIAC's missing emissions (CH_4 , N_2O , HFCs, PFCs and SF_6) have been complemented with the emission contribution estimates published in the IPCC AR4, therefore this source is marked with an asterisk. For anthropogenic land-use related CO_2 emissions in panel (b), in addition to year 2000 values (thick solid bars), the annual time series from 1996 to 2005 is shown (thin solid line) as well as the decadal average (dashed line) for the values of the PRIMAP projections based on data officially reported to the UNFCCC.

— all starting from officially reported data — is developed. For creating these composite emissions pathways, we use the composite source generator method of the Potsdam Real-time Integrated Model for the Probabilistic Assessment of Emission Paths (PRIMAP) (Nabel et al., 2011). This method generates a composite emission path based on a hierarchical list of initial sources. We use three different sets of literature data to complement the officially reported data (see table 3.1). Data contained in sources with the highest priority are used unmodified, while lower priority sources are used to complement, inter- or extrapolate.

Table 3.1: Overview of emission data sources used for the construction of projections based on officially reported historical data.

Emission projection name	PRIMAP A	PRIMAP B	PRIMAP C
Hierarchical list of sources ^a	1. CRF 2. NATCOM 3. MATCH	1. CRF 2. NATCOM 3. CDIAC 4. IEA 5. EDGAR 6. POLES 7. MATCH 8. MNP SRESA1B	1. CRF 2. NATCOM 3. EDGAR 4. CDIAC 5. MATCH
<i>Global GHG emissions excl. land-use related CO₂ emissions in 2000 (GtCO₂eq)</i>			
	32.8	32.8	33.1
<i>Global land-use related CO₂ emissions in 2000 (GtCO₂)</i>			
	0.40	0.4	0.41

^a Explanation: PRIMAP: Potsdam Real-time Integrated Model for the Probabilistic Assessment of Emission Paths (Nabel et al., 2011); CRF: national inventory submissions to the UNFCCC — ‘officially reported’ (UNFCCC, 2009a); NATCOM: national communications to the UNFCCC — ‘officially reported’ (UNFCCC, 2009f); MATCH: downscaled SRESA1B scenario from the Ad Hoc Group for the Modelling and Assessment of Contributions of Climate Change (Höhne et al., 2011a); CDIAC: Carbon Dioxide Information and Analysis Center (Boden et al., 2009); EDGAR: Emission Database for Global Atmospheric Research (JRC and PBL, 2009); IEA: International Energy Agency, World Energy Outlook 2009 (IEA, 2009); POLES: Prospective Outlook on Long-term Energy Systems model (ENERDATA, 2009); MNP SRESA1B: downscaled SRESA1B scenario of the Netherlands Environmental Assessment Agency (van Vuuren et al., 2006).

Table 3.1 lists the initial sources which were used for the respective emission projections. Following the officially reported data, the PRIMAP A projection uses scaled growth rates from a composite scenario based on a downscaling of the SRESA1B pathway which was developed in the framework of the Ad Hoc Group for the Modelling and Assessment of Contributions of Climate Change (MATCH) (Höhne et al., 2011a), the PRIMAP B projection uses country resolution historical emission data from fossil fuel and cement production from the Carbon Dioxide Information Analysis Center (CDIAC) (Boden et al., 2009), and the PRIMAP C projection uses data from the Emission Database for Global Atmospheric Research (EDGAR) (JRC and PBL, 2009) to accomplish these extensions. Despite the different character of the sources used, the resulting global 2000 emission levels of the three extensions show only a very small variation between them, with a maximum absolute discrepancy of about 0.35 GtCO₂eq or 1.0% of corre-

sponding SRES levels in the year 2000 (see figure 3.3 and table 3.1). This variation is relatively small given the fact that Annex I countries report data for 2000 and for most non-Annex I countries the nearest point for extrapolation is 1994, with a small set of non-Annex I countries also reporting data for 2000. The three land-use emission estimates derived from officially reported data show an even smaller spread as fewer historical growth assumptions on a country level are available in the peer-reviewed literature (Höhne et al., 2011a; Houghton, 2008), and therefore these estimates have a similar evolution.

3.2.6 Composite official estimates versus other sources

A comparison of the 2000 emission values based on officially reported data with the SRES 2000 emission values shows significant discrepancies. For global total anthropogenic emissions excluding land-use related emissions this discrepancy is of the order of 5-6% of SRES 2000 values. Estimates based on officially reported data are in general at the very low end, and even below (for example, see the IPCC AR4 estimates) the uncertainty ranges of other global emission inventory exercises.

For anthropogenic land-use related emissions the relative discrepancy is an order of magnitude larger, with emissions based on officially reported data being 90% lower than SRES estimates in 2000 and below all uncertainty ranges of other emission inventories. Land-use related emissions show a high interannual variability which is smoothed in top down assessments like SRES. Therefore also the yearly values for the decade encompassing the year 2000 are given, together with the average level in this time period (see figure 3.3). This decadal average shows an even larger discrepancy between officially reported land-use related emissions and other global inventories, including a change of sign and amounting to 126% relative to SRES values in 2000. Some reasons for these discrepancies are probably (a) the often low capacity currently in non-Annex I countries to make inventories over their entire national territory, (b) inventories that do not necessary span all GHG emissions and all sectors, and (c) strategic issues related to the negotiations of future allowances and compliance.

The discrepancies between land-use related emissions based on officially reported data and other inventories are large, and none of the analyses in the literature incorporate officially reported data for land-use related emissions in their global estimates. Other sources are used which are based on global historical estimates (Houghton, 2008; Nakicenovic and Swart, 2000). In this paper we will therefore focus on the harmonization of emissions excluding land-use related emissions.

3.3 Harmonization methodologies

Three harmonization methodologies are presented and their influence quantified and discussed: uniform scaling harmonization, tapered scaling harmonization and offset harmonization. The uniform scaling harmonization approach looks at the relative difference between the 2000 emission levels (E) from a given pathway and the reference values (E_{ref}), and scales the entire pathway for all years (t) to get the harmonized emissions ($E_{harmono}$):

$$E_{harmono}^{scale}(t) = E(t) \left(\frac{E_{ref}(2000)}{E(2000)} \right) \quad (3.1)$$

The tapered scaling harmonization approach starts from the same point as the previous method, but relaxes the scaling from the starting year t_0 over time until a year t_{match} is reached. After year t_{match} no scaling is applied:

$$\begin{aligned} t < t_{match} & : E_{harmono}^{taper}(t) = E(t) \left(\frac{E_{ref}(2000)}{E(2000)} + \left(1 - \frac{E_{ref}(2000)}{E(2000)} \right) \left(\frac{t-t_0}{t_{match}-t_0} \right) \right) \\ t \geq t_{match} & : E_{harmono}^{taper}(t) = E(t) \end{aligned} \quad (3.2)$$

Finally, the offset harmonization methodology offsets the entire emission pathway with the difference in emission levels observed in the year 2000:

$$E_{harmono}^{offset}(t) = E(t) + (E_{ref}(2000) - E(2000)) \quad (3.3)$$

The three harmonization procedures are applied to the PRIMAP B pathway described above together with historical SRES emissions as reference values, and their influence on 2020 emission levels resulting from an assessment of the pledges under the Copenhagen Accord (Rogelj et al., 2010a) is analysed and discussed. The latter assessment developed two sensitivity cases: one pessimistic (case 1) and one optimistic (case 2). We look at the range defined by both cases and compare it to an illustrative 2020 emission benchmark of 44 GtCO₂eq (see figure 3.1) to see how they would influence policy advice. For the tapered scaling harmonization, 2050 is chosen as the year in which the scaling factor returns to 1, consistent with the default choice for harmonizing the emissions of the new IPCC scenarios named Representative Concentration Pathways (RCP) (Meinshausen et al., 2011c).

The three presented harmonization methods implicitly assume that the discrepancy in historical emissions is to be attributed to different reasons. Uniform scaling harmonization could be interpreted as the appropriate method if officially reported data are spanning all sectors, but emission values for each sector are consistently reported to be lower than in reality. It also assumes that countries will continue to do so to the same extent in the future. Tapered scaling harmonization could also be interpreted in that sense, but assumes that emissions at a certain point in the future will be subject to solid and integer international rules in a way such that the discrepancy between reported and real emissions is minimized. Finally, offset harmonization might be interpreted as implicitly assuming that officially reported emission inventories missed a constant source of emissions or did not span all the emission sectors of other emissions inventory exercises. Therefore, a fixed offset might be considered an appropriate method to cope with this kind of discrepancy.

3.4 Results and discussion

All methods yield significant increases in 2020 emission levels of 4-6% (see table 3.2), with the largest increase for the uniform scaling method. Although the latter method inflates the 2020 levels the most, it is the only method which would conserve the relationship between base and target year emissions for emission targets that are defined relatively. For example, a reduction target like the one put forth by the USA of 17% from 2005 levels would remain intact with this

approach. This method, however, implies that also negative emissions are scaled in the opposite direction. This could be alternatively executed by offsetting the pathway by its maximum negative value during scaling. However, given the fact that negative emissions as emission targets are far from the current negotiation reality (UNFCCC, 2010d), and 2020 emission levels are virtually certain to not be negative in any scenario, this drawback of uniform scaling is minimal for 2020 emission assessments. With tapered scaling harmonization and offset harmonization, the relationship for relatively defined emission targets is not conserved. Furthermore the offset method would not increase sinks. Finally, a drawback of offset harmonization is the fact that it will influence the year of a possible future switch to negative emissions. Both scaling harmonization methods do preserve this year in their pathways.

Table 3.2: Overview of the influence of three harmonization methods on (a) absolute 2020 emission levels, (b) relative changes of 2020 emission levels and (c) the resulting gap resulting between the absolute 2020 emission levels and an illustrative 2020 benchmark in line with a 2°C target.

Scenario	Harmonization method			
	No harmonization	Uniform scaling	Tapered scaling	Offset
<i>2020 emission levels [GtCO₂eq]</i>				
Case 1	53.2	56.5	55.2	55.4
Case 2	47.4	50.4	49.2	49.6
<i>% increase of 2020 emission levels with respect to no harmonization</i>				
Case 1 [%]	0	6	4	4
Case 2 [%]	0	6	4	5
<i>Illustrative 2°C 'gap': abs. diff. from illustrative benchmark of 44 GtCO₂eq [GtCO₂eq]</i>				
Case 1	9.2	12.5	11.2	11.4
Case 2	3.4	6.4	5.4	5.6
<i>% increase of the 'Gap' with respect to no harmonization</i>				
Case 1 [%]	0	36	22	24
Case 2 [%]	0	88	53	65

The presented harmonization approaches are not exhaustive and should not be imperatively applied homogeneously to all countries. As an illustrative example, emission inventories of industrialized countries might cover all sectors but systematically underestimate actual emissions, while developing countries could have only a partial sectoral coverage. In line with the discussion above, differentially applying the uniform scaling method to industrialized countries and the offset method to developing countries could therefore be considered. This differentiated approach results in an increase of the gap in 2020 of 36-124%. This is higher than the three homogeneous approaches shown in table 3.2.

An alternative harmonization approach would be to perform adjustments on historical data before calculation of future emission levels. However, IPCC SRES emission data are not available on a country level. Scaling single countries' historical emissions before calculation of future emission levels would therefore not yield very different results. This kind of harmonization could alternatively involve an analysis at the sector level of each country's emissions. This approach lies outside the scope of this paper.

In the harmonization methodology we present here, the emissions of the IPCC SRES scenarios are used as the historical reference. This choice is motivated by the fact that all studies which provide 2020 emission benchmarks in line with a temperature target are relying on these historical SRES emissions estimates. However, if benchmark studies were to become available which were based on other historical emission estimates (for example the RCPs), the harmonization should be adjusted accordingly.

Assessing 2020 emission levels does not unambiguously define the probability of exceeding a certain temperature target (Meinshausen et al., 2009). Cumulative emissions (Meinshausen et al., 2009; Allen et al., 2009; Matthews et al., 2009; Zickfeld et al., 2009) are in that respect a much more robust indicator. Due to constraints on the economic and technical rate of change, a 2020 emission level correlates with the minimum amount of cumulative emissions over a longer period, as modelled in socio-economically and technically feasible pathways (Clarke et al., 2009; den Elzen et al., 2007; Edenhofer et al., 2009; IPCC, 2007b; Knopf et al., 2009; O'Neill et al., 2009). Therefore, 2020 emissions levels can provide a reasonable and policy-relevant indicator as to whether global emissions are 'on track' for pathways which can limit global mean temperature increase to 2 °C or lower. Finally, the implication of the explored mismatch between officially reported data and global emission estimates is important for studies using the benchmark approach to define whether we are 'on track' on, for example, a 2 °C path. Many of the above-mentioned studies calculate the difference between where current pledges add up to and the 2 °C benchmark of their choice. This so-called 'gap' is then communicated as the central message of those studies. Whereas before harmonization the emission 2020 levels resulting from the optimistic scenario (case 2) in Rogelj et al. (2010a) might have been considered compliant with 'emission levels that limit the probability of exceedance of 2 °C to 50%', all three harmonization methods yield emissions levels which are outside that range (see figure 3.1). The latter statement can therefore not be supported any more, as the lowest forecasted 2020 emission level shifts from 47.4 to 49.2 GtCO₂eq, i.e. from below to above the upper limit of the above-mentioned 2 °C benchmark range (48 GtCO₂eq). Furthermore, the gap between the 44 GtCO₂eq benchmark and the forecasted 2020 emission levels would increase from 3.4-9.2 GtCO₂eq to 5.4-12.5 GtCO₂eq, or a relative increase of 22-88%, based on the harmonization methods discussed here.

This paper shows that a rigorous adjustment for the historical emission levels linked to the benchmark approach (in line with IPCC SRES), consistently increases the gap in 2020 and thereby influences the conclusions and policy messages based on it. Using the benchmark approach without the harmonization step presented here could underestimate the insufficiency of current mitigation pledges.

Part III

Scenario comparability for climate and impact assessments

Chapter 4

Global warming under old and new scenarios using IPCC climate sensitivity range estimates

Global warming under old and new scenarios using IPCC climate sensitivity range estimates

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Abstract

Climate projections for the Fourth Assessment Report (IPCC, 2007d) (AR4) of the Intergovernmental Panel on Climate Change (IPCC) were based on scenarios from the Special Report on Emissions Scenarios (Nakicenovic and Swart, 2000) (SRES) and simulations of the third phase of the Coupled Model Intercomparison Project (Meehl et al., 2005) (CMIP3). Since then, a new set of four scenarios (the Representative Concentration Pathways or RCPs) was designed (Moss et al., 2010). Climate projections in the IPCC Fifth Assessment Report (AR5) will be based on the fifth phase of the Coupled Model Intercomparison Project (Taylor et al., 2011) (CMIP5), which incorporates the latest versions of climate models and focuses on RCPs. This implies that by AR5 both models and scenarios will have changed, making a comparison with earlier literature challenging. To facilitate this comparison, we provide probabilistic climate projections of both SRES scenarios and RCPs in a single consistent framework. These estimates are based on a model setup that probabilistically takes into account the overall consensus understanding of climate sensitivity uncertainty, synthesizes the understanding of climate system and carbon-cycle behaviour, and is at the same time constrained by the observed historical warming.

4.1 Introduction

A thorough comparison of SRES scenarios and RCPs would ideally be based on results computed by the exact same set of models. Running the new RCPs with the full suite of CMIP3 atmosphere-ocean general circulation models (AOGCM) is unrealistic because many models are now obsolete or unmaintained, and also because the computational cost is prohibitive. The latter restriction also applies to running all SRES scenarios with current versions of AOGCMs. We therefore use a reduced complexity carbon-cycle and climate model MAGICC (Meinshausen et al., 2011a) version 6 to compare SRES scenarios and RCPs. The MAGICC model closely emulates (Meinshausen et al., 2011b) the global and annual mean behaviour of significantly more complex AOGCM and C⁴MIP carbon-cycle models. We use historical constraints and calculate probabilistic time-evolving temperature projections for both sets of scenarios (see Methods). We derive a climate sensitivity distribution starting from the overall consensus understanding of climate sensitivity uncertainties and then re-sample the joint distribution of climate model parameters such that historically observed ocean's surface and land's air temperatures in both hemispheres (Brohan et al., 2006), as well as ocean heat uptake observations (Domingues et al., 2008) are matched. The resulting model setup closely reflects the uncertainties in radiative forcing, carbon-cycle and climate sensitivity from the AR4 (see Methods and Meinshausen et al. (2009)).

Equilibrium climate sensitivity (ECS) — the change in global mean surface temperature at equilibrium following a doubling of atmospheric carbon dioxide (CO₂) concentrations — remains a critical source of uncertainty in long-term temperature projections (IPCC, 2007d). It is not a physical quantity which can be measured directly through observations, but can be estimated with different indirect methods (see Knutti and Hegerl (2008) and references therein). The IPCC AR4 concludes (IPCC, 2007d) that ECS is likely (greater than 66 per cent probability (IPCC, 2005a)) in the range from 2 °C to 4.5 °C, with a most likely value (mode) of about 3 °C. Furthermore, ECS is very likely (greater than 90 per cent probability (IPCC, 2005a)) larger than 1.5 °C, while values substantially higher than 4.5 °C cannot be excluded. These values currently appear to be rather robust estimates as they haven't moved much for almost two decades (see Table 4.1 and more recent studies have supported these estimates (Roe and Baker, 2007; Royer et al., 2007; Tomassini et al., 2007)). The concluding statements of the IPCC AR4 synthesize the literature but no probability density function (PDF) was provided. For our probabilistic model framework we require such a distribution and thus apply a methodology that aims at incorporating the IPCC AR4 synthesizing statements transparently into one distribution. This necessarily requires additional assumptions beyond AR4 (see Supplementary Table 1 in the Supplementary Online Information¹), which are partly subjective but do not strongly affect the results. In fact, our main result, the quantitative analysis of the differences between RCPs and SRES, is hardly affected at all, which we tested by assuming alternative ECS distributions from the literature (see Supplementary Table 2). Our methodology translates the AR4 consensus understanding on climate sensitivity uncertainty into a PDF, noting that this still relies on an initial expert assessment of the multiple lines of evidence. A methodology to formally combine climate sensitivity estimates from different lines of evidence will remain a

¹Supplementary Online Material for this publication is available at: <http://www.nature.com/nclimate/journal/v2/n4/extref/nclimate1385-s1.pdf>

Table 4.1: Key characteristics of illustrative Bayesian equilibrium climate sensitivity (ECS) distributions from the literature (non-exhaustive), and from this study's representative ECS distribution and 10000-member ECS ensemble. Note that the studies listed are only a small selection of the Bayesian ECS distributions displayed in Figure 4.1, are not all independent and present only a small subset of studies that informed the IPCC AR4 conclusions on ECS, which were taken based on multiple lines of evidence (Knutti and Hegerl, 2008). Also note that the different studies use different prior distributions for climate sensitivity (Frame et al., 2005). More details are provided in Supplementary Table 4.

Study	Probability			Most likely value
	above 1.5 °C	between 2.0 °C and 4.5 °C	above 4.5 °C	
Illustrative individual studies (non-exhaustive)				
(Hegerl et al., 2006)	87%	44%	34%	2.0 °C
(Forster and Gregory, 2006)	82%	46%	20%	1.6 °C
(Annan and Hargreaves, 2006)	98%	88%	5%	2.9 °C
(Knutti et al., 2006)	95%	71%	20%	3.2 °C
(Murphy et al., 2004)	100%	86%	14%	3.2 °C
(Piani et al., 2005)	99%	72%	24%	3.2 °C
(Frame et al., 2006)	100%	85%	12%	2.8 °C
'No Expert' priors case (Forest et al., 2006)	100%	90%	6%	2.8 °C
Multiple lines of evidence				
IPCC FAR (IPCC, 1990), SAR (IPCC, 1996), TAR (IPCC, 2001)	-	1.5 °C to 4.5 °C (no probability)	-	-
IPCC AR4 (IPCC, 2007d)	>90%	>66%	Not excluded	About 3 °C
This study's representative climate sensitivity distribution	95%	76%	14%	3.0 °C
Minimum maximum values in this study's 10000-member ECS ensemble	90 to >99%	66 to 96%	<1 to 33%	2.6 to 3.6 °C

challenge, as the various estimates are not fully statistically independent (Knutti and Hegerl, 2008). In our interpretation of the AR4 ECS assessment we follow the guidelines of the IPCC (IPCC, 2005a) on the interpretation of likelihood ranges, but note that also other interpretations exist in the literature (Socolow, 2011).

4.2 Results and discussion

Earlier studies have used different analytical forms to generate a PDF from IPCC statements (e.g. see Wigley and Raper (2001)). We apply a more generalised approach and create an ensemble of ten thousand distributions (Figure 4.1 and Methods) which all comply with these AR4 synthesizing statements and of which the spread spans the range which is left open by the IPCC AR4 assessment (Figure 4.1). A representative distribution is computed by taking the arithmetic mean over all ten thousand distributions. The computed distribution by design complies with the AR4 ranges (Table 4.1) and the shape lies within the range found in the literature (Knutti and Hegerl, 2008). Our average ECS distribution represents a mean result over ten thousand possible outcomes, and is hence neither the most conservative nor the most opti-

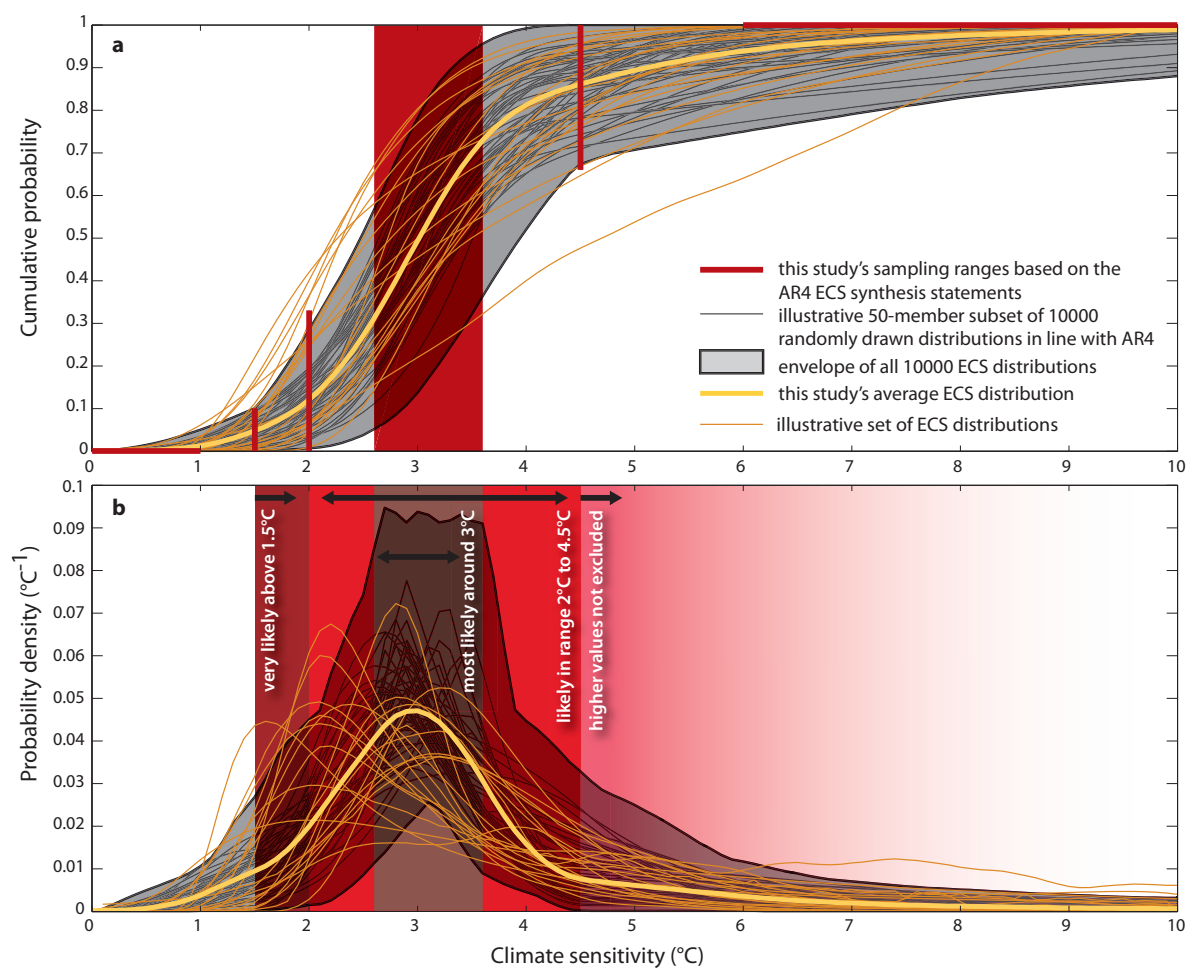


Figure 4.1: Ensemble of equilibrium climate sensitivity (ECS) distributions from this study and from the literature. **a**, Cumulative distribution functions (CDFs) of ECS. Thick red lines and areas indicate sample ranges for start, end and intermediary points of the CDFs based on the IPCC AR4 ECS synthesizing statements. The shaded grey area bounded by a thick black line represents the envelope of all 10000 randomly drawn ECS distributions (thin black lines) which are in line with these AR4 ECS statements. Thin orange lines are illustrative Bayesian ECS distributions (references in Knutti and Hegerl (2008) and Supplementary Table 4). Note that not all curves of this illustrative set are equally credible and that the IPCC synthesizing statements were based on additional lines of evidence, some of them tending to suggest a higher most likely value compared to the illustrative set of Bayesian literature PDFs shown here. The thick yellow line is this study's representative distribution based on the IPCC AR4 ECS synthesizing statements; **b**, Corresponding probability density functions (PDFs). Note that although the horizontal axis is truncated at 10°C, the randomly drawn distribution were not constrained to values below 10°C.

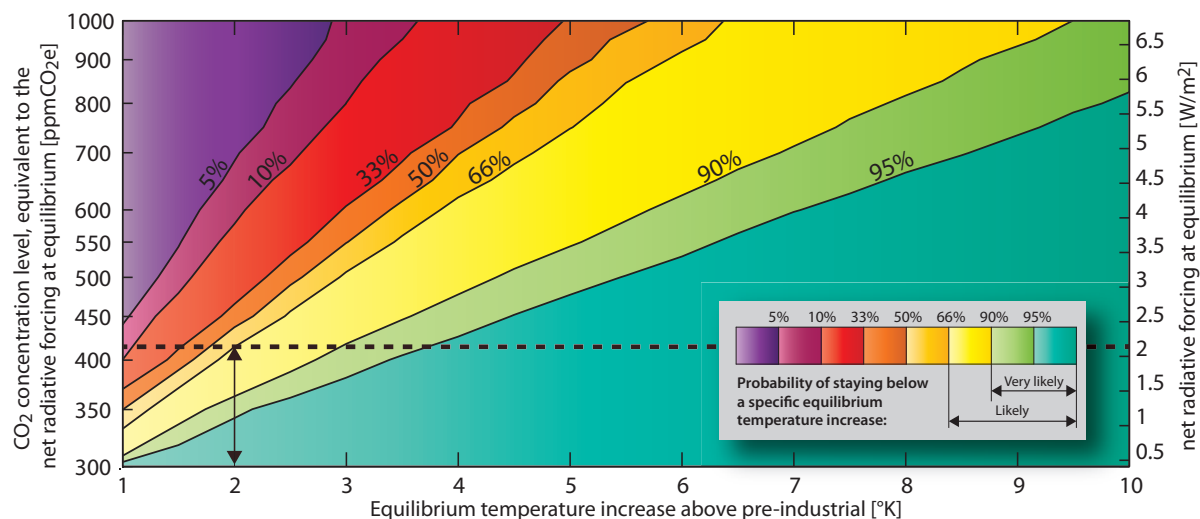


Figure 4.2: Probability to stay below specific equilibrium temperature increases relative to pre-industrial as a function of equivalent atmospheric CO₂ concentration stabilisation levels based on this study's representative ECS distribution. Note that the left scale indicates the CO₂ concentration level, equivalent to the net radiative forcing at equilibrium resulting from all forcing agents. It includes both the contributions of short (e.g. soot and aerosols) and long-lived (e.g. CO₂) forcing agents. The right scale directly shows the equivalent net radiative forcing. The arrow in the figure illustrates that to limit global temperature increase to below 2 °C with a 'likely' (greater than 66 per cent) probability, equivalent CO₂ concentrations at equilibrium should be lower than 415 parts per million (ppmCO₂e) or the net radiative forcing at equilibrium below about 2.1 W/m².

mistic interpretation of the IPCC AR4 ECS statements. ECS values in our average distribution are higher than 1.5 °C with 95 per cent probability, fall between 2 and 4.5 °C with 76 per cent probability, and exceed 4.5 °C with 14 per cent probability (Table 4.1). The most likely value (mode) of our distribution is at 3 °C. The exact shape is irrelevant for our core conclusions. Of importance is that the same model and parameters are used to compare SRES scenarios and RCPs.

A deeper level of uncertainty in the ECS distribution exists and is illustrated by the envelope of all possible ECS distributions in line with the AR4 ECS synthesis assessment. We have quantified this uncertainty by means of a sensitivity analysis of our results for the RCPs with a selection of four ECS distributions. These four distributions represent extremes within our 10000-member ECS distribution ensemble. We selected the ECS with the highest cumulative probability below 1.5 °C, with the highest cumulative probability above 4.5 °C, and with the highest and the lowest temperature difference between the 17 and 83 per cent cumulative probabilities (i.e. a very broad and a very narrow distribution), respectively.

A straight-forward application of the computed ECS distribution is to link it to atmospheric greenhouse gas (GHG) concentrations in a probabilistic way, as proposed by Knutti et al. (2005). Other examples are analyses regarding the relationship between GHG concentrations and 2 °C (Meinshausen, 2006) and Table 10.8 of the AR4 (Meehl et al., 2007). The latter links equilibrium temperature increase to the CO₂ concentration level equivalent to the net radiative forcing at equilibrium from all forcing agents. It therefore takes into account the contributions

of both short (for example, soot or other aerosols) and long-lived species. For an equivalent CO₂ concentration of 450 parts per million CO₂-equivalent (ppmCO₂e) Table 10.8 of the AR4 gives a best-guess temperature increase above pre-industrial at equilibrium of 2.1 °C ('very likely' or with greater than 90 per cent probability (IPCC, 2005a) above 1.0 °C, and 'likely' or with greater than 66 per cent probability (IPCC, 2005a) in the range 1.4 to 3.1 °C). In our results, a 450 ppm CO₂e concentration level is consistent with a probability of 60 per cent to exceed a 2 °C temperature increase at equilibrium (Figure 4.2) with a minimum-maximum range of 57 to 89 per cent over our four sensitivity cases (see earlier). Likewise, limiting the global temperature increase at equilibrium to 2 °C (1.5 °C) above pre-industrial levels with a 'likely' (greater than 66 per cent) chance, would require stabilisation of equivalent atmospheric CO₂ concentrations from all forcing agents at less than 415 (370) ppm CO₂e. Based on our four sensitivity cases of ECS distributions, we find ranges of 380 to 420 ppm CO₂e for 2 °C, and 350 to 375 ppm CO₂e for 1.5 °C. The ability to draw such links in a simple, transparent way that is consistent with a consensus assessment of ECS is becoming more important with international climate policy starting to focus on temperature limits (like the 1.5 and 2 °C limits mentioned in the Cancún Agreements (UNFCCC, 2010a) and in the outcome of the Durban Climate Change Conference).

With a representative ECS distribution at hand, the core question of this paper can be analysed. Therefore we first compute temperature projections for the six SRES marker scenarios. Our median temperature estimates (Figure 4.3 and Table 4.2) are by definition different from the 'best estimate' temperature projections in the AR4 which were defined as the mean over all CMIP3 AOGCM model projections (Knutti et al., 2008). The mean absolute difference between our median projections and the AR4 'best estimate' is however small (less than 0.07 °C).

For the 'likely' (greater than 66 per cent probability (IPCC, 2005a)) ranges of the temperature projections in the IPCC AR4, a -40 to +60 per cent range around the multi-model mean was given (Knutti et al., 2008). This range was developed based on expert judgement and all available estimates (Knutti et al., 2008). Our results for the 90 per cent uncertainty range are close to the above-mentioned 'likely' AR4 range (Figure 4.3b and Table 4.2). This contraction of the uncertainty ranges in our results is due to the fact that we use an average ECS distribution and a single consistent probabilistic modelling framework for our projections. Structural model uncertainty in the energy-balance approach is not considered. In addition, our approach assumes the range of carbon-cycle climate feedbacks in C⁴MIP to be representative of the full uncertainties. While this is plausible, IPCC assessments try to additionally account for uncertainties that may not be fully sampled by the ensembles of opportunities (Tebaldi and Knutti, 2007), and attempt to include structural model uncertainty and uncertainty in methodological frameworks. Because our approach doesn't do so, the contraction of the uncertainty ranges in our results should not be seen as an improvement or correction of the IPCC assessment. Rather, the strength of our results lies in the fact that they provide comparison data for the SRES scenarios and RCPs derived from one single probabilistic framework which is closely in line with the IPCC AR4 assessment.

Table 4.2: Probabilistic estimates of temperature increase above pre-industrial levels based on this study's representative ECS distribution for the six SRES marker scenarios and the four RCPs. Note that estimates in AR4 were given relative to 1980-1999. The 'likely range' denotes the 'greater than 66 per cent' probability range as suggested by the IPCC (IPCC, 2005a). The '66% range' labels denote the 66 per cent range as such. RCP results are from concentration-driven runs. Results for emission-driven RCP runs are provided in Supplementary Table 3.

Scenario	Temperature increase above pre-industrial [°C]					
	2090 to 2099 period		2100		2300	
IPCC AR4	Best estimate	Likely range	Median	66% range	Median	66% range
SRESB1	2.3	1.6-3.4	-	-	-	-
SRESA1T	2.9	1.9-4.3	-	-	-	-
SRESB2	2.9	1.9-4.3	-	-	-	-
SRESA1B	3.2	2.2-4.9	-	-	-	-
SRESA2	3.9	2.5-5.9	-	-	-	-
SRESA1FI	4.5	2.9-6.9	-	-	-	-
This study	Median	66% range	Median	66% range	Median	66% range
SRESB1	2.4	2.0-3.1	2.5	2.0-3.2	-	-
SRESA1T	2.9	2.5-3.7	3.0	2.5-3.8	-	-
SRESB2	2.9	2.4-3.5	3.0	2.6-3.7	-	-
SRESA1B	3.4	2.8-4.2	3.5	2.9-4.4	-	-
SRESA2	3.9	3.2-4.8	4.2	3.5-5.2	-	-
SRESA1FI	4.7	3.9-5.8	5.0	4.1-6.2	-	-
RCP3-PD	1.5	1.3-1.9	1.5	1.3-1.9	1.1	0.9-1.5
RCP4.5	2.4	2.0-2.9	2.4	2.0-3.0	2.8	2.3-3.5
RCP6	2.9	2.5-3.6	3.0	2.6-3.7	4.1	3.4-5.3
RCP8.5	4.6	3.8-5.7	4.9	4.0-6.1	10.0	7.9-14.1

Table 4.3: Main similarities and differences between temperature projections for SRES scenarios and RCPs. See also Supplementary Figure 2.

RCP	SRES scenario with similar median temperature increase by 2100	Particular differences
RCP3-PD	None	The ratio between temperature increase and net radiative forcing in 2100 is $0.88\text{ }^{\circ}\text{C}/(\text{W}/\text{m}^2)$ for RCP3-PD, while all other scenarios show a ratio of about $0.62\text{ }^{\circ}\text{C}/(\text{W}/\text{m}^2)$ i.e. RCP3-PD is closer to equilibrium in 2100 than the other scenarios.
RCP4.5	SRES B1	Median temperatures in RCP4.5 rise faster than in SRES B1 until mid-century, and slower afterwards
RCP6	SRES B2	Median temperatures in RCP6 rise faster than in SRES B2 during the three decades between 2060 and 2090, and slower during other periods of the twenty-first century
RCP8.5	SRES A1FI	Median temperatures in RCP8.5 rise slower than in SRES A1FI during the period between 2035 and 2080, and faster during other periods of the twenty-first century

Finally, we estimate what temperature increase the RCPs (Meinshausen et al., 2011d) would have yielded based on two different methods: emission- and concentration-driven. The emission-driven modelling results are comparable to the SRES results, and the Earth System Model-driven RCP experiments in CMIP5, while the concentration-driven model runs allow for a better comparability to the majority of CMIP5 experiments, in which AOGCMs prescribe atmospheric concentration levels for CO_2 , CH_4 , N_2O and other GHGs. The concentration-driven and emission-driven estimates provide a proxy for RCP results from the previous CMIP3 inter-comparison and C⁴MIP inter-comparison, respectively (cf. Meinshausen et al. (2011b)). Here we present the concentration-driven results (Figure 4.3 and Table 4.2). For comparison, the emission-driven results are also given in Figure 4.3b and Supplementary Table 3.

The RCPs span a large range of stabilization, mitigation and non-mitigation pathways. The resulting range of temperature estimates is therefore larger than the range of the SRES scenarios, which cover non-mitigation scenarios only (Table 4.2). RCP8.5, representing a high-emission, non-mitigation future, yields a range of temperature outcomes of 4.0 to $6.1\text{ }^{\circ}\text{C}$ by 2100 (66 per cent range). The lowest RCP (van Vuuren et al., 2007), assuming significant climate action, limits global temperature increase to below $2\text{ }^{\circ}\text{C}$ with a 'likely' chance (greater than 66 per cent probability). The latter result is hence also consistent with some AOGCMs yielding temperature projections that will exceed $2\text{ }^{\circ}\text{C}$ for the lowest RCP. Based on our four sensitivity ECS distributions, we find that the 66 (90) per cent uncertainty ranges for the temperature projections for the RCPs in 2100 (as reported in Table 4.2 based on our average ECS distribution), can be up to 13 (41) per cent wider or up to 38 (41) per cent narrower when using one of these four extreme ECS distributions from our set (see Supplementary Figure 1).

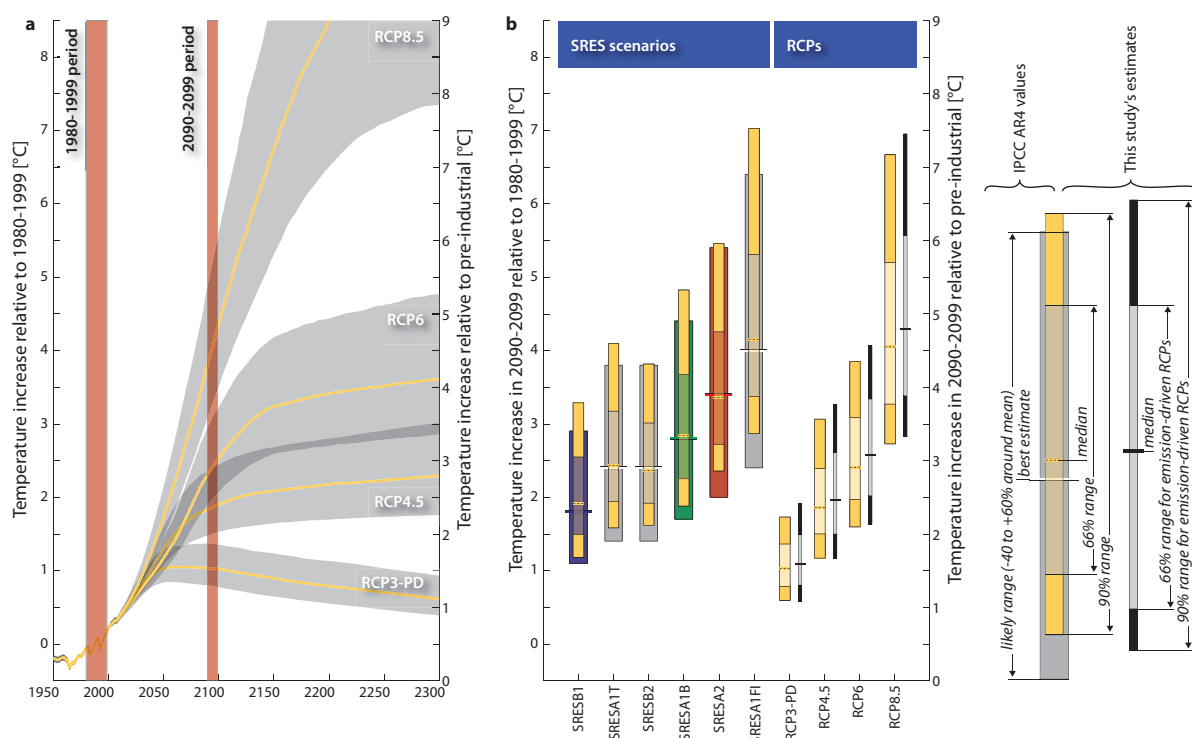


Figure 4.3: Temperature projections for SRES scenarios and RCPs. **a**, Time-evolving temperature distributions (66 per cent range) for the four concentration-driven RCPs computed with this study's representative ECS distribution and a model setup representing closely the climate system uncertainty estimates of the AR4 (grey areas). Median paths are drawn in yellow. Red shaded areas indicate time periods referred to in panel b; **b**, Ranges of estimated average temperature increase between 2090 and 2099 for SRES scenarios and RCPs respectively. Note that results are given both relative to 1980-1999 (left scale) and relative to pre-industrial (right scale). Yellow and thin black ranges indicate results of this study; other ranges show the AR4 estimates (see legend). Colour-coding of AR4 ranges is chosen to be consistent with the AR4 (see Figure SPM.5 in (IPCC, 2007d)). For RCPs, yellow ranges show concentration-driven results, while black ranges show emission-driven results.

Although the RCPs were not developed to mimic specific SRES scenarios, pairs with similar temperature projections over the 21st century can be found between the two sets (see also Table 4.2, Table 4.3, and Figure 4.3). The highest RCP (Riahi et al., 2007) would yield temperature projections close to those of the SRES A1FI scenario. RCP6 temperature projections are similar to those of SRES B2 and, likewise, RCP4.5 temperature projections to those of SRES B1.

Global mean temperature projections by the end of the 21st century for the RCPs are very similar to those of their closest SRES counterparts (Table 4.2). However, the transient trajectories differ in various ways (Table 4.3 and Supplementary Figure 2). These different warming rates between SRES scenarios and RCPs with similar year 2100 forcing, are due to different transient forcings up to then. These differences can be of importance when assessing shorter-term climate impacts under RCPs and comparing them to earlier literature.

All SRES scenarios are non-intervention scenarios with an increasing forcing path during the twenty-first century. The new, lowest RCP scenario (van Vuuren et al., 2007) is fundamentally different from these. Its radiative forcing peaks during the 21st century at around 3 W/m² and declines afterwards. Our probabilistic results show distinct characteristics for RCP3-PD, which will have to be validated once the comprehensive new CMIP5 data set is available. For example, for monotonically increasing forcing paths, global transient temperature changes linearly with the forcing (Gregory and Forster, 2008; Knutti and Hegerl, 2008) or, alternately, with the global transient climate response determined from AOGCMs or observations (Knutti and Tomassini, 2008). The ratio between the temperature increase by the end of the twenty-first century and the net anthropogenic radiative forcing shows little variation in our projections, except for RCP3-PD. For all monotonically increasing forcing scenarios that we analyse, this ratio has a mean value in 2100 of 0.62 °C/(W/m²) with a standard deviation of 0.03. For RCP3-PD, the only scenario with a peak and decline evolution of its radiative forcing, this ratio becomes 0.88 °C/(W/m²), which indicates that by 2100 RCP3-PD is closer to or even above the equilibrium warming that corresponds to its 2100 forcing.

With the probabilistic projections of this study, a consistent comparison between SRES scenarios and RCPs is established. A direct comparison, by either computing the new RCPs with old AOGCM versions or computing at least one of the SRES scenarios with the new model versions, could yield even more insights. Therefore, the inclusion of one of the SRES scenarios (e.g. SRES A1B) in the set of scenarios ran by the CMIP5 models would be advantageous. Such an inclusion would greatly facilitate determining whether differences between CMIP3 and CMIP5 AOGCM results are due to the new scenarios or due to updated model versions.

4.3 Methods

Climate sensitivity characterizes the global surface temperature response on timescales of several centuries and includes the feedbacks due to water vapour, lapse rate, clouds and surface albedo, i.e. the feedbacks that scale with temperature and that are implemented in CMIP3-type models. Feedbacks that have their own intrinsic long timescale (slow vegetation changes or ice sheets) are not considered and would enhance this concept to what is often called 'Earth system sensitivity' (see Knutti and Hegerl (2008)).

In this study we define an average equilibrium climate sensitivity (ECS) probability density function which is consistent with the overall consensus understanding of ECS of the IPCC AR4. We create ten thousand ECS distributions by spline interpolation between uniform sampled constraints based on the uncertainty ranges defined in the IPCC AR4. A total of eight constraints are sampled which define six points of a cumulative probability density function (Figure 4.1 and Supplementary Table 1): the temperature at the starting point, the cumulative probability at respectively 1.5 °C, 2 °C, 4.5 °C and at the point of inflection, the temperature at the point of inflection, the slope at the point of inflection, and the temperature at the end point. These constraints are sampled randomly from uniformly distributed ranges which are chosen in a way such that they do not infer additional constraints beyond the synthesizing statements of the IPCC AR4 but, on the contrary, facilitate an as broad sampling of the remaining space as possible (see Supplementary Figure 3). Each set of eight parameters yields a cumulative ECS distribution by applying a cubic spline interpolation through the six points the parameters define. Subsequently, each cumulative sensitivity distribution is tested for validity. For example, there is no evidence in the literature that supports multimodal distributions of ECS (Knutti and Hegerl, 2008). For each distribution, we check that: (1) the cumulative probability between 2 °C and 4.5 °C is at least 66 per cent, (2) only one maximum (peak) is present, (3) the cumulative probability density function increases monotonically (this implies that the cumulative probability density function does not undershoot zero probability and does not overshoot 100 per cent probability), and (4) no sudden changes in the first derivative of the probability density function are allowed (i.e. the distribution is kept relatively smooth by limiting the curvature outside a 1 °C range around the peak to a maximum value). Finally, our representative ECS distribution is computed by taking the arithmetic mean over all ten thousand randomly drawn distributions.

ECS is not the only source of uncertainty for projecting transient global-mean temperatures for specific emission scenarios, that is taken into account in our setup of the MAGICC model. From a large 82-dimensional joint distribution of climate and radiative forcing parameters affecting the transient climate response, we draw our parameter sets such that the marginal ECS matches a specific distribution (Meinshausen et al., 2009). When deriving this joint distribution, we applied year 2005 uncertainty distributions for radiative forcings as prior distributions following Table 2.12 in Forster et al. (2007) and used observed hemispheric land/ocean temperatures (Brohan et al., 2006) and ocean heat uptake (Domingues et al., 2008) as historical constraints, as described in Meinshausen et al. (2009). In addition to the historically constrained climate response parameters, we reflect uncertainties in future carbon-cycle responses by using at random one of 9 C⁴MIP carbon-cycle model emulations. These emulations with MAGICC closely reflect the carbon pool dynamics when taking into account C⁴MIP carbon-cycle climate

(Meinshausen et al., 2011a). In earlier setups (Rogelj et al., 2010b; UNEP, 2010b), a specific ECS distribution from the literature was matched (Meinshausen et al., 2009). Here we apply the same methodology to match the ECS distribution described in this study.

Whereas the SRES scenarios provide GHG emissions pathways, the RCPs are GHG concentration pathways. In our setup, we use the GHG emissions pathways as provided in Nakicenovic and Swart (2000), and the concentration pathways described by Meinshausen et al. (2011c), as recommended for CMIP5. We also provide results for emission-driven RCP runs in Supplementary Table 3.

Temperature projections 'relative to pre-industrial' are calculated relative to the 1850 to 1875 base period.

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Author Contributions All authors were involved in designing the research; M.M. developed the setup of the MAGICC model; J.R. developed the climate sensitivity sampling methodology and performed the analysis; all authors contributed to writing the paper.

Part IV

Pathways for limiting global temperature increase

Chapter 5

Emission pathways consistent with a 2 °C global temperature limit

Emission pathways consistent with a 2 °C global temperature limit

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Abstract

In recent years international climate policy has increasingly focussed on temperature limits besides greenhouse gas (GHG) concentration-related objectives. The 2010 Cancún Agreements recognize that countries should take urgent action to hold the increase in global average temperature below 2 °C relative to pre-industrial levels. If this is to be realized in practice, policy makers need robust information on the amount of future GHG emissions that are consistent with such temperature limits. This requires understanding of both the processes that link emissions to temperature, and the technical and economic implications of reducing emissions. In this study we consider both of these aspects. For this, we re-analyse, in a risk-based climate modelling framework, a large ensemble of published mitigation and non-intervention scenarios from integrated assessment models (IAMs) to estimate their probabilities to stay below specific temperature limits. We find that median global 2020 GHG emissions of published scenarios that limit global temperature increase to below 2 °C with a greater than 66% chance are 44 billion tons of carbon-dioxide equivalence (GtCO₂e), with a 15-85% quantile range of 31 to 46. This range can give an indication about whether emissions estimated from country pledges are 'on track' to limit global warming to 2 °C or not.

5.1 Introduction

Cumulative emissions of long-lived species approximately define the temperature response of the climate system at timescales of centuries to millennia (Allen et al., 2009; Meinshausen et al., 2009; Matthews et al., 2009) because a significant fraction of carbon-dioxide (CO₂) emissions, the dominant anthropogenic GHG, is removed very slowly from the atmosphere (Plattner et al., 2008; Archer et al., 2009). The temperature response will therefore continue, even when global emissions return to zero, or when concentrations are stabilised (Plattner et al., 2008; Lowe et al., 2009). Cumulative emissions provide very little information on the technical feasibility and cost implications of following a particular 'emissions pathway', information which is needed for policy-makers who are deciding now on emissions goals for the coming decades. Path-dependent assessments, like the United Nations Environment Programme's 'The Emissions Gap Report' (UNEP, 2010b), are therefore highly policy-relevant. This work extends the pathway analysis of that report (see Supplementary Information¹).

The Cancún Agreements refer to holding global mean temperature increase below 2 °C. Therefore, we do not allow a temperature overshoot in this study, although concentrations may temporarily overshoot a level that in equilibrium would lead to an exceedance of the temperature limit. There is increasing evidence from recent studies (Held et al., 2010; Lowe et al., 2009; Solomon et al., 2010) that a decline of temperature might be unlikely on timescales relevant to human societies in the absence of strongly negative emissions. The slow ocean mixing which currently delays warming due to anthropogenic radiative forcing would also limit the amount of cooling for many decades to centuries (Held et al., 2010; Schewe et al., 2011; Solomon et al., 2010).

Scenarios developed by IAMs represent analyses of how society could evolve given assumed constraints of feasibility. In general, 'feasibility' encompasses technological, economic, political and social factors. IAMs account for some of these factors by assuming a set of mitigation technologies, constraining their potential and the rate at which these technologies can be introduced, amongst other things. Examples of such constraints include assumptions about the maximum feasible technology penetration rates, maximum cost, constraints on the use of renewables based on their intermittency and a maximum speed of specific system changes. Societal and political factors have typically only received limited attention: for instance, nearly all scenario assume full participation of all parties.

Scenarios from different IAMs consistent with different policy targets have been compared in previous studies (Clarke et al., 2009; Edenhofer et al., 2010). Most of these focus on optimal (least-cost) pathways to achieve GHG concentration stabilisation. Only recently, modelling comparison studies (Clarke et al., 2009) have started focusing on second-best scenarios, which assume limited/delayed international participation of countries and/or reduced technology availability implying delayed emission reductions. The range in IAM outcomes for similar targets is broad, and reflects prevailing uncertainties captured by different methods and underlying assumptions (Clarke et al., 2009; IPCC, 2007b; van Vuuren and Riahi, 2011). Considering the combined impact on mitigation targets of both climate and technical and economic constraints and uncertainties, has thus far received little attention.

¹Supplementary Online Information is available at: <http://www.nature.com/nclimate/journal/v1/n8/extref/nclimate1258-s1.pdf>

We here present a scenario re-analysis focusing on temperature targets. We use the carbon-cycle and climate model MAGICC6 (Meinshausen et al., 2011a), constrained by historical observations, to obtain estimates of future atmospheric GHG concentrations and transient temperatures (see Methods). This approach eliminates the uncertainty due to differing climate representations within the individual IAM studies (van Vuuren et al., 2011a). We compiled a set of 193 emissions pathways from the literature (see Methods and Supplementary Information). Of this set, roughly one third represents baseline scenarios (i.e. possible developments in the absence of climate policy intervention) while the remainder represents emission mitigation scenarios.

Due to the uncertainty in our quantitative understanding of the climate system and carbon-cycle response to emissions, the projected results can be defined in terms of a probability of staying below a given temperature target. The choice of which target and with which probability it is to be reached can be informed by science but is fundamentally a political question depending on risk and value judgements. Policy makers in Cancún did not specify such a probability, neither quantitatively nor qualitatively. To cover a range of possible choices, we evaluate pathways for three options: a 'very likely' (greater than 90%), a 'likely' (greater than 66%), and an 'at least fifty-fifty' (greater than 50%) probability throughout the 21st century (see Methods). Pathways with a 'very likely' 2 °C probability are a subset of pathways with a 'likely' probability, which are in turn a subset of the pathways with an 'at least fifty-fifty' probability of limiting temperature increase to below 2 °C.

5.2 Results and discussion

In our set, none of the baseline scenarios is able to limit the global temperature increase to below 2 °C. On the other hand, 3, 26 and 39 pathways have a 'very likely', 'likely' and 'at least fifty-fifty' chance to limit global temperature change to below 2 °C during the 21st century, respectively (Table 5.1, Figure 5.1). In all pathways, emissions peak in the short term and decline later in order to stay below 2 °C. We start from estimated median 2010 emissions across our harmonised set (see Methods) of about 48 GtCO₂e. For pathways with a 'likely' chance of staying below 2 °C we find the following characteristics: median 2020 emissions are 44 GtCO₂e, with a 15 to 85% quantile range of 31-46 GtCO₂e. The great majority of these pathways (at least 85% of all cases) peak global emissions before 2020. After the peak, emissions decline. Still for the same pathways, median annual post-peak CO₂ reduction rates (see Methods) are around 2.7% (range 1.5-3.4%), and global total GHG emissions in 2050 show a median reduction of 45% (range 35- 55%) below 1990 levels of 36.6 GtCO₂e.

Besides a 2 °C limit, the Cancún Agreements furthermore include a commitment to review and consider strengthening the long-term goal, particularly in relation to a 1.5 °C limit. No ensemble member (including even the most stringent mitigation scenarios) limits warming to less than 1.5 °C throughout the entire century for any of the probability options. However, some scenarios in our set bring warming back below 1.5 °C by 2100: a first scenario (from 'POLES' in Edenhofer et al. (2010)) does so with a probability of about 50%, and a second scenario (from 'MERGE' in Edenhofer et al. (2010)) with a 'likely' chance (>66%).

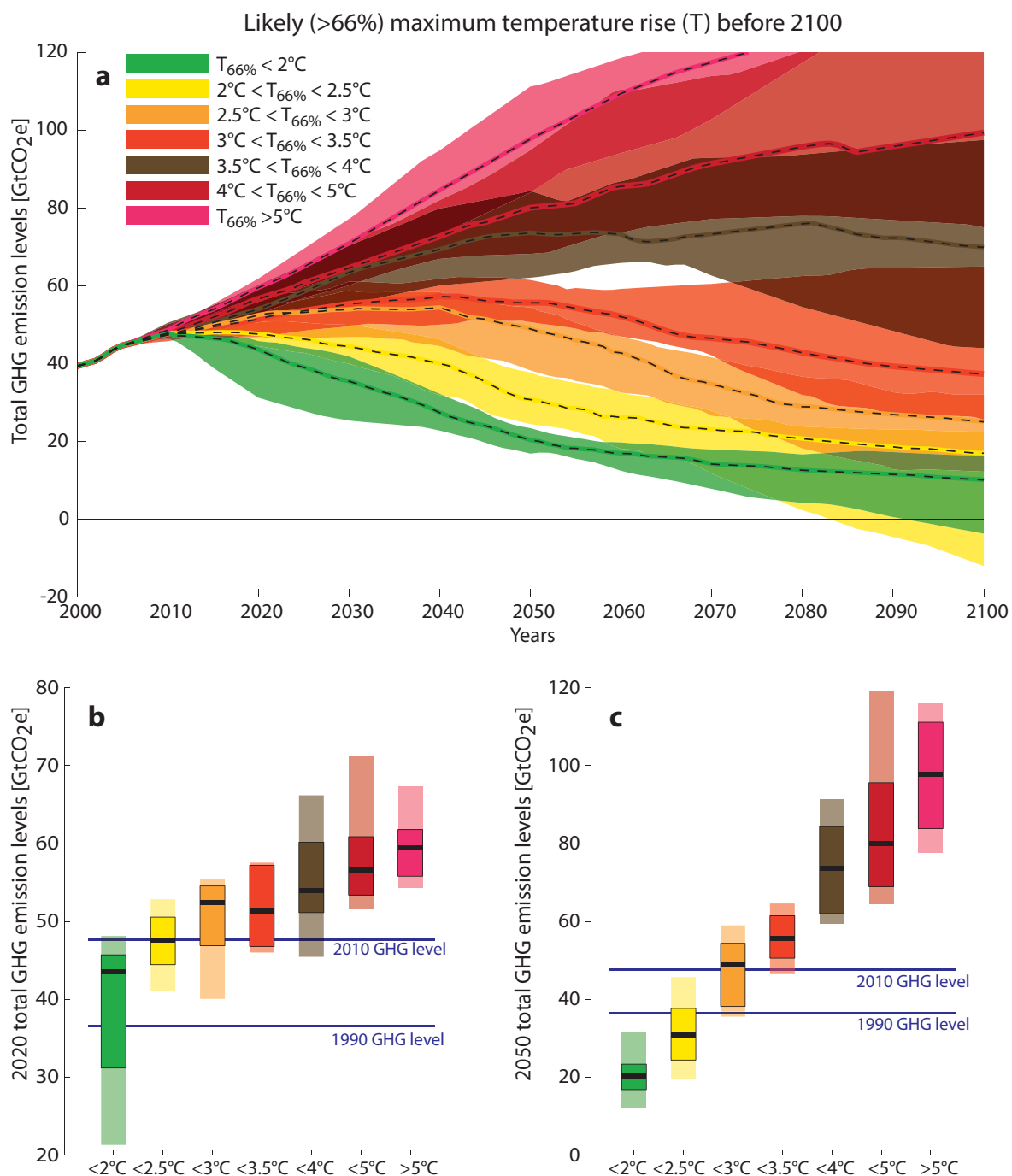


Figure 5.1: Emission ranges of published IAM scenarios, colour-coded as function of the likely (greater than 66% probability) avoided temperature increase. **a**, 15 to 85% quantile ranges over time of global total GHG emissions of pathways sets consistent with a given temperature limit during the 21st century. Colour coding defines the respective temperature limit per pathway set. Black dashed lines show the median for each respective pathway set. **b**, 2020 and **c**, 2050 time slices of global total emissions consistent with a temperature limit during the 21st century. Shaded areas represent the minimum-maximum ranges; the coloured bounded boxes the 15 to 85% quantile ranges, and the thick black horizontal lines the median values for each temperature level, respectively. Horizontal blue lines represent median 1990 and 2010 emissions. Ranges for the other probability options (>90% and >50%) and time slices are in Supplementary Fig. 1-5.

Table 5.1: Overview of pathway characteristics of emission pathways that limit temperature to below 2 °C relative to pre-industrial levels during the 21st century. Data is provided for three probability options: a 'very likely' (greater than 90%), a 'likely' (greater than 66%) or 'at least fifty-fifty' (greater than 50%) chance. Format: minimum(15% quantile[median]85% quantile)maximum

	Number of pathways [-]	Peaking decade ^a [2000+year]	Total GHG emissions in 2020 [GtCO ₂ e]	Average industrial CO ₂ post-peak reduction rates ^b [% of 2000 emissions/year]
<i>'Very likely' chance (>90% of staying below 2 °C during 21st century^c)</i>				
Without global net negative industrial CO ₂ emissions	0	-	-	-
With global net negative industrial CO ₂ emissions	3	10(-[10]-)15	41(-[43]-)44	3.2(-[3.3]-)3.3
All pathways	3	10(-[10]-)15	41(-[43]-)44	3.2(-[3.3]-)3.3
<i>'Likely' chance (>66% of staying below 2 °C during 21st century)</i>				
Without global net negative industrial CO ₂ emissions	14	10(10[10]10)20	21(26[42]45)48	0.0(1.0[2.3]3.3)3.6
With global net negative industrial CO ₂ emissions	12	10(10[10]15)15	41(41[44]46)48	1.5(1.7[3.0]3.5)3.8
All pathways	26	10(10[10]15)20	21(31[44]46)48	0(1.5[2.7]3.4)3.8
<i>'At least fifty-fifty' chance (>50% of staying below 2 °C during 21st century)</i>				
Without global net negative industrial CO ₂ emissions	20	10(10[10]15)20	21(28[44]47)48	0.0(1.3[2.4]3.1)3.6
With global net negative industrial CO ₂ emissions	19	10(10[10]20)30	41(42[45]48)50	1.2(1.7[3.0]3.6)5.9
All pathways	39	10(10[10]15)30	21(38[44]47)50	0(1.5[2.7]3.5)5.9

^a The year given is an indication of the middle of the decade in which the peaking occurs in the scenarios.

^b Being relative to constant 2000 emissions, these reduction rates differ from exponential reduction rates (see Methods).

^c Due to the low number of pathways, only minimum, median and maximum values are given for the 'very likely' option.

An important difference (van Vuuren and Riahi, 2011) is noted between pathways that do not show global CO₂ emissions from energy and industry to become negative compared to those that do. Net negative emissions from the energy and industry sector may be possible through the application of a combination of capture and geological storage (IPCC, 2005b) of CO₂ (CCS) and bio-energy (Azar et al., 2010) (BECCS). In the pathways with no negative emissions, the median 2020 values for the 'likely' option are 2 GtCO₂e lower at 42 GtCO₂e (Table 5.1). Pathways that have net negative emissions (28 in total) feature higher rates of post-peak emission reductions while not exhibiting significant differences for the peak period. An in-depth analysis of the influence of BECCS on the global peak of emissions is not possible with the available scenarios and would require specifically designed experiments that address this question.

Weakening the stringency of the 2 °C limit and accepting a lower chance of success (at least 50% instead of 66% probability), slightly shifts the 15-85% quantile range of scenarios in 2020 to 38-47 GtCO₂e (the median remains at 44 GtCO₂e). The peaking period remains during the current decade (precision-limited by the decadal-resolution data from the IAMs) and the median post-peak emission reduction rates are virtually the same as for the 'likely' case in more than 85% of the cases. Finally, the three pathways with a 'very likely' (greater than 90%) chance of success show a peak during this decade, 2020 emissions not exceeding 44 GtCO₂e and post-peak reduction rates which are higher than the medians from the other cases. These three pathways have negative emissions. Atmospheric CO₂ and CO₂-equivalent concentrations in 2100 of the pathways 'likely' consistent with 2 °C (Table 5.2) are around 425 ppm CO₂ (range 415-460) and 465 ppm CO₂-equivalent (range 435-475), respectively. Pathways consis-

Table 5.2: Overview of 2020 emissions, 2100 atmospheric CO₂, and total GHG concentrations of pathways that hold global average temperature increase below a specific temperature limit. Data is provided for pathways that hold temperature increase to below a given temperature limit during the 21st century with a 'likely' (greater than 66%) chance. Results are given for temperature bins defined by the temperature limit and its preceding limit. For example, the '3 °C' row shows characteristics for emission pathways that limit warming below 3 °C with a 'likely' chance, but above 2.5 °C. See also Figure 5.1 and Supplementary Figure 6. Data for the other probability options is presented in Supplementary Fig. 3,5,7 and 8, and in Supplementary Table 1 and 2. Format: minimum(15% quantile[**median**]85% quantile)maximum

	Number of pathways [-]	Total GHG emissions in 2020		Atmospheric concentrations in 2100	
		[GtCO ₂ e]	CO ₂ [ppm CO ₂]	Total GHG [ppm CO ₂ e]	
<i>Emission pathways with a 'likely' (>66%) probability to limit temperature increase to below:</i>					
1.5 °C			Insufficient data		
2 °C	26	21(31[44]46)48	375(412[423]457)468	400(436[463]476)486	
2.5 °C	46	41(44[48]51)53	376(416[490]506)542	422(472[526]554)557	
3 °C	45	40(47[52]55)55	477(501[542]574)616	554(561[609]636)645	
3.5 °C	22	46(47[51]57)58	540(562[602]659)709	647(649[669]751)775	
4 °C	18	45(51[54]60)66	649(661[726]811)890	759(782[833]869)939	
5 °C	19	52(53[57]61)71	678(746[817]958)1104	851(922[993]1101)1134	
Above 5 °C	10	54(56[59]62)67	888(905[975]1046)1049	1116(1153[1207]1318)1482	

tent with 2 °C with a 'likely' or 'fifty-fifty' chance have peaked CO₂ concentrations during the 21st century (see Methods) in about 30 and 40% of the cases, respectively. CO₂-equivalent concentrations peaked in about 40% of the cases for both probability options. If scenarios do not peak concentrations, they stabilize during the 21st century. A decline afterward is not excluded. All 'very likely' chance pathways show a peak and decline in CO₂-equivalent concentrations of GHGs. More than 70% of the 'likely' chance scenarios assume global net negative CO₂ emissions from industry and energy to achieve such peaking. Furthermore, all scenarios that would comply with a 'fifty-fifty' chance and are outside the 'likely' subset, include such negative emissions.

There are a number of caveats in interpreting our results. First, by describing the 15 to 85% quantiles over time, the intertemporal relationship between different emission paths is masked. Although the median path can be considered as a representative evolution of emissions for 'likely' pathways, the 15 and 85% quantile paths cannot. Emissions near the 85% quantile path in the first half of the century, are followed by emissions near the 15% quantile path in the second half and vice-versa (see Supplementary Fig. 9).

Second, besides results from the 15 to 85% quantiles, also results outside this range give insights. They provide information about potential future worlds in the tails of the distributions. A few pathways (Loulou et al., 2009; Barker and Scrieciu, 2010) (three in total) suggest that emissions could decline globally to about 30% to 40% below 1990 levels by 2020. On the other side of the spectrum, one pathway (Krey and Riahi, 2009) peaks at 48 GtCO₂e in 2020 due to delayed participation and still stays below 2 °C with a 'likely' chance. Another scenario (Calvin et al., 2009) shows steep emission reduction rates of 5.9% after peaking at 50 GtCO₂e around 2030, while still having an 'at least fifty-fifty' probability to stay below 2 °C. CCS contributes massively to the mitigation portfolio in this scenario, capturing up to almost double the current global CO₂ emissions per year by 2065. For most scenarios in our set, a peak in

world emissions in 2030 would be more consistent with a 'likely' chance to stay below 3 °C instead of 2 °C.

A third issue is that for many scenarios the potential for net negative global CO₂ emissions from energy and industry is a crucial factor (van Vuuren and Riahi, 2011). The potential of BECCS (IPCC, 2005b; Azar et al., 2010) is currently already included in many IAMs. However, similar to other advanced technologies, BECCS has not been demonstrated on a significant scale in the real world. Concerns exist with respect to CO₂ storage potential (IPCC, 2005b) as well as with respect to competition of large-scale bio-energy systems (Wise et al., 2009) with food production, biodiversity and ecosystem services. Other negative emission technologies, like direct air capture of CO₂, are currently not explicitly included in most models.

Fourth, our set of pathways represents scenarios that are considered feasible by IAMs. The extent to which the realization of such scenarios is plausible in the real world goes beyond techno-economic and physical constraints represented by the IAMs, and also depends highly on factors such as political circumstances and public acceptance. Our analysis of the scenario space relies on the soundness and quality of the underlying IAM studies, and does not imply any independent assessment of the feasibility of the latter factors. We also acknowledge the fact that only a limited set of scenarios were run for the low temperature targets discussed here, and that IAMs who find these targets infeasible often do not report on their results (Clarke et al., 2009). Our findings, in particular with respect to low emissions scenarios, therefore should be interpreted as an indication of the stringency of mitigation that would need to occur in order to keep specific targets within reach. They should, however, not be interpreted as a comprehensive assessment of the feasibility of the required mitigation action.

Related to this, it should be noted that most of the IAM scenarios used in this study tried to find cost-effective pathways for long-term climate targets. Scenarios that would look at economically less attractive (Clarke et al., 2009; O'Neill et al., 2009) options could feature higher and/or later peaks with steeper declines afterwards. The ensemble we used was not designed to systematically sample all possible options, but represents an 'ensemble of opportunity' (Tebaldi and Knutti, 2007). Clearly, IAMs do not set 'hard laws' on the consideration of whether achieving a particular scenario is possible. They are based on modellers' assumptions about technological and economic constraints, which are subject to change. Finally, a better understanding of socioeconomic impacts of regional climate change and their inclusion in IAMs might have a large influence on the medium and long-term cost-efficiency of emission pathways. As understanding evolves it will be necessary to update assessments as the one presented here and develop studies that address this question directly. Furthermore, the treatment of political feasibility, including the will of national Governments to implement transitions to low-carbon economies remains a big unknown.

This analysis implies that the range of published IAM scenarios in line with the goal to stay below 2 °C with a 'likely' chance would peak during this decade and have annual 2020 emissions of around 44 GtCO₂e (range of 31-46 GtCO₂e). Our scenario set hardly includes scenarios that take into account delayed participation of regions in international carbon markets. However, not assuming this may currently seem optimistic given the reluctance of some major emitters to join such a system. Following higher 2020 emissions and later peaking as a result of weaker early mitigation action would significantly reduce the chances for staying be-

low 2 °C. Without a firm commitment to put in place the mechanisms to enable an early global emissions peak followed by steep reductions thereafter, there are significant risks that the 2 °C target, endorsed by so many nations, is already slipping out of reach.

5.3 Methods

We re-analysed an ensemble of 193 emission pathways from IAMs. This ensemble includes reference and mitigation pathways from model intercomparison studies (Clarke et al. (2009); Edenhofer et al. (2010); Luderer et al. (2012), amongst others, see Supplementary Table 3 for an overview of all references), as well as from other stabilisation and non-intervention scenarios. All members are treated equally likely in the set.

Historical emission estimates come with a typical uncertainty range of 20 to 30% (Rogelj et al., 2011a). Therefore, for each member of the ensemble, the historical emissions up to 2005 are harmonised to the historical multi-gas emission inventory developed in the framework of the Representative Concentration Pathways (Meinshausen et al., 2011c; Granier et al., 2011) (RCPs). Emissions of each ensemble member are adjusted with a tapered scaling factor which returns to unity in 2050. This approach prevents possible amplification of negative emissions in the second half of the century (Rogelj et al., 2011a). When future emissions of a particular gas are missing, the multi-gas characteristics of the RCP3-PD scenario (van Vuuren et al., 2011b) are assumed, including sulphate aerosols, organic carbon, black carbon and atmospheric ozone precursors. The RCP3-PD scenario models strong environmental and climate policies. This choice is therefore consistent with our setup to primarily analyse mitigation pathways which reduce emissions as to be consistent with international temperature limits. Ozone depleting substances controlled by the Montreal Protocol are assumed to follow a gradual phase-out during the 21st century.

After harmonisation, six IAM pathways that show a decline or stabilisation in historical emissions from 2005 to 2010 are excluded from the final ensemble. We also excluded one scenario for which insufficient detailed information about the underlying assumptions were available (as in Clarke et al. (2009)).

Each member of the harmonised multi-gas emission pathway ensemble is analysed probabilistically with the reduced-complexity climate system and carbon-cycle model MAGICC (Meinshausen et al., 2011a), version 6. MAGICC has been calibrated and shown to be able to reliably determine the atmospheric burden of CO₂ concentrations following high-complexity carbon-cycle models (Meinshausen et al., 2011a,b). It is also able to project global average near-surface warming in line with estimates made by complex atmosphere-ocean general circulation models for a range of forcing scenarios, as assessed in the IPCC AR4 (IPCC, 2007d). Here it has been setup with historical constraints for observed hemispheric land/ocean temperatures and ocean heat-uptake (see Supplementary Information), emulating the C⁴MIP carbon-cycle models (Friedlingstein et al., 2006) and with the same climate sensitivity probability distribution as the 'illustrative default case' by Meinshausen et al. (2009) which closely reflects IPCC estimates (IPCC, 2007d). Herewith, the uncertainties in climate sensitivity, ocean heat-uptake and the response of the carbon-cycle to a given emissions pathway is taken into

account. For each pathway, a 600-member ensemble is calculated to determine its resulting time-evolving temperature probability distribution.

We performed a sensitivity analysis on the climate sensitivity choice and on the assumptions regarding anthropogenic aerosols, soot and organic carbon, and found that our results are robust under those sensitivity cases (see Supplementary Information and Supplementary Table 4).

The range of results from this re-analysis of IAM pathways always refers to the median, and the 15 to 85% quantile range (as an approximation of the one standard deviation range around the mean). This provides a point of comparison with the approach in the IPCC AR4 (IPCC, 2007d). For completeness, also the minimum-maximum range is given. Total GHG emissions refer to emissions included in the Kyoto basket of GHGs which contains carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF₆) (see Supplementary Information). 'Negative CO₂ emissions' refer to net global emissions from energy and industry, excluding land-use emissions. The 'post-peak' reduction rates are calculated over the period between 10 and 30 years after the peak. To allow comparison and ensure consistency with the IPCC AR4, reduction rates are computed for global CO₂ emissions from energy and industry, and relative to 2000 levels. If less than 10 pathways were available in a particular subset, only median, minimum and maximum values are provided. If a pathway yields atmospheric CO₂ concentrations in 2100 that are at least 5% lower than the maximum concentration during the 21st century, this pathway is defined to have peaked concentrations during this century. The same approach applies to the total GHG (CO₂e) concentrations.

Temperatures projections 'relative to pre-industrial' are calculated relative to the 1850 to 1875 base period.

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Chapter 6

2020 emissions levels required to limit warming to below 2 °C

2020 emissions levels required to limit warming to below 2 °C

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Abstract

This paper presents a systematic scenario analysis of how different levels of short-term 2020 emissions would impact the technological and economic feasibility of achieving the 2 °C target in the long term. We find that while a relatively wide range of emissions in 2020 — from 41 to 55 billion tons of carbon-dioxide equivalent (GtCO₂e/yr) — may preserve the option of meeting a 2 °C target, the size of this 'feasibility window' strongly depends on the prospects of key energy technologies, and in particular on the effectiveness of efficiency measures to limit the growth of energy demand. A shortfall of critical technologies — either for technological or socio-political reasons — would narrow the feasibility window, if not close it entirely. Targeting lower 2020 emissions levels of 41-47 GtCO₂e/yr would allow to stay below 2 °C under a wide range of assumptions, and thus help to hedge against the risks of long-term uncertainties.

6.1 Introduction

A large body of scientific literature shows that stabilizing global temperatures requires a limit on the cumulative amount of long-lived greenhouse gases (GHG) emitted to the atmosphere (Allen et al., 2009; Matthews et al., 2009; Meinshausen et al., 2009; Zickfeld et al., 2009). International climate agreements (UNFCCC, 2010a) contain aspirational global temperature targets but do not explicitly contain such a long-term global GHG limit. Instead, pledges are made to reduce emissions in the short term, for example, by 2020. In this paper we provide an explicit quantification of the relationship between such short-term policy decisions and the feasibility of long-term mitigation within a single, fully-consistent integrated assessment modelling (IAM) framework capable of exploring uncertainty across a range of underlying assumptions.

Previous studies have analysed an array of IAM scenarios found in the literature and tested if they achieve the 2 °C target (Bowen and Ranger, 2009; Meinshausen et al., 2009; UNEP, 2010b; Rogelj et al., 2011b). Based on this information, these studies have defined a desirable range of 2020 emissions levels that are *consistent with the 2 °C warming limit* and compared this range with the pledges (UNEP, 2010b, 2011a). Their verdict is that a gap exists between 2020 emission levels implied by the current country pledges and by IAM scenarios consistent with 2 °C. However, because most scenarios in the current literature represent cost-optimal emissions pathways, they cannot definitively say that such 2 °C-consistent levels are *required*.

To determine a range of *required* emissions, we conduct a large-scale experiment and sensitivity analysis to identify the feasibility frontier for global emissions in 2020, illustrating the emissions levels at which reaching the 2 °C target would become infeasible. We use a combination of two well-established modelling frameworks: MESSAGE (Riahi et al., 2007; Rao and Riahi, 2006), a technology-rich IAM with a detailed representation of the global energy system, and MAGICC (Meinshausen et al., 2011a; Rogelj et al., 2012b), a probabilistic climate model (see Methods). We explicitly test how high emissions could be in 2020 before a 'point of no return' is reached in our model that would foreclose reaching 2 °C with a high probability. Figure 6.1 provides a conceptual overview of our analysis, which is further explained in the Methods section.

6.2 Exploring 'feasibility'

'Feasibility' of emission reductions is a subjective concept and depends entirely on what is deemed possible or plausible in the real world (Anderson and Bows, 2011). It encompasses multiple aspects, be they (1) technological, (2) economic, (3) societal or (4) political in nature. Given the substantial inertia of the energy system (Roehrl and Riahi, 2000), there is a limit to how deeply GHG emissions can be reduced by 2020. At the same time, in the absence of ambitious short-term actions, it may ultimately become infeasible to limit warming to below 2 °C in the long term. A range of emission levels in 2020 may thus exist that, on the lower end, could still feasibly be reached over the next decade and that, on the upper end, would retain the possibility of holding global temperature increase to below 2 °C throughout the twenty-first

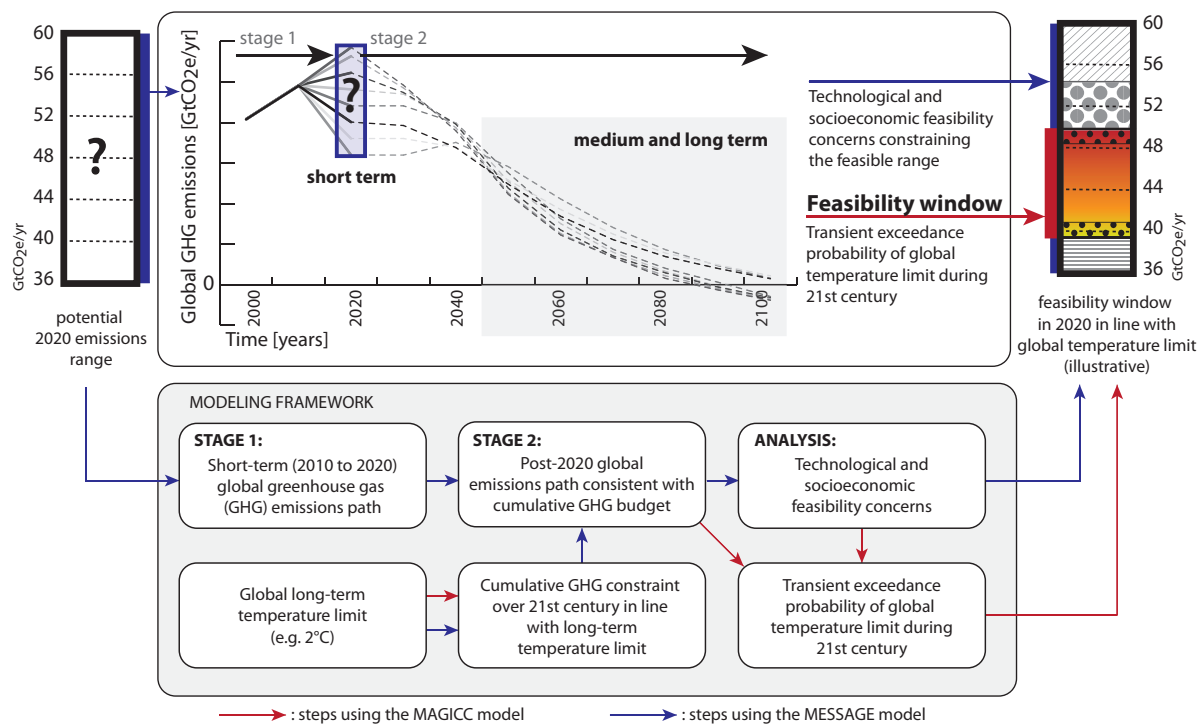


Figure 6.1: Schematic representation of the 2-stage model setup to quantify the feasible 2020 emission windows to stay below 2°C. After having simulated the transition from 2010 to a given GHG emission level in 2020 (Stage 1), MESSAGE optimizes the energy system configuration, for the rest of the century, given a cumulative GHG constraint which limits global temperature increase to below 2°C relative to pre-industrial (Stage 2). Each scenario is analysed in terms of technological and socioeconomic feasibility concerns. With the MAGICC model, the risk of overshooting the 2°C limit during the twenty-first century is computed for each feasible scenario. The final 'feasibility window' is colour-shaded as a function of the overshooting risk. A detailed legend for the feasibility window at the right hand side is provided in Figure 6.2.

century. We refer to this emission range as the 2020 'feasibility window' and further develop this concept throughout the paper.

We use four main criteria to define the feasibility of a scenario. Feasibility concerns attributed to (1) short-term technological transitions, which arise when the model cannot find sufficient mitigation options to reduce emissions by 2020. Feasibility concerns attributed to (2) long-term technological transitions, which arise when the model is unable to find long-term mitigation options to reduce emissions from their 2020 levels down to levels that are consistent with the global temperature goal. The other two criteria are attributed to (3) strong or (4) very strong economic penalties, indicating whether mitigation cost increases are especially large and fast. Economic penalties arise when a large mismatch exists between the level of GHG mitigation achieved by 2020 and the level required afterward. Of these four criteria, 'strong economic penalties' are flagged as an issue in the results, but are not considered infeasible *per se*; 'very strong economic penalties', on the other hand, signify an infeasible scenario in our analysis.

We define 'very strong economic penalties' as a jump in carbon price between 2020 and 2030 of at least 1000US\$/tCO_{2e}. 'Strong economic penalties' are flagged when this increase is between 500-1000US\$/tCO_{2e}. These ranges are comparable to an increase in the price of crude oil over a 10-year period of about 135-270US\$/barrel (strong penalty) or more (very strong penalty), relative to the 2011-2012 level of 100-120US\$/barrel. For comparison, crude oil prices increased by about 100 US\$/barrel between 2000 and 2008 from a relatively low 25US\$/barrel in January 2000. Our strong economic penalty would thus clearly be a cause for concern, while our very strong penalty could substantially hamper future economic development.

Whether a particular mitigation goal is infeasible in our study depends on a number of factors, including the availability of low-carbon technologies, the levels of energy demand, and various political and social factors affecting how policies are implemented. We therefore carry out this analysis for a reference case and a number of different sensitivity cases (based on Riahi et al. (2012)), each defining a unique collection of assumptions and constraints on technologies, demands and policies. Our cases are summarized in Table 6.1, and a more detailed description is provided in the Supplementary Information¹ (SI). The cases span a range of possible futures, but they should not be considered exhaustive of all potential outcomes. The intent is to use the cases to provide core insights. For each case, an ensemble of scenarios is run with different 2020 emission levels.

In our reference case ('intermediate demand'), energy demand follows historical trends (i.e., energy intensity improvements are only slightly faster than historical trends), and the scale-up of all low-carbon energy-supply technologies is assumed to be successful and pervasive worldwide. On the policy side, all countries are assumed to fully participate in a global climate agreement that aims at achieving the 2°C target: whether by 2020, if climate policies are assumed to be in place by that time, or immediately thereafter. The sensitivity cases vary these core assumptions one-by-one to assess the resulting changes in the feasibility windows (see Table 6.1, and SI).

¹Supplementary Online Information is available at: <http://www.nature.com/nclimate/journal/vaop/ncurrent/extref/nclimate1758-s1.pdf>

Table 6.1: Description of all cases. Further details for each case can be found in SI. Note that 'Technology-limiting' cases are independent from each other. For example, although the 'No new nuclear' case implements a phase-out of nuclear power, the 'no CCS' case again allows for the continued use of nuclear power.

Case	Description	Influence rel. to Reference
<i>Demand cases</i>		
Intermediate demand	Demand and energy efficiency improvements follow development paths that are only slightly faster than historical trends. The full portfolio of low-carbon energy-supply technologies are successful worldwide. All countries join in global mitigation efforts from now until 2020 (if required) and onwards.	Reference case
Low demand	As the reference case, however, substantial improvements in energy intensity in all end-use sectors (buildings, industry, transport), made possible through stringent efficiency measures and lower-energy lifestyles (includes 'advanced transportation', see below).	Window-opening
<i>Supply cases</i>		
<i>'Technology-limiting' cases</i>		
No new nuclear	No new investments into nuclear power from 2020 onwards; existing plants are fully phased out by 2060.	Window-closing
Limited land-based measures	Limitations are set to the mitigation potential from biomass, land use and forestry. The maximal total global biomass potential is further limited compared to the reference case (from 145 (220) EJ/yr to 80 (125) EJ/yr in 2050 (2100)); based on van Vuuren et al. (2009)), and afforestation is not allowed explicitly for climate mitigation.	Window-closing
No CCS	The technology to capture and geologically store carbon dioxide (CCS) never becomes available. This impacts both to potential to implement lower emission options with fossil fuels and the possibility to generate 'negative emissions' when combined with bio-energy.	Window-closing
<i>'Technology breakthrough' cases</i>		
Advanced transportation	Greater than expected progress with electric vehicle technologies, allowing them to meet a far greater share of mobility demands worldwide.	Window-opening
Advanced non-CO ₂ mitigation	Continuous improvements in the mitigation potential of non-CO ₂ greenhouse gases, from agricultural CH ₄ and N ₂ O sources, beyond best practice of presently available technologies.	Window-opening
<i>'Policy framework' cases</i>		
Delayed participation	The global 'South' delays its participation in global mitigation efforts until after 2030; emissions in these countries rise unconstrained until that time. The 'South' in this sensitivity case consists of all countries outside Europe, North America, the former Soviet Union, Australia, Japan, and New Zealand. It includes the emerging economies like Brazil, India, and China (see Table S5 and Figure S8 for details).	Window-closing
1.5 °C GHG budget	The cumulative global GHG emission budget for the 21 st century is further reduced so that temperature increase relative to pre-industrial levels returns to below 1.5 °C by 2100 with a 50 per cent probability; overshoot of the target is allowed prior to 2100.	Window-closing

6.3 Quantified 'feasibility windows'

We find that in the reference case GHG emissions must stay below 55 GtCO₂e/yr in the short term (2020) if global temperature increase is to be limited to less than 2 °C above pre-industrial levels in the long term. If emissions are higher than this level, our model indicates that it will be either technologically or economically infeasible (or both) to reduce GHGs fast or far enough after 2020 to meet the 2 °C target. The feasible lower limit to short-term mitigation in our reference case is 41 GtCO₂e/yr. Therefore, we estimate the 2 °C-consistent 'feasibility window' for 2020 to be 41-55 GtCO₂e/yr (Figure 6.2) — larger than estimates based on cost-optimal scenarios currently found in the literature (Rogelj et al., 2011b).

An important caveat is that the feasibility windows we estimate are based on the results of a single IAM. Previous model intercomparison studies (Clarke et al., 2009) have shown, that the spread across models can be quite significant, owing to key structural differences and varied assumptions. This suggests that if similar analyses were conducted with other IAMs, the emission ranges would likely differ from those shown here. Our emission pathways are at the high end of the literature range of 2 °C-consistent scenarios (Rogelj et al., 2011b) (Figure 6.3a). This is because our analysis explicitly explores the maximum range of emissions in 2020, rather than exploring cost-optimal pathways.

By comparison, if the unconditional emissions reduction pledges in the Cancún Agreement are ultimately met, then 2020 emissions are estimated (UNEP, 2011a) to be 55 GtCO₂e/yr (median; 51-60 GtCO₂e/yr minimum-maximum range). This range lies directly on the upper frontier of the feasibility window of our reference case. To put our feasibility window results further in context, the lower end of our range is about 20% below global emissions levels in 2010, while the upper end is about 10% above 2010 emissions and represents a reduction from (unmitigated, no climate policy) baseline emissions of about 7.5%. Our baseline sees emissions growing to 59 GtCO₂e/yr in 2020; this is at the high end of the range from the SRES marker scenarios (Nakicenovic and Swart, 2000) (47-60 GtCO₂e/yr). In all our scenarios, global emissions peak in 2020 at the latest. If emissions were to peak at a later date, the upper end of the feasibility window would close further.

When specific mitigation technologies are excluded, the 2020 feasibility window becomes compressed (Figure 6.2). The 'no new nuclear' case, for example, narrows the 2020 window by 5 GtCO₂e/yr, reducing the upper end to 50 GtCO₂e/yr. More strikingly, both the 'limited land-based measures' and 'no CCS' (no carbon capture and storage) cases close the window entirely. This means that, assuming an intermediate level of future energy demand, no feasible transformation paths for 2 °C could be found by the model in these cases. A principal reason for this is the reduced or entirely eliminated potential for 'negative emissions' (Azar et al., 2010). Negative emissions are typically assumed to be achieved through a combination of biomass energy and capture and geological storage of the emitted carbon-dioxide (IPCC, 2005b). In our reference case, negative emissions scale up from around 0.6 GtCO₂e/yr in 2030 to 12 GtCO₂e/yr in 2100, well below the maximum of 30 GtCO₂e/yr in 2100 found in the literature (1-13 GtCO₂e/yr interquartile range, computed from scenarios with CCS from biomass energy (IPCC, 2011)).

In contrast, when additional, more optimistic assumptions on mitigation options are made than in the reference case, the 2020 feasibility window widens. Figure 6.2 shows, in fact, that

feasibility windows of global 2020 greenhouse gas emissions required to limit warming to below 2 °C

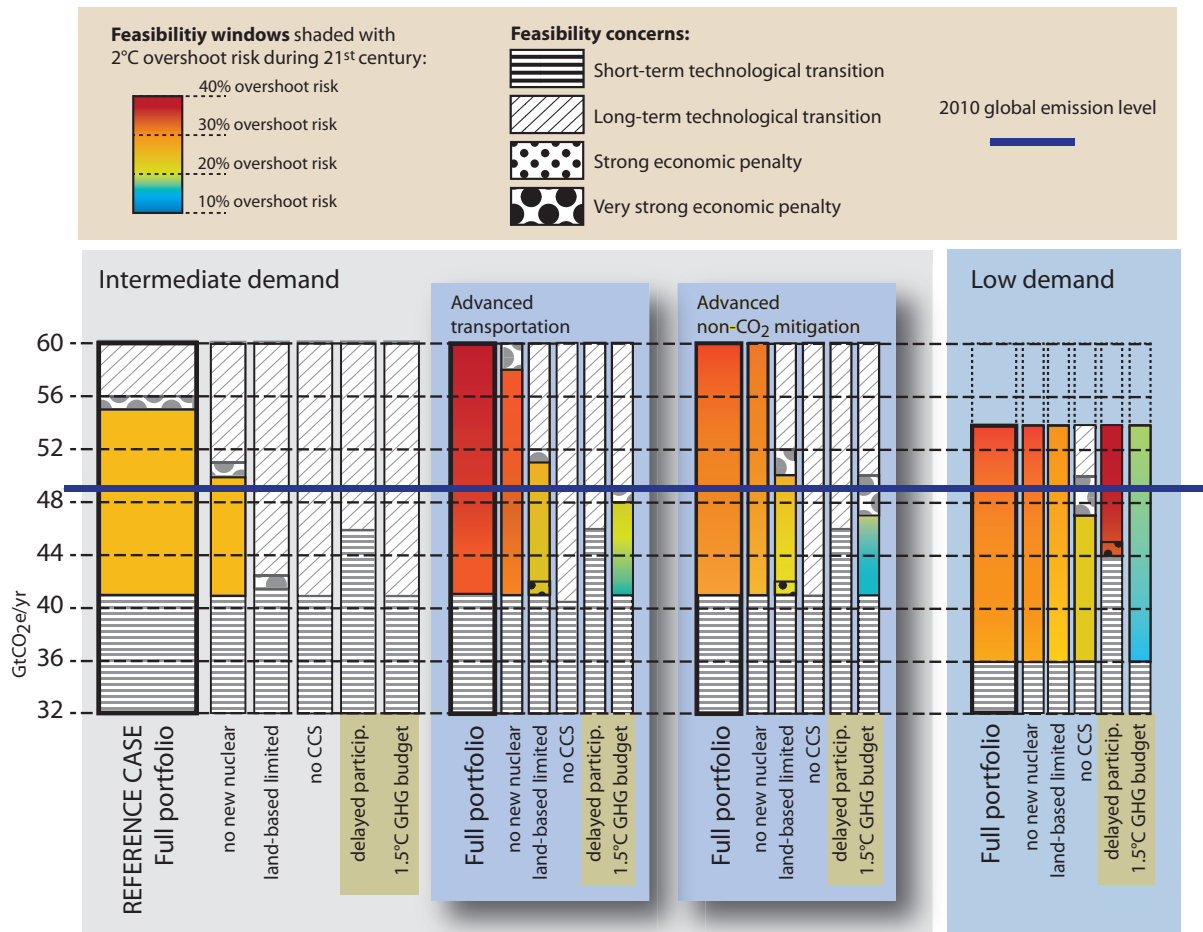


Figure 6.2: Feasibility windows for global GHG emissions in 2020 required to limit global temperature increase to below 2 °C relative to pre-industrial levels. Twenty-four unique cases are shown. Feasibility windows (see also Figure 6.1) in line with the 2 °C target for each case are represented by the colour-shaded inner parts of each bar, respectively. The 2 °C overshoot risk is the probability of exceeding the 2 °C temperature limit at any time during the twenty-first century (and equals 1 minus the probability to stay below 2 °C). For each case, areas with hatching represent ranges where no feasible scenarios were found due to the lack of short-term (horizontal) or long-term (diagonal) technological mitigation options. Dotted areas represent economic feasibility concerns.

in both the full portfolio 'advanced transportation' and 'advanced non-CO₂ mitigation' cases, it becomes feasible to reach the 2 °C target without any GHG mitigation before 2020. Note, however, that any future technological advancement or breakthrough hinges on investments in research and development that begin immediately. Even if the 'no new nuclear' assumption is added to these cases, little or no mitigation by 2020 is required to keep the 2 °C target feasible. Assuming that these breakthroughs take place but that land-based measures are limited has a stronger effect, bringing the 2020 emissions limit down to 50-51 GtCO₂e/yr. Finally, if CCS is assumed to be unavailable, the 2 °C target remains infeasible (the window closes entirely) despite the technological breakthroughs.

If future energy demand is substantially limited (the 'low demand' cases, see Table 6.1 and SI), baseline emissions in 2020 only reach 53 GtCO₂e/yr, compared to 59 GtCO₂e/yr in the reference case (Figure 6.2). This is the result of non-climate-related energy efficiency and other demand reduction policies, which are assumed to be already in place by 2020. Under these conditions, no additional short-term mitigation (beyond important efficiency improvements) is required to keep the long-term 2 °C target feasible, a robust finding that holds even if additional constraints on nuclear and land-based mitigation measures are assumed. Furthermore, in contrast to all other cases, the 'low demand' case is the only one that retains the feasibility of achieving the 2 °C target when CCS is assumed to be unavailable; however, this case does require limiting emissions in 2020 to just 47 GtCO₂e/yr. As a result of demand reduction measures, the low end of the feasibility window (36 GtCO₂e/yr) is also lower than in the reference (intermediate demand) case.

Under a fragmented international policy framework, in which there is late accession of the global 'South' (including emerging economies like Brazil, India, and China; see definition in Table 6.1 and SI) into a global climate regime, it becomes considerably more difficult to reach the long-term 2 °C target. In fact, for the 'delayed participation' cases, in which the South does not join the global mitigation effort until after 2030, we find no feasible solutions as long as future energy demand remains at the intermediate level. Interestingly, this picture does not change even in the more technologically optimistic 'advanced transportation' and 'advanced non-CO₂' cases. Only if there is a global shift toward more energy-efficient modes of living does the feasibility window begin to open again (44-53 GtCO₂e/yr, Figure 6.2). Previous model intercomparison studies (Clarke et al., 2009) have also shown the infeasibility of limiting CO₂ concentrations to low levels when there is delayed participation among certain major international players.

Finally, we consider a situation in which Parties of the UNFCCC decide to switch to a lower long-term temperature target of 1.5 °C (cf. UNFCCC (2010a)). We find that the 1.5 °C target cannot be reached from our reference case and would require either breakthrough mitigation technologies or a slowing of energy demand growth. In the 'advanced transportation' and 'advanced non-CO₂ mitigation' cases, for instance, the feasibility window remains open: 41-48 GtCO₂e/yr and 41-47 GtCO₂e/yr, respectively. On the other hand, if the world were to follow an ambitious high-efficiency and low demand path, the 2020 emissions window for reaching 1.5 °C would open significantly — much beyond what earlier assessments have found using simpler methods (UNEP, 2010b, 2011a; Ranger et al., 2012).

6.4 Pathway characteristics, costs, and risks

The transformation toward a low-carbon energy system will inevitably require major changes in how energy is produced and consumed. For example, traditional coal-fired power plants (without CCS) will be some of the first technologies to be abandoned, given that coal has the highest carbon intensity of all conventional fossil fuels. Because coal plants typically have very long life-times (approximately 50 years), early retirement of existing coal power infrastructure is a real possibility. We find that although the timing of this premature retirement differs depending on which 2020 GHG emission level is achieved, the total amount of prematurely shut-down capacity by the end of the 2020s does not differ markedly (Figure 6.3d). The total global installed coal-fired power capacity in 2010 in our model is about 1400 GW. We find that either about 65% of existing coal plants are retired by 2020 and almost none afterward, or only 5% of the fleet is retired by 2020 but 55% in the following decade. In the 'low demand' case, 30-50% less infrastructure is retired prematurely (Figure S1).

A second anticipated element of any major energy system transition will likely be a pronounced shift toward renewable energy sources. In our baseline 'intermediate demand' cases, for example, in the absence of climate policy by 2020, the global share of renewable energy in total primary energy supply (TPES, direct-equivalence method) is about 10% in 2020 (Figure 6.3b). Under more stringent climate policy regimes, the share of renewables increases significantly: reducing emissions to 44 GtCO₂e/yr by 2020 would necessitate a doubling of the renewables share (to approximately 20%) relative to the baseline case. In the low demand case (Figure S2), a doubling of the renewable share (relative to no climate policy) would help to reduce global emissions in 2020 to 40 GtCO₂e/yr. Note that the literature shows a 2 °C-consistent range (UNEP, 2011a) of renewable shares of 11-38% (2020 emissions: 39-49 GtCO₂e/yr).

In addition, we find that both short- and long-term mitigation costs depend strongly on the emission reductions that have been achieved by 2020 (Table 6.2, Figure S3). The more stringent the 2020 target, the higher the required mitigation costs and associated carbon prices by 2020 to achieve it — but the lower are the long-term mitigation costs (and also carbon prices in 2030) since less rapid reductions are required after 2020 to meet the 2 °C target. Lowering 2020 emissions implies thus greater mitigation costs in the short term, but generally reduced costs in the longer term. However, there is a 2020 emission level at which longer-term costs (2020 to 2050) become minimal. Letting emissions rise until 2020 above the least-cost level (around 44 GtCO₂e/yr for the reference case) implies consistently and significantly higher costs (up to 30% by 2050, up to 50% by 2100; see Table 6.2 and S1) for staying below 2GtCO₂eC in the long term. The stringency of emissions abatement by 2020 thus critically determines carbon prices and abatement costs post-2020.

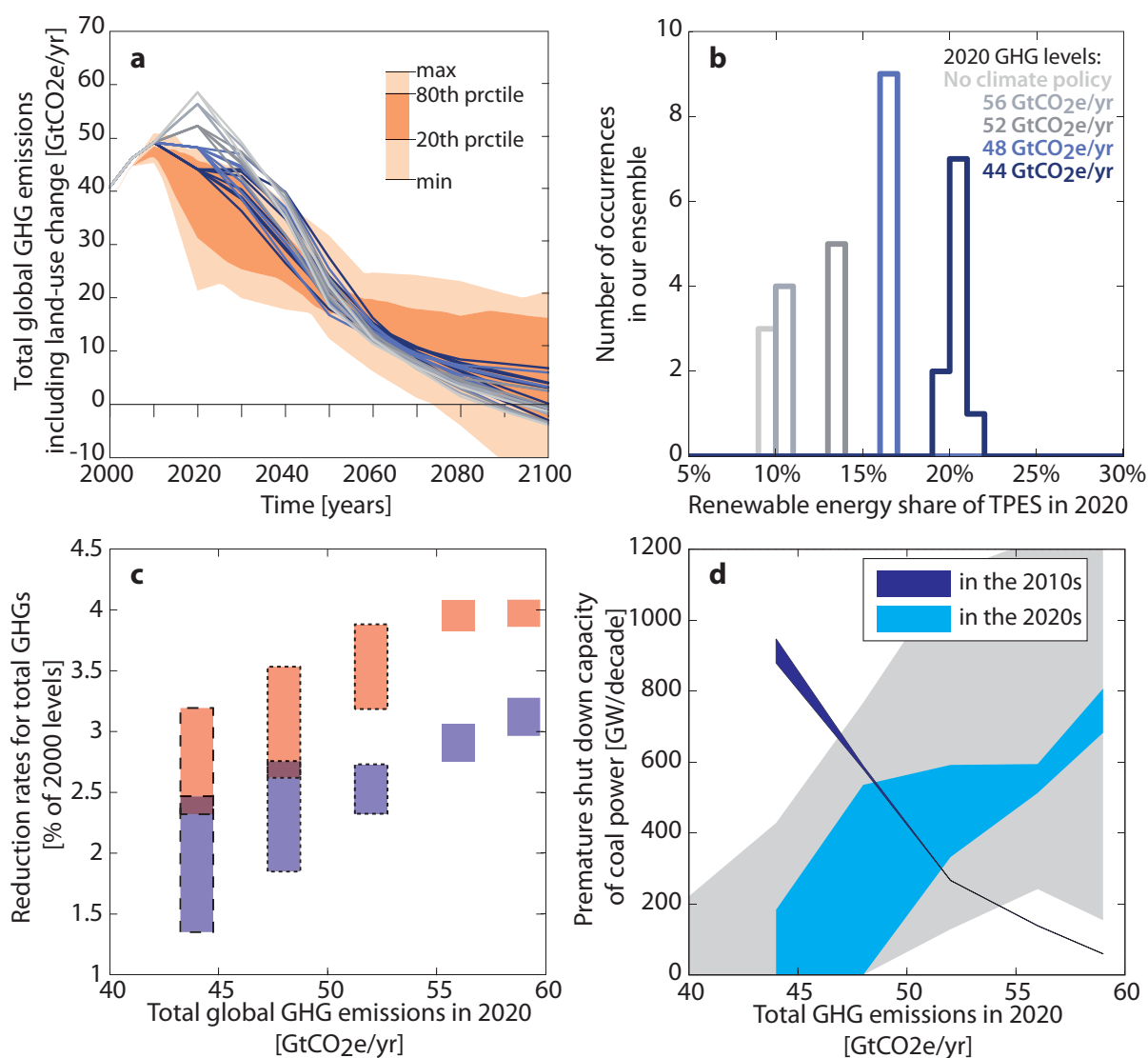


Figure 6.3: Characteristics of all feasible 2°C scenarios with intermediate energy demand. **a**, total global GHG emissions (blue lines) compared to range of scenarios in the literature (orange) with >66% probability to stay below 2°C from (Rogelj et al., 2011b); **b**, share of renewables in total global primary energy supply (TPES, direct equivalence method) as a function of total GHG emissions in 2020; **c**, post-2020 reduction rates for total GHGs (minimum-maximum ranges), for both the maximum decadal (red) and average (blue) reduction rates from 2020 to 2050. Edges summarize the proportion of scenarios considered feasible at that particular emission level: 50-75% (dashed edges), 25-50% (dotted edges), <25% (no edges); **d**, premature shut-down of coal-fired power capacity. Both prematurely shut down capacity in the 2010s (between 2010 and 2020, dark blue area) and in the 2020s (light blue area) are shown. Grey shaded areas indicate infeasible scenarios.

Table 6.2: Overview of costs as a function of emissions in 2020 for our 2 °C technology cases. Costs for a scenario without climate policy (baseline) are presented in terms of cumulative discounted energy system costs until 2020, and from 2020 until 2050. Mitigation costs are provided relative to the baseline and are given for all cases and feasible scenarios, respectively. The background colouring shifts from green, over yellow to orange as a function of increasing mitigation costs. Infeasible scenarios are marked with 'inf' and in red. Costs are discounted to the beginning of each period, respectively.

Intermediate future energy demand														
Cumulative discounted energy system costs in scenario without climate policies [billion US\$2005]:														
Until 2020: 14'347								From 2020 until 2050: 38'450						
Mitigation costs [% relative to scenario without climate policies]														
2020 total GHG level [GtCO₂e/yr]														
	NoCP	56	52	48	44	40	36	NoCP	56	52	48	44	40	36
Reference case														
	Until 2020:							From 2020 until 2050:						
Full portfolio	inf	inf	3%	9%	17%	inf	inf	inf	inf	66%	61%	56%	inf	inf
No new nuclear	inf	inf	inf	9%	17%	inf	inf	inf	inf	inf	73%	66%	inf	inf
Land-based limited	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf
No CCS	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf
Advanced transportation														
Full portfolio	0%	1%	3%	9%	17%	inf	inf	47%	43%	41%	37%	36%	inf	inf
No new nuclear	inf	1%	3%	9%	17%	inf	inf	inf	54%	53%	47%	44%	inf	inf
Land-based limited	inf	inf	inf	9%	17%	inf	inf	inf	inf	inf	72%	68%	inf	inf
No CCS	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf
Advanced non-CO₂ mitigation														
Full portfolio	0%	1%	3%	9%	17%	inf	inf	50%	45%	44%	40%	38%	inf	inf
No new nuclear	0%	1%	3%	9%	17%	inf	inf	61%	53%	52%	48%	45%	inf	inf
Land-based limited	inf	inf	inf	9%	17%	inf	inf	inf	inf	inf	82%	77%	inf	inf
No CCS	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf
Low future energy demand														
Cumulative discounted energy system costs in scenario without climate policies [billion US\$2005]:														
Until 2020: 13'279								From 2020 until 2050: 30'003						
Mitigation costs [% relative to scenario without climate policies]														
2020 total GHG level [GtCO₂e/yr]														
	NoCP	52	48	44	40	36	32	NoCP	52	48	44	40	36	32
Reference case														
	Until 2020:							From 2020 until 2050:						
Full portfolio	0%	0%	2%	7%	14%	26%	inf	24%	22%	21%	20%	23%	30%	inf
No new nuclear	0%	0%	2%	7%	14%	27%	inf	26%	24%	22%	21%	24%	32%	inf
Land-based limited	0%	0%	2%	7%	15%	29%	inf	44%	39%	37%	34%	32%	39%	inf
No CCS	inf	inf	inf	7%	15%	29%	inf	inf	inf	inf	65%	52%	53%	inf

NoCP: no climate policy
inf: infeasible

Another important insight from Table 6.2 is that lower emissions by 2020 keep more options open and hence reduce the risk that limiting global temperature increase to below 2 °C becomes infeasible in the long term. In other words, low 2020 emissions hedge against the risk of undesirable technology 'surprises'. For instance, in case of the failure or limitation of specific key technologies (e.g., the 'no new nuclear' and 'limited land-based measures' cases), pathways with lower 2020 emissions still achieve the 2 °C target in the long term, albeit at higher costs.

In addition to cost metrics, annual global emission reduction rates are often used in mitigation analyses as a proxy for whether an emission pathway could be feasible or not (Rogelj et al., 2010b; Macintosh, 2010; Anderson and Bows, 2011). On this point, our analysis corroborates previous findings in the literature (IPCC, 2007b; den Elzen et al., 2010b): between 2020 and 2050, none of our scenarios show average GHG reduction rates exceeding 3.3% per year relative to emissions in the year 2000 (Figure 6.3c), and the maximum post-2020 CO₂ emission reduction rates in our scenario set never exceed 5.7% per year relative to 2000 emissions (Figure S4a). Most of the reduction rates that we find over longer time periods and for all GHGs are thus significantly lower than the maximum rates of reduction of CO₂ only.

Finally, although we use a cumulative emission budget as a proxy for staying below 2 °C when constructing our scenarios (see Methods), the risk of overshooting this target (colour-shaded feasibility windows in Figure 6.2) varies depending on the trajectory (Smith et al., 2012; Meinshausen et al., 2009; Allen et al., 2009) and mix of gases (Smith et al., 2012; Meinshausen et al., 2009). This risk is higher when (1) short-term emissions in 2020 are higher, (2) larger contributions of negative emission technologies are allowed in the long term, (3) non-CO₂ gases (in particular methane) have a relatively larger share in the cumulative budget (and especially a higher emission rate at the time of the temperature peak (Smith et al., 2012)), or (4) a combination of these is true. By the time negative emissions technologies (primarily from fuel and electricity production from biomass combined with CCS) are sufficiently scaled up in our scenarios — which occurs at some point during the middle part of the century — the cumulative GHG budget has already been exceeded. Only later in the century do emissions return to within the allowable budget. Following a path in which the potential of and dependence on negative emissions is limited or eliminated (as in the 'limited land-based mitigation' or 'no CCS' cases) significantly reduces the overshoot risk. The opposite is true if technologies for very rapid and deep reductions become available during the century (e.g., 'advanced non-CO₂ mitigation' and 'advanced transportation'). Furthermore, some pathways have relatively lower methane emissions than other pathways, either because the methane mitigation potential is larger ('advanced non-CO₂ mitigation'), or because CO₂ mitigation potential is smaller ('limited land-based mitigation' and 'no CCS'). This contributes to the relatively lower transient overshooting risk in these pathways. In the 'advanced transportation' and 'low demand' pathways, where CO₂ emissions can be reduced rapidly, methane emissions are the highest.

6.5 Discussion

With our sensitivity cases, we can assess the relative importance of measures in achieving the 2 °C target. First and foremost, improving the efficiency of energy systems is key (cf. von Weizsäcker et al. (1997); Riahi et al. (2012)). Substantially limiting energy demand has the largest impact on our feasibility window, in that it significantly relaxes the necessary emission reductions that must be achieved by 2020. Second, consistent with earlier studies (van Vliet et al., 2012; Clarke et al., 2009), the availability of CCS and the immediate participation of all regions in global mitigation efforts also appear to be very important factors. It is infeasible to achieve 2 °C in our framework if these two critical assumptions are not realized, unless demand is low. Third, the full potential of land-based mitigation measures appears to be required in our scenarios to achieve the 2 °C target (cf. Wise et al. (2009)), unless breakthrough mitigation technologies (advanced transport and non-CO₂ mitigation) are available. Finally, while the availability of nuclear power as a mitigation option opens the 2020 feasibility window to some extent, nuclear power does not appear to be a required mitigation option (unless 2020 emissions exceed 49 GtCO₂e/yr; consistent with IEA (2011); Riahi et al. (2012)).

Taking into account all aspects of our analysis, limiting global GHG emissions in 2020 to the window of 41 to 47 GtCO₂e/yr would keep the widest array of options open to achieve the 2 °C target. This range is similar to the multi-model emissions range consistent with 2 °C (with >66% chance) based on least-cost scenarios from the literature (Rogelj et al., 2011b), as well as to global 2020 emission benchmarks based on simpler scenario methods (see Rogelj et al. (2011a)) and references therein). However, the range presented here contains much richer information. Staying within this window in 2020 hedges against the risks of potential technological failures and the uncertainty of future socio-political developments; yet even outside this window, feasible, yet more risky, pathways are found to exist. In our model, the 47 GtCO₂e/yr emission limit would thus maintain the feasibility of the 2 °C target in the event the contribution of nuclear, land-based mitigation measures, or CCS is either restricted or completely unavailable. However, the feasibility of such transformations will critically depend on the level of future energy demand.

Finally, if the long-term climate goal would be strengthened in 2015 to 1.5 °C, the 41-47 GtCO₂e/yr window for 2020 might still preserve the option of achieving this goal, contingent on major technological breakthroughs in transportation or non-CO₂ mitigation options or on a low energy demand future. Current emissions are slightly above 50 GtCO₂e/yr (Montzka et al., 2011). Global emissions would therefore have to peak and decline before the end of this decade in order to land in the 41-47 GtCO₂e/yr window in 2020. In contrast, current unconditional emission reduction pledges would lead to global emissions in 2020 of 55 GtCO₂e/yr (central estimate from UNEP (2011a)) and thus do not constitute a robust path for limiting global temperature increase to below 2 °C.

6.6 Methods

We employ the MESSAGE IAM to project and analyse possible future evolutions of global GHG emissions in combination with the reduced complexity climate and carbon-cycle model MAGICC (Meinshausen et al., 2011a,b), version 6. An elaborated description of the MESSAGE model is given in SI and earlier literature (O'Neill et al., 2009; Riahi et al., 2007, 2012). MAGICC is setup to probabilistically (Meinshausen et al., 2009) span the uncertainties in carbon-cycle (Friedlingstein et al., 2006), climate system (Meehl et al., 2007) and climate sensitivity (Rogelj et al., 2012b) of the IPCC AR4, is constrained by historical observations of hemispheric land/ocean temperatures (Brohan et al., 2006) and historical estimates for ocean heat-uptake (Domingues et al., 2008), and is used to compute the transient exceedance probabilities for each scenario. Temperature increase relative to pre-industrial values is computed relative to the average temperature between 1850 and 1875.

In this analysis we run MESSAGE in a two-stage setup (see O'Neill et al. (2009), and Figure 6.1). In the first stage, the model simulates a possible range of GHG emission outcomes through 2020. It has no knowledge of the future beyond 2030 (referred to as 'myopic') and therefore makes no attempt to optimize the energy system toward an eventual long-term climate target. We represent climate policies by 2020 with global carbon caps of varying stringency, ranging from the level likely to be realized in the absence of climate policy (about 59 GtCO₂e/yr in the reference case) down to the level at which it becomes technologically infeasible within our modelling framework to realize further short-term emission reductions (about 40 GtCO₂e/yr in the reference case). Subsequently, the state of the global energy system through 2020 is frozen, and at that time the model immediately and unexpectedly learns about a global GHG emission budget constraint for the remainder of the century. In this second stage, the model optimizes the energy system evolution over the twenty-first century such that cumulative GHG emissions stay within this constraint.

Due to climate policies, fossil-fuel technologies will be substituted with renewables which emit low or zero levels of short-lived climate forcers (SLCFs) like black carbon or sulphur oxides. Therefore, emissions of SLCFs will likely decrease across the board as well (McCollum et al., 2011; Rafaj et al., 2010; Heyes et al., 2011). No additional measures are assumed on these species. The emission budget we specify equals 2500 GtCO₂e over the 21st century, which has been iteratively estimated from standard, cost-optimal (one-stage, full-century) MESSAGE runs so that it limits global temperature increase to below 2 °C with >66% probability given an IPCC AR4-consistent setup of MAGICC (Rogelj et al., 2012b). This budget includes emissions of all GHGs of the so-called 'Kyoto basket of gases', which contains carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorinated compounds (PFCs) and sulphur hexafluoride (SF₆), and is expressed in terms of carbon-dioxide-equivalent emissions (CO₂e) computed with 100-year global warming potentials reported in the IPCC (IPCC, 2007d).

Each combination of short-term emission level and long-term budget, within the given scenario family (i.e., technology or policy framework case), represents a unique scenario. Every scenario is assessed to determine if possible feasibility concerns arise. In this study, a scenario is considered infeasible if supply and demand side technologies cannot match useful energy demands (across all regions and time periods) at reasonable costs (see Riahi et al. (2012); Mc-

Collum et al. (2011)). Failure to do so could be the result of, for example, limits to the rate of technological diffusion, constraints on the scale of technologies due to intermittency and variability concerns, and limits to the size of the available resource base. Our model can also employ so-called backstop technologies to meet energy demand. Backstops represent technologies whose characteristics are not yet known today but which are assumed to be able to supply low-carbon energy at a very high cost in the future. In practice, no feasible scenario in our set contained backstops. Consistent with earlier literature (Clarke et al., 2009), we assume pathways are infeasible that have discounted carbon prices exceeding 1000 US\$/tCO₂ in 2012.

We span the entire possible range of GHG emission levels in 2020 with 4 GtCO₂e increments. The upper and lower borders of each emission window are subsequently sampled at 1 GtCO₂e increments. For the analysis of the various additional aspects of the 2020 feasibility window (e.g., costs, shares of renewable energy, etc.) only data at the coarse 4 GtCO₂e increment resolution is taken. Because of the uncertainty in historical emission inventories (Prather et al., 2009; Rogelj et al., 2011a), we indicate the historical 2010 emission level used by the MESSAGE model in Figure 6.2 as a point of comparison for the 2020 emission windows. This value (49 GtCO₂e/yr) is closely in line with recent estimates (Montzka et al., 2011).

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Part V

Integration of knowledge across disciplines

Chapter 7

**UN's new 'Sustainable Energy For All'
initiative compatible with 2 °C**

UN's new 'Sustainable Energy For All' initiative compatible with 2 °C

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Abstract

Progress towards climate protection has been modest over the past decades despite the ever-increasing urgency for concerted action against global warming. Partly as a response to this, but more directly as a means to promote sustainable development and poverty eradication, the United Nations has initiated a process to promote three global energy objectives: energy access, renewable energy, and energy efficiency. In this article we discuss the consistency of the proposed energy-related objectives with the overarching climate goal of limiting global temperature increase to below 2 °C. We find that achievement of the three energy objectives could provide an important entry point to climate protection, and that sustainability and poverty eradication can go hand in hand with mitigating climate risks. However, using energy indicators as the sole metrics for climate action may ultimately fall short of the mark: eventually, only limits on cumulative greenhouse gas emissions will lead to stringent climate protection.

7.1 Introduction

In the past couple of years, progress towards effective climate protection has been limited under the United Nations Framework Convention on Climate Change (UNFCCC) (Rogelj et al., 2010b). Due to this impasse in limiting the growth of greenhouse gas (GHG) emissions (Friedlingstein et al., 2010; Montzka et al., 2011; Peters et al., 2012), also alternative approaches are now being considered that could put the world on a path that protects the global climate. One of those focuses on the promotion of energy-related objectives.

Climate change is driven by the cumulative amount of GHGs emitted to the atmosphere (Allen et al., 2009; Matthews et al., 2009; Meinshausen et al., 2009; Zickfeld et al., 2009; Solomon et al., 2010; Smith et al., 2012), in particular of long-lived species like carbon dioxide (Huber and Knutti, 2012) (CO_2). Therefore, to halt anthropogenic climate change global GHG emissions need to be reduced to virtually zero in the long term (Matthews and Caldeira, 2008). Achieving this will require massive transformations of all GHG-emitting sectors. Given that the global energy system (which supplies fuels and electricity to the residential/commercial, industrial, and transportation end-use sectors) is currently responsible for about 80% of global CO_2 emissions (RCP Database, 2009; Boden et al., 2012; Meinshausen et al., 2011c), transformations in this sector will be essential for realizing a low-carbon future. Moreover, the need for transformational change in the energy system has also been advocated for other important reasons, for instance to spur sustainable development or to improve the well-being of the impoverished billions in our society who lack regular access to modern forms of energy to meet their basic needs. In this paper we look at how energy-related targets fostering the abovementioned objectives would or would not be consistent with global climate protection.

7.2 Energy at the core of development

Energy plays a critical role in enabling sustainable development, as highlighted at the Rio+20 Sustainable Development Conference (United Nations, 2012). Furthermore, United Nations Secretary-General Ban Ki-moon declared 2012 the year of 'Sustainable Energy for All' (SE4ALL), and launched a new global initiative (United Nations, 2011) which explicitly focuses on taking energy as an entry point to achieve several global sustainability objectives, including defeating poverty and ultimately halting anthropogenic climate change. The SE4ALL initiative is built on three core energy objectives, each of which should be reached by 2030:

- **ensuring universal access to modern energy services:** this implies that access to modern forms of energy is guaranteed for the world's poorest (High-level Group on Sustainable Energy for All, 2012). Three billion people currently lack access to either electricity or clean fuels for cooking, or both; this has severe, adverse implications for human health (UNEP and WHO, 2009). In practice, ensuring universal access means providing electricity to remote and poor rural areas, as well as the substitution of traditional biomass (e.g., fuel wood) by clean and modern energy carriers and appliances (e.g., natural gas, biogas, liquefied petroleum gas/LPG).
- **doubling the share of renewable energy in the global energy mix:** this requires increasing the share of renewables in final energy (the energy available to actual users)

from 15% to 30% by 2030 (High-level Group on Sustainable Energy for All, 2012). Renewable energy sources include, for example, wind power, solar power, hydropower, biomass (modern and traditional), geothermal power, etc.

- **doubling the rate of improvement in energy efficiency:** interpreted as the 'energy efficiency of the global economy', this objective has been translated to an average improvement rate for global energy intensity (measured here in units of final energy per gross world product MJ/US\$, (High-level Group on Sustainable Energy for All, 2012)). More specifically, this means that global energy intensity improves by an average rate of 2.4% per year between 2010 and 2030 (compared to the historical rate of 1.2% per year).

Note that we rely on one specific interpretation of the SE4ALL targets (High-level Group on Sustainable Energy for All, 2012), but the main initiative text (United Nations, 2011) leaves room for ambiguity. To reduce this, more distinctly defined targets would be needed.

7.3 Energy system transformation and CO₂ emissions

The most important way for short-term energy objectives to enable climate stabilisation is by effectively stimulating the phase-out of CO₂ emissions. Achieving this objective through transformational change in the energy system is possible through concerted action in two dimensions: energy intensity (EI) and carbon intensity (CI) improvements. Energy intensity is defined in this context as the amount of final energy (FE) used per unit of gross world product (GDP), carbon intensity as the amount of CO₂ emissions emitted per unit of final energy. Ultimately, the amount of emissions resulting from the energy system are given by the relationship $CO_2 = CI * EI * GDP$ (a variation of the well-known Kaya identity (Kaya, 1990)). Achieving emission reductions in the energy sector thus requires a reduction in either energy or carbon intensity, or both. Actively constraining GDP growth (Lawn, 2010) would also limit emissions; however, this option falls outside the scope of this paper, which explicitly focuses on the energy system.

Two of the three SE4ALL objectives are directly linked to the two abovementioned dimensions and can therefore, in principle, help to achieve climate protection (Figure 7.1). The renewable energy objective will improve the carbon intensity of the energy system while the energy efficiency objective aims to lower its energy intensity. Critical questions remain, however, regarding the extent to which the SE4ALL energy objectives are consistent with climate protection. Herein lies our motivation for exploring the potential of the SE4ALL energy objectives to serve as an entry point for stringent climate protection and the question of whether or not the energy indicators can be robustly and reliably used as yardsticks for tracking progress on climate action.

7.4 Our modelling approach

Like others before us (IPCC, 2007b, 2011; Yumkella et al., 2012), we approach such research questions through scenario analysis and integrated assessment modelling (IAM). IAM combines insights from various fields — such as economics and the geophysical, biological, social,

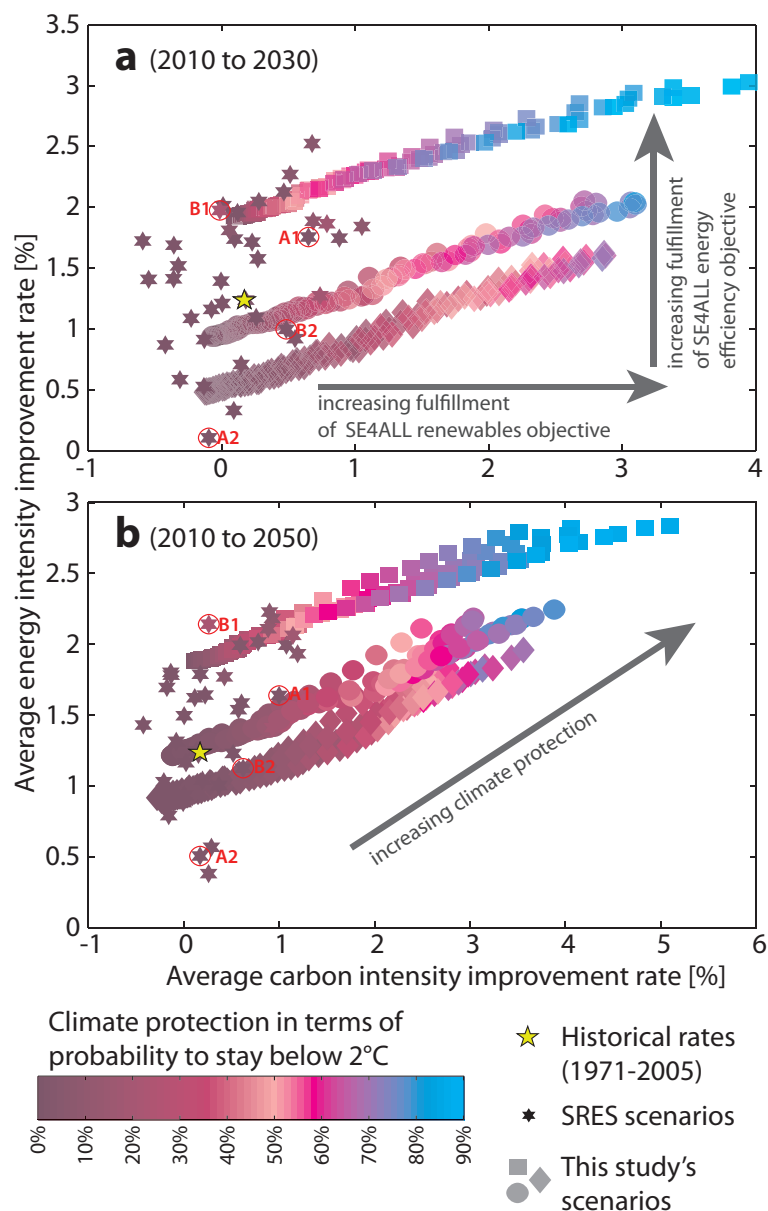


Figure 7.1: Joint influence of carbon intensity and energy intensity improvements for limiting global temperature increase to below 2°C during the 21st century in a large illustrative set of scenarios ($n > 500$). Panel **a** shows average global rates between 2010 and 2030, panel **b** between 2010 and 2050. The yellow star indicates the historically observed rate between 1971 and 2005, hexagrams the values found in the SRES scenarios (Nakicenovic and Swart, 2000). SRES marker scenarios are highlighted in red. Grey arrows in panel **a** indicate the direction along which scenarios will move when achieving two of the three SE4ALL objectives, in panel **b** the arrow illustrates the direction of increasing climate protection. Other symbols are colour-coded as a function of their probability to limit warming to below 2°C and the shape of the symbols reflects the base level of future energy demand assumed in the scenarios (diamond: high, circle: intermediate, square: low). Note that while all scenarios of this study assume a consistent evolution of climate mitigation over the course of the full century, the SRES scenarios represent baseline scenarios without climate mitigation. The long-term development in the SRES might thus differ from their short-term trends.

and engineering sciences — for the systematic analysis of possible future development pathways. Generally, the interactions between different sectors of the economy are represented within a single framework in order to evaluate the impact of a variety of energy and environmental policies (e.g., energy security (McCollum et al., 2011; Riahi et al., 2012), air pollution (Kelly, 2006), climate change (Clarke et al., 2009; van Vuuren et al., 2011b), or land-use change (Wise et al., 2009)) or to better understand the uncertainties of alternative future development paths (Nakicenovic and Swart, 2000). Scenarios developed by IAM thus describe — under an internally consistent set of assumptions — how the future could potentially unfold, what the impact of specific policies might be, or what costs and benefits they would entail. IAM scenarios are neither predictions nor forecasts and have even been described as 'stories about what happened in the future' (Armstrong and Green, 2012). Their value rests on their ability to shed light on the dynamics of future changes and to provide valuable insights into the circumstances that could lead to robust and cost-effective paths for achieving specific objectives.

Here we develop a large ensemble of more than 500 detailed energy-environment-economy-engineering (E4) scenarios that minimise total cost of climate mitigation over time with the MESSAGE IAM framework (Riahi et al., 2007; O'Neill et al., 2009; Riahi et al., 2012). We vary the stringency of climate protection and the underlying technological and socio-economic assumptions (described in Rogelj et al. (2012a)). Our scenarios build upon the IAM work from the recently published Global Energy Assessment (Riahi et al., 2012) (GEA), which explored a variety of potential pathways for achieving the energy transformation. For example, our scenarios distinguish between vastly different future energy demand developments, ranging from high demand futures to scenarios that envision aggressive efforts to temper energy demand growth. In addition, we delve into the highly uncertain technological dimension by exploring scenarios with future restrictions on key technologies — such as the phase-out of nuclear energy or limitations on carbon capture and storage (CCS) — or scenarios that allow for possible technological breakthroughs — such as greater-than-expected advances in electric vehicles or non-CO₂ mitigation measures (for details see Riahi et al. (2012); Rogelj et al. (2012a)). The scenarios identify portfolios of measures consistent with climate protection. They do not prescribe, however, the policy instruments (like feed-in tariffs or carbon tax) that would trigger the implementation of specific measures. With this diverse set of GHG mitigation scenarios, we evaluate the consistency of the near-term SE4ALL energy objectives with the long-term goal of limiting global temperature increase to below 2 °C relative to preindustrial levels. (Climate impacts are computed with the probabilistic climate model MAGICC (Meinshausen et al., 2011a, 2009) in a set-up (Rogelj et al., 2011b) consistent with (IPCC, 2007d).) To be sure, renewable shares and energy efficiency improvements have not been used as 'exogenous' control variables in our analysis; rather, they can be seen as emerging properties of a low-carbon energy system on a path toward mitigating climate change. We can therefore only determine whether the SE4ALL energy objectives are consistent with stringent climate protection, not if they represent some kind of necessary pre-conditions for it to take place. And although our scenarios span a fairly large range, they are by no means exhaustive of all possible future outcomes.

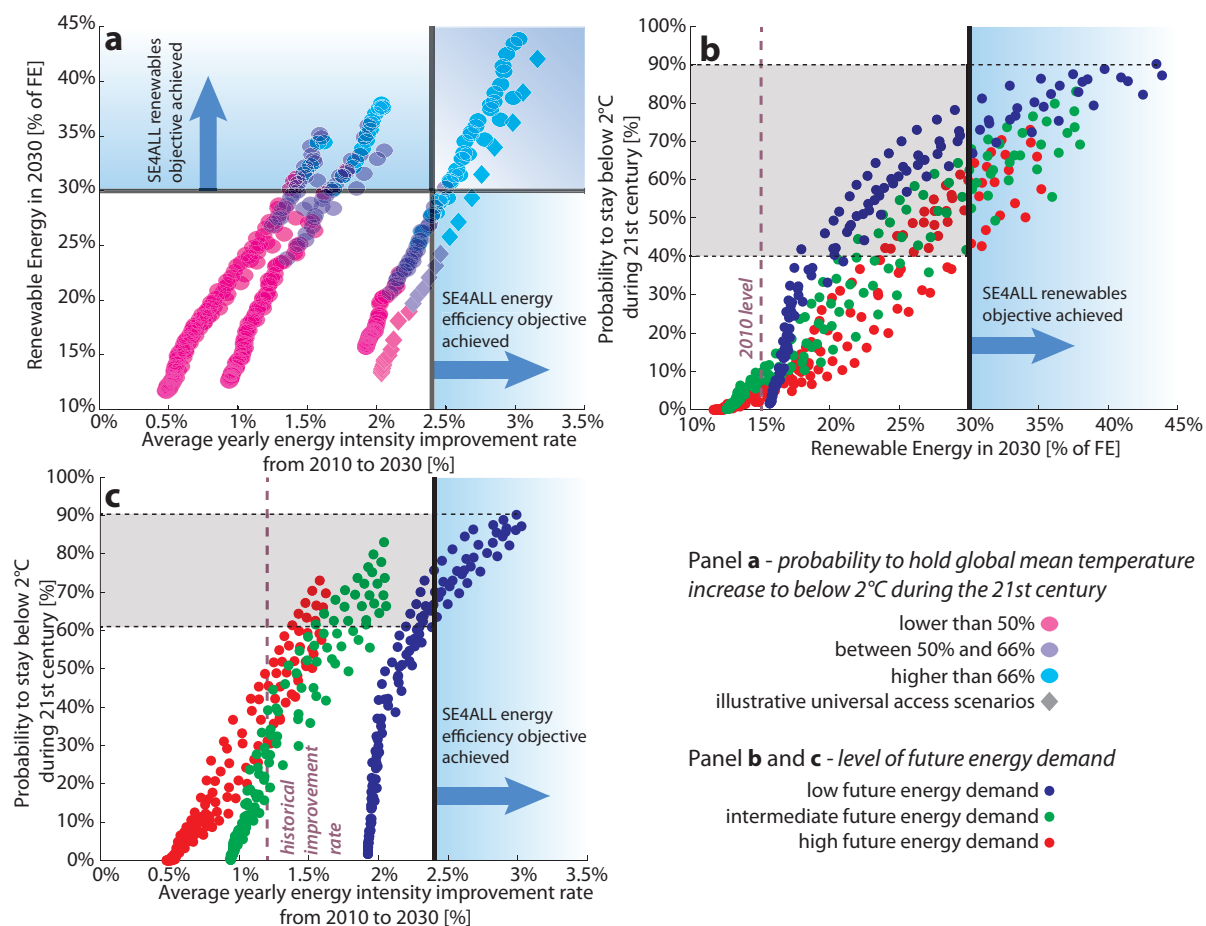


Figure 7.2: Consistency of the three SE4ALL energy objectives and a global climate target of 2°C. **a**, Yearly energy intensity improvement rates against share of renewable energy in terms of final energy in our scenarios. Scenarios are colour-coded as a function of their probability to limit warming to below 2°C during the 21st century. Diamonds show scenarios with low future energy demand which additionally ensure universal energy access to modern energy services; **b**, Probability to limit warming to below 2°C as a function of the share of renewable energy in terms of final energy in 2030 in our scenarios, and for three levels of future energy demand; **c**, As panel **b**, but for average yearly energy intensity improvements between 2010 and 2030.

7.5 SE4ALL objectives and climate protection

Analysis of the scenario ensemble indicates that simultaneously achieving all three SE4ALL energy objectives by 2030 would be consistent with limiting global temperature increase to below 2 °C with high likelihood (Figure 7.2a). Despite their near-term nature, fulfilling the objectives would help to kick-start the energy system transformation and thus put it on course to ensure the long-term protection of the global climate. Likewise, global climate action would facilitate reaching the SE4ALL objectives. It must be emphasized, however, that in order to be consistent with limiting temperature change to below 2 °C, the SE4ALL objectives will have to be implemented concertedly and globally (see further below), be complemented by other GHG mitigation measures, and efforts to reduce GHG emissions will need to continue long after 2030 at the same level of stringency.

7.5.1 Renewable energy indicators

The share of renewable energy in 2030 (as a percentage of total FE) is closely related to climate protection. More specifically, the subset of our scenarios that achieve the renewable energy objective scores much better in terms of climate protection than the bulk of scenarios that do not. Yet, while this may be intuitive, it is interesting to note that the probability of staying below 2 °C in these scenarios ranges from 40 to about 90%. In other words, if only the SE4ALL renewable energy objective is fulfilled, the chance that temperatures could rise above 2 °C is still >50%. Such a result makes clear that an increase in the global share of renewable energy sources will not necessarily guarantee sufficient reductions in total emissions. Whether this is the case depends on total global energy demand. For example, in the not unlikely case that future energy demand is high (Figure 7.2b, red dots), a doubling of the renewable energy share in the global energy mix appears to be a rather weak indicator for stringent climate protection.

7.5.2 Energy intensity improvement indicators

Similar to the renewable energy objective, the likelihood of successful climate protection generally appears to be higher in the scenarios of our ensemble that see a doubling of the average rate of global energy intensity improvement (Figure 7.2c). Probabilities of staying below 2 °C range from about 60 to 90% in these cases. These results are quite sensitive, however, to our underlying assumptions, in particular for future GDP growth (discussed further below). In Figure 7.2c, we show that only in scenarios with relatively low future energy demand growth (through the implementation of substantial energy efficiency and conservation efforts in all end-use sectors: residential/commercial, industry, and transport) can the SE4ALL energy efficiency target be achieved. Such moderation of demand, while still allowing for enhanced living standards globally, would require a suite of aggressive policies aimed at promoting behavioural changes with respect to energy consumption and the rapid introduction of stringent efficiency regulations, technology standards, and the inclusion of environmental costs in energy prices (commonly called 'externalities', e.g. health and ecosystem damages from air-pollution) (Rahi et al., 2012). To achieve all of this, major societal and political efforts are indeed required.

Yet, despite its apparent robustness, the main disadvantage of the energy intensity indicator is that the resulting energy demand and associated emission reductions are strongly dependent on future economic growth. High economic growth would entail relatively lower climate change mitigation from this objective, and vice versa. In our analysis we have adopted the intermediate economic growth assumptions from the GEA (Riahi et al., 2012), which correspond to an average global GDP growth rate of about 2.8% per year between 2010 and 2030. This compares to a literature range of between 2.1 to 3.3% per year (10-90 percentile range, based on (IPCC, 2007b)). Simple calculations outside of our modelling framework reveal that for the same levels of energy demand as in our intermediate projections, future energy intensity improvements would shift under the alternative GDP assumptions between -0.7 to +0.4 percentage points per year (relative to the initial 2.4%). This would shift the vertical line in Figure 7.2c to the left or right accordingly, thereby resulting in a greater or lesser number of scenarios fulfilling the SE4ALL energy efficiency objective. Nevertheless, our main conclusion remains: unless the world embarks on a high-efficiency, low energy-demand pathway (blue dots, Figure 7.2c) in the near future, reaching the SE4ALL energy efficiency objective appears out of reach.

Another way of illustrating the possible effect of different GDP assumptions is to assume that the change in economic growth would alter final energy demand to the same degree, with energy intensity thus remaining constant. Assuming that carbon intensity is unchanged, we find that emissions could be 13% lower to 9% higher (10-90 percentile range) relative to the scenarios based on our 'middle-of-the-road' GDP assumption. This shows that emissions in 2030 could vary by 22 percentage points while energy intensity remains virtually the same. Because it is emissions that ultimately affect the global climate, our analysis suggests a certain amount of caution against the isolated use of energy intensity as a climate action indicator.

7.5.3 Universal energy access and climate action

Finally, we find that although it is essential for eradicating poverty, the provision of universal access to modern energy services has a limited impact on the achievement of the other SE4ALL objectives and for climate protection. Energy access gradually improves over time in our scenarios due to increasing economic growth and affluence in the developing world. Absent targeted efforts to speed up this process, however, we find that universal access is not likely to be achieved before the 2060s. To study the potential impact of the SE4ALL objective, we explicitly modify a subset of our scenarios so that the timing of achieving universal access is brought forward to 2030. As indicated by other studies (IEA, 2010; Pachauri et al., 2012), the GHG effect of providing universal energy access is negligible, particularly compared to the total GHG emissions levels expected by 2030. Our analysis further suggests that ensuring universal access to modern energy services by 2030 would facilitate reaching the SE4ALL energy efficiency objective but would in turn reduce the global renewables share of final energy by about 2 percentage points in the same year (Figure 7.2a). The former is brought about by the substitution of inefficient traditional energy use (biomass burning for cooking has an average efficiency of about 10-15% (Reddy, 2003; Ekholm et al., 2010) by modern carriers and cooking appliances with higher efficiencies (LPG: 60%, electricity: 75% (Ekholm et al., 2010)). The slight reduction in renewable energy shares, on the other hand, occurs because in our frame-

work energy access (for cooking and heating) is provided mainly by switching from biomass to low-pollution fossil alternatives (with fuel-price support for LPG). Of course, whether traditional biomass should be considered a truly renewable resource is debatable, as it is often harvested in an unsustainable way. (This is anecdotal: essentially no studies are available on the topic.) In conclusion, the interplay between the decreased renewables share and increased overall efficiency of the energy system results in scenarios that have very similar probabilities for holding warming to below 2 °C, irrespective of the timing of when universal access to modern energy services is achieved, whether by 2030 or much later.

7.6 How to meet multiple targets

So if it is in fact true, as our analysis illustrates, that the concurrent achievement of all three near-term SE4ALL objectives can indeed provide an entry point to long-term climate protection, the question then becomes: how daunting is the task? An in-depth look into the transformational changes required in our scenarios reveals that it is pretty daunting indeed.

For starters, the contribution of renewables to total primary energy in scenarios that achieve the renewable energy target (in terms of final energy) and limit global warming to below 2 °C (with >66% probability) almost triples between 2010 and 2030. In certain instances, namely for those renewable energy options which have a large potential but are currently underdeveloped globally, this change could be up to an order of magnitude larger, for example, more than tenfold and more than thirtyfold for wind and solar, respectively (Figure 7.3a). This translates to double-digit annual growth rates for these technologies over the coming two decades (consistent with similar historical growth rates for these technologies between 2000-2010). While the values given here should only be taken as illustrative, the scale and relative magnitude of such an endeavour are arguably model independent (IPCC, 2011).

The good news is that the massive task of scaling up renewable energy supply options can be complemented by the simultaneous achievement of the SE4ALL energy efficiency target. Energy efficiency improvements will reduce the overall energy demand of the economy, and therewith ease the pressure on energy supply options to scale up massively in the short term. As illustrated in Figure 7.3b, the global contribution of renewable energy sources to primary energy supply is reduced in absolute terms by about 20% in 2 °C-consistent scenarios that achieve both the renewable energy and energy efficiency objectives. In other words, only trying to achieve the renewables target, without achieving the energy intensity objective, would make the climate protection endeavour even more ambitious.

Renewables are not the only potential source of low-carbon energy in the future, however. Other options in our scenarios include fossil fuels in combination with carbon capture and storage (fossilCCS) and nuclear power. The former allows for the continued use of fossil fuels by capturing the CO₂, compressing it, and putting it into pipelines for permanent storage in geological formations (IPCC, 2005b). The latter obviates the need for fossil fuels altogether. In either case, drastic reductions in CO₂ emissions can be achieved. The problem is, massive deployment of both of these technologies is contingent upon a range of factors, many of them uncertain. These uncertainties relate not only to a host of economic and technological challenges, but also to the public's acceptance of these technologies and its perception of the

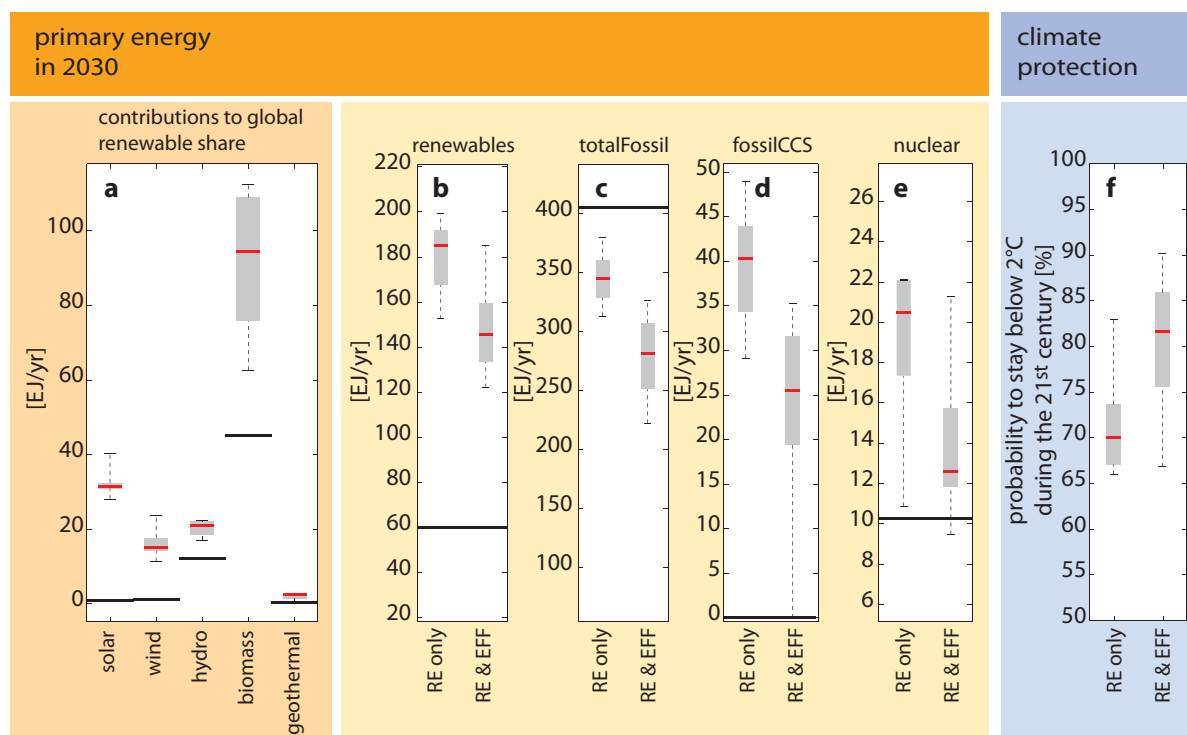


Figure 7.3: Global contributions to primary energy supply of key technologies in our 2°C consistent scenarios. **a**, global absolute contributions to total primary energy supply (TPES) of renewable energy technologies in 2030 in our scenarios that reach the renewable energy target and limit warming to below 2°C with at least 66% probability during the 21st century; **b-e**, global contributions to TPES of renewables, fossil fuels (totalFossil), fossil fuels in combination with CCS (fossilCCS), and nuclear power in scenarios that limit warming to below 2°C with at least 66% probability for (1) scenarios achieving the renewable energy target only (RE only), and (2) scenarios achieving the energy efficiency and renewable energy target (RE & EFF); **f**, probabilities to limit warming to below 2°C for the groups defined in panels **b-e**. Red lines show median values, grey boxes the 25th to 75th percentile range, whiskers the full range. Black horizontal lines show the 2010 contributions. Note that TPES of renewables is computed with the direct equivalence method, arguably understating their contributions.

risks involved. These issues acknowledged, we find that in our scenarios, trying to achieve the 2 °C climate objective in the absence of concerted energy efficiency and conservation efforts requires contributions from both nuclear power and fossilCCS (Figure 7.3d-e). On the other hand, if substantial progress is made along the energy efficiency path, then future reliance on these technologies can be significantly reduced and in some cases eliminated. Higher demand-side efficiency also increases flexibility within the portfolio of renewable energy technologies: if one technology would not be able to scale up as expected, the shortfall could be picked up by another.

7.7 Regional contributions to the global objectives

When zooming down to the regional level, we see that although the SE4ALL objectives are formulated as global targets, a cost-effective regional approach toward their implementation can result in quite some regional differences. In our scenarios all regions, no matter from the developed or developing world, make a significant contribution to the global 30% renewable energy share target (Figure 7.4a). The exact portfolio of renewables varies markedly by region, however, in accordance with available potentials and relative economics. For example, biomass energy is likely to play a more important role in Sub-Saharan Africa and Latin America by 2030 than it is in North America or China. Wind power, in turn, will likely make up a bigger slice of the pie in North America and Europe, while solar power capacity is projected to be the preferred option in the Middle East, Centrally Planned Asia (China), and South Asia (India). The SE4ALL process would do well to appreciate this need for a differentiated regional approach, as it will indeed be fundamental to the achievement of the 30% global renewable target in the most cost-effective manner possible.

Carbon and energy intensity improvements are also likely to vary regionally toward the global goals. For example, whereas our scenarios foresee Sub-Saharan Africa undergoing the most rapid declines in carbon intensity over the next decades, they would at the same time see the lowest rates of energy intensity improvement (Figure 7.4b-c). In other words, energy production in Sub-Saharan Africa would become less carbon-emitting, but would see comparatively slower decreases in the amount of energy consumed per unit of GDP. This owes to the currently rapid growth of population in Africa which increases demand for energy at relatively lower economic productivity. To be sure, economic development in our scenarios is not impaired by the SE4ALL objectives. In fact, GDP growth is projected to remain strong in those parts of the world where it has remained so over the past decade — China, India, and Pacific Asia (e.g., Vietnam, Thailand, Malaysia, etc.). Historical experience shows that energy intensity can drop the quickest during periods of such dramatic growth, owing to rapid turnover of the capital stock and modernization of the economy (Grubler et al., 2012) (historical values in Figure 7.4c). The energy intensity improvements in Asia are thus among the highest among all regions in our modelling framework, a key finding given that the contribution of this region to the fulfilment of the global SE4ALL energy efficiency objective will be critical.

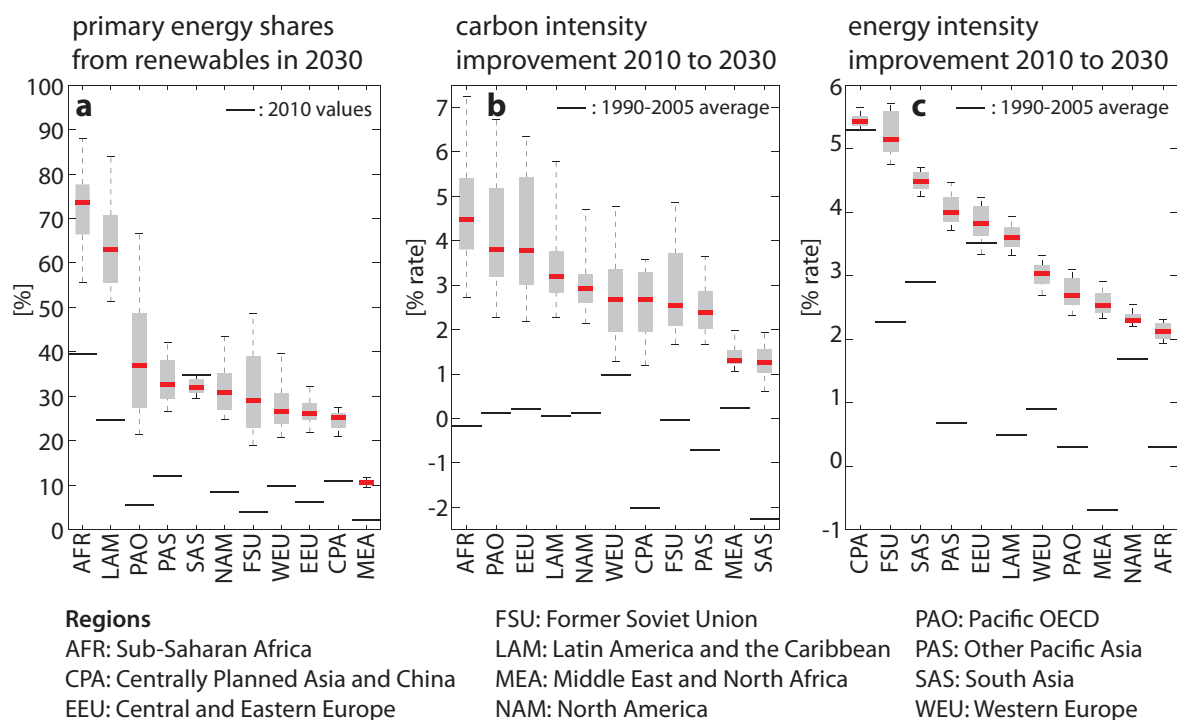


Figure 7.4: Regional differences in energy indicator values in our 2°C consistent scenarios that meet both the energy efficiency and renewable energy SE4ALL objectives. **a**, Primary energy share from renewable energy sources in 2030. Note that TPES of renewables is computed with the direct equivalence method, arguably understating their contributions; **b**, Average regional carbon intensity improvement rates between 2010 and 2030 (in final energy); **c**, Average regional energy intensity improvement rates between 2010 and 2030 (in final energy). Regions are described in detail in Rogelj et al. (2012a). Red lines show median values, grey boxes the 25th to 75th percentile range, whiskers the full range, thick black lines historical values based on data from the International Energy Agency (IEA, 2010) and Boden et al. (2010).

Table 7.1: Overview of global investments in the energy sector in scenarios achieving the SE4ALL renewables and energy intensity objectives.

	Annual energy investments [billion US\$2005/yr]	
	in 2010 average	in 2030 average (minimum-maximum)
Energy efficiency objective	not applicable	357 (322-429) ^a
Renewable energy objective (total)	187	432 (326-572)
<i>Renewable electricity</i>	151	302 (246-357)
<i>Bioenergy extraction and liquid fuels from renewable resources</i>	35	120 (80-215)
Universal access	-	-(36-41) ^b
Total investments in the energy sector in scenarios achieving SE4ALL objectives	966	1620 (1457-1959)
Total investments in entire energy sector in absence of any SE4ALL policies	966	1361
Global GDP in our scenarios	50'265	88'165

^a Additional efficiency-related investments to double energy intensity compared to historical rates of intensity improvement of 1.2%.

^b From Riahi et al. (2012), which only provides a range and no average.

7.8 Investing in a sustainable energy future

The energy efficiency and renewable energy transitions described above will clearly not occur without mobilizing the necessary financial resources. Table 7.1 summarizes the required investments for achieving the three SE4ALL objectives. Meeting the renewables and energy efficiency targets, for instance, would require scaling up average annual investments by 2030 to roughly the same order of magnitude — about US\$430 billion and US\$350 billion per year, respectively. For renewables, this would imply an increase of a factor 2.3 relative to the current level of global investment (Riahi et al., 2012). The energy efficiency figures represent the required demand-side investment and are estimated as the additional investment required to double the energy intensity improvement rate from its historical 1.2% per year level. Finally, estimated annual investments in the range of US\$36-41 billion are required by 2030 in order to ensure universal access to modern energy services (Riahi et al., 2012).

The sum of all investments that work towards achieving the SE4ALL objectives would amount to about half of total investment into the entire global energy system in 2030. While large in absolute terms, as a share of economic output the additional investments required to achieve the three SE4ALL objectives by 2030 would be relatively small: some 0.1 to 0.7% of global GDP over and above investment in the baseline scenario. (For comparison, total energy sector investments in a baseline scenario that assumes no climate action and no increased energy efficiency efforts are projected to amount to roughly US\$1360 billion in 2030.) The increase in total investments is thus by far smaller than the financial requirements for renewables and efficiency. This is so, because investments into these two options reduce the need to invest into other energy options, in particular fossil extraction, supply and conversion technologies.

As noted earlier, sustained investments will also be critically needed in areas outside the scope of the SE4ALL initiative (e.g., deforestation prevention). Moreover, an effective imple-

mentation of the SE4ALL objectives will not necessarily put us on the most cost-optimal path to climate protection; and in terms of who pays for the transformational change required globally, there is still no clear consensus. How the investment burden ought to be distributed over countries and regions is not a scientific or technical question, but rather a political and ethical one.

7.9 Conclusion

We find that concerted achievement of the three SE4ALL objectives could put the world on a path toward global climate protection (Figure 7.3f). Taking into account various uncertainties — some outside the energy field — we find that the SE4ALL objectives could provide multiple sustainability benefits that go hand in hand, such as eradicating poverty, enhancing energy security (McCollum et al., 2011) and public health (McCollum et al., 2011, in press), and kick-starting the process of climate protection.

However, our results also show that using energy indicators like energy intensity as the sole yardstick to measure climate action would be inappropriate, as additional measures are also required and such a strategy could therefore result in unintended, undesirable consequences on the climate protection side. While achieving the SE4ALL objectives in the energy sector would represent an important step toward climate protection, climate action can only be measured and assessed in terms of the effectiveness of policies to actually limit and significantly reduce the absolute amount of greenhouse gases emitted to the atmosphere.

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Chapter 8

Combining short and long-term mitigation efforts to limit global mean warming

Combining short and long-term mitigation efforts to limit global mean warming

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(in preparation)

Note that this version is not yet approved by all contributing authors.

Abstract

Despite intentions to avoid dangerous climate change (UNFCCC, 1992, 2010a), mitigation action for achieving this has been limited (Rogelj et al., 2010b; UNEP, 2011a). To inform policy-makers, the United Nations Environment Programme (UNEP) recently published synthesis reports on three interlinked areas: (a) climate stabilization and greenhouse gas (GHG) mitigation (UNEP, 2011a), (b) short-lived climate forcers (SLCF) and clean-air benefits (UNEP, 2011c; UNEP/WMO, 2011), and (c) hydrofluorocarbons (UNEP, 2011b) (HFCs). Here we integrate their insights to assess their implications for limiting the rate of near-term climate change and for 2020 emission ranges consistent with staying below 2 °C. While HFC emission projections for developing countries may not increase significantly in the short term, they would require mitigation to prevent their influence after 2020. Black carbon (BC) emission reductions allow to a very small degree for higher 2020 levels of Kyoto-GHG emissions in 2 °C-consistent scenarios (~1% of current emissions), and partially offset the warming emerging from sulfur-dioxide emission reductions under a low carbon future and/or stringent air-pollution control. Methane emission reductions are an integral part of 2 °C scenarios, and can temper the rate of near-term temperature change. Due to lock-in and path dependency, also early reductions in long-lived Kyoto-GHGs substantially influence the rate of temperature change. Our results robustly confirm (Myhre et al., 2011; Smith et al., 2012) that early action (i.e. now instead of 2 decades from now) on SLCFs has little influence on the question whether 2 °C warming is exceeded and does not buy time for mitigation of carbon-dioxide (CO₂). However, it can independently limit near-term temperature increase and provide benefits for public health and agriculture.

8.1 Introduction

For about two decades, international policy is discussing options to avoid dangerous anthropogenic interference with the climate system (UNFCCC, 1992, 2010a). So far, the net outcome in terms of mitigation action for achieving this has been limited (Rogelj et al., 2010b; UNEP, 2011a). To inform policy-makers about possible options and challenges related to climate protection, the United Nations Environment Programme (UNEP) recently published several synthesis reports on three interlinked areas: (a) climate stabilization and greenhouse gas (GHG) mitigation (UNEP, 2011a), (b) short-lived climate forcers (UNEP, 2011c; UNEP/WMO, 2011) (SLCFs) and clean-air benefits, and (c) hydrofluorocarbons (UNEP, 2011b) (HFCs). Here we integrate their findings and assess how new projections of HFCs, together with reductions of SLCFs and long-lived GHGs can achieve climate protection. In particular, we look at their implications for limiting the rate of global mean near-term climate change and for 2020 emission ranges consistent with limiting global mean temperature increase to below 2 °C during the 21st century¹. Reductions in SLCFs have also important health and agricultural benefits, which are not further discussed in this analysis.

Each of the UNEP reports published in 2011 looks at climate protection from a different angle. The 'Bridging the Emissions Gap' report (UNEP, 2011a) (henceforth 'Gap Report') presents a re-analysis of the mitigation scenario literature, and an analysis of current real-world pledges by countries. The assessed scenarios represent possible futures which are considered technologically and economically feasible by integrated assessment models (IAMs). The Gap Report groups these scenarios based on their probability to keep global temperature increase to below specific temperature limits, and presents the characteristics of each group, for example, in terms of their emissions in 2020 (Supplementary Figure B.1 in Appendix B). This methodology is re-applied for part of the analysis presented in this study.

The reports 'Integrated Assessment of Black Carbon and Tropospheric Ozone' (UNEP/WMO, 2011) and 'Near-term Climate Protection and Clean Air Benefits' (UNEP, 2011c) (henceforth 'SLCF Reports') assess how reducing emissions of some SLCFs like BC, and tropospheric ozone via methane provide multiple benefits in improving public health, reduce crop-yield losses and slow the rate of near-term climate change. The report on 'HFCs: A Critical Link in Protecting Climate and the Ozone Layer' (UNEP, 2011b) (henceforth 'HFC Report') assesses new projections for HFCs, which take into account increases in HFC emissions due to their use as a replacement for ozone depleting substances controlled under the Montreal Protocol.

The challenge in integrating the findings of these reports is the different nature and interdependence of climate forcers. For example, SLCFs do not all have the same net forcing effect (Table 2.12, from IPCC (2007d)): BC aerosols have an overall warming effect, while sulfate aerosols are cooling. Furthermore, BC is always emitted with a host of other pollutants, including organic carbon (OC), nitrogen oxides (NO_x), carbon-monoxide (CO), non-methane volatile organic compounds (NMVOC), and sulfur-dioxide (SO₂), of which mix and amounts depend on fuel and source type. Since the climate forcing and its sign varies among these species, the net warming outcome of SLCF mitigation is not intuitively explainable, and requires a detailed analysis of the magnitude of often interdependent forcing signals.

¹Supplementary information for this study is available in Appendix B.

In our analysis, we change the assumptions for BC-related SLCFs and applicable GHGs in the original Gap Report scenarios (Rogelj et al., 2011b), based on those presented in the SLCF and HFC Reports (see section 8.4, Table 8.1, Supplementary Figure B.2). With these scenarios we then assess issues related to global mean temperature increase, in particular: (1) how the window for emissions in 2020 consistent with keeping warming below 2 °C is influenced, and (2) which factors constrain the rate of near-term temperature change. It is important to note that measures for reducing methane (which is a Kyoto-GHG, see section 8.4) are included in the portfolios of both the Gap and the SLCF reports. The reference in this study against which all BC-related changes are compared assumes the same reference SLCF emissions (i.e. BC, OC, CO, NO_x, SO₂, NH₃, NMVOC) as in the SLCF Reports (see Case 1 in Table 8.1). For reasons of comparability with the SLCF Reports, we also adopt the arbitrary assumption that SLCF emissions remain at the 2030 level throughout the century in some of our calculations, although such constant emission levels would be inconsistent with the energy consumption levels of climate stabilization scenarios. Our approach therefore only allows for an assessment of the first order effects. A more elaborate approach would involve the creation of a massive new scenario ensemble which varies timing, stringency, and underlying assumptions of interlinked SLCF and Kyoto-GHG emissions.

8.2 Results and discussion

8.2.1 Emissions in 2020 consistent with 2 °C

The Gap Report analyzed which emission scenarios manage to limit warming below 2 °C, and provided information about the ranges of emissions in 2020 that are found in these scenarios. Starting from the original scenario ensemble, which had little to no variation in its SLCF emissions (Rogelj et al., 2011b), we develop a set of cases based on the BC-related SLCF emission trajectories from the SLCF Reports (see section 8.4 and Table 8.1). About 50% of the BC-related SLCF reduction measures can be achieved through measures which result in net cost-savings (Case 2 in this study), while the remainder of measures could be implemented at 'moderate cost' (UNEP, 2011c; Shindell et al., 2012) (Cases 3, 5, and 8 in this study, with 'moderate cost' here <75US\$/tCO₂e, see also section 8.4). Here we take a closer look at whether and by how much these BC-related measures could help easing mitigation requirements of Kyoto-basket GHG emissions by 2020 in line with a likely chance to stay below 2 °C.

In the original scenarios (Rogelj et al., 2011b), the median of Kyoto-basket GHG emissions in 2020 (see section 8.4) consistent with 2 °C with a likely (>66%) chance (Mastrandrea et al., 2010) is 44 billion metric tons of annual carbon-dioxide equivalent emissions (GtCO₂e/yr), with a 15-85 percentile range of 31-46 GtCO₂e/yr (Figure 8.1, and supplementary Figure B.1 and Table B.1). Putting these numbers into context: year 2010 global GHG emissions are estimated at about 50 GtCO₂e/yr with a 95% uncertainty range of about 10% (i.e., ±5 GtCO₂e/yr) surrounding this number (Friedlingstein et al., 2010; Montzka et al., 2011; UNEP, 2012).

By applying the 'reference SLCF' (Case 1) and 'moderate cost' BC-related SLCF measures (Case 3) to our scenarios and comparing the results, the influence on 2020 Kyoto-GHG emis-

Table 8.1: Description of cases analyzed in this study. Cases marked with * contain SO₂ emissions which after 2030 are not consistent with a long-term reduction in carbon-dioxide emissions.

Case number	Case label	Case description
0	Original scenarios	193 scenarios from the integrated assessment modeling (IAM) literature, with harmonized SLCF emissions following RCP3-PD, modified and re-analyzed for this study as described below.
1*	Reference SLCF*	<i>Original scenarios</i> with all SLCF excluding methane substituted by the reference SLCF emissions from the SLCF Reports. This case is used as the reference against which other cases are compared in this study.
2*	BC-related SLCF cost-savings*	<i>Original scenarios</i> with all SLCF excluding methane substituted by the cost-saving mitigation pathway for SLCF emissions from the SLCF Reports. SO ₂ is not reduced below the reference path.
3*	BC-related SLCF moderate cost*	<i>Original scenarios</i> with all SLCF excluding methane substituted by the moderate-cost measure SLCF emissions from the SLCF Reports. SO ₂ is not reduced below the reference path.
4	20 year delayed BC-related SLCF moderate cost	Identical to Case 3, but with BC-related SLCF reductions delayed by 20 year.
5	BC-related SLCF moderate cost and SO ₂ mitigation	Identical to Case 3, and with SO ₂ emissions following the mitigation pathway from the <i>original scenarios</i> .
6	Accelerated BC-related SLCFs with SO ₂ mitigation	Original scenarios with all BC-related SLCF emissions substituted by the moderate-cost mitigation pathway, but only if leading to lower emissions than in the <i>original scenarios</i> .
7	Accelerated BC-related SLCFs with SO ₂ and methane mitigation	Identical to Case 6, with additional accelerated long-term methane mitigation from RCP3-PD.
8*	Enhanced direct BC warming effect*	Identical to Case 3, and with the direct warming effect of BC doubled.

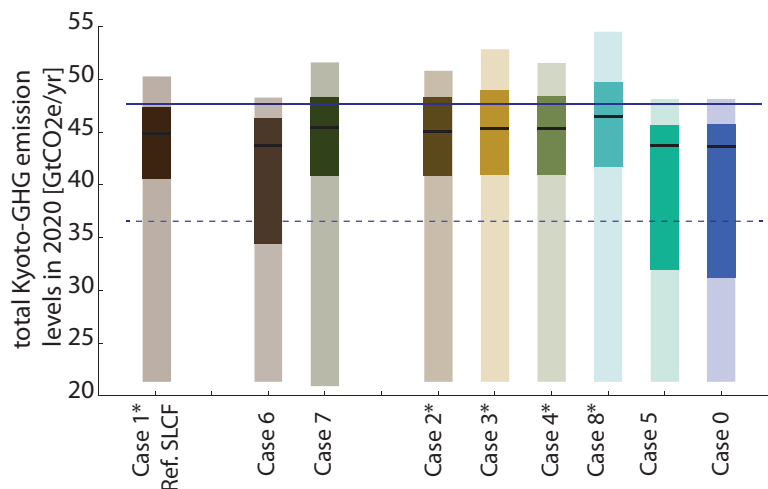


Figure 8.1: Emission ranges of global total Kyoto-GHG emissions in 2020 of scenarios which limit global temperature increase to below 2°C relative to pre-industrial with a likely ($>66\%$) chance. A conceptual illustration of the ranges provided in Supplementary Figure B.1. Thick black lines show median estimates, dark colored boxes 15-85 percentile ranges, and light shaded boxes minimum-maximum ranges. Blue horizontal dashed and solid lines show median 1990 and 2010 emissions, respectively. Case descriptions are given in Table 8.1, numerical values in Supplementary Table B.1.

sion levels of scenarios consistent with 2°C can be assessed. Although incrementally higher 2020 Kyoto-GHG emission levels are allowed when action on BC-related SLCFs is assumed, this change is small (~ 0.5 GtCO₂e/yr) compared to current emissions (Montzka et al., 2011; UNEP, 2012), the uncertainties surrounding these (about ± 5 GtCO₂e/yr) (Friedlingstein et al., 2010; Montzka et al., 2011; UNEP, 2012) and the gap between current pledges by countries and 2°C -consistent pathways (in the order of 10 GtCO₂e/yr) (UNEP, 2012). Finally, implementation of BC-related SLCF measures does not substantially influence the timing of peaking of global Kyoto-GHG emissions in our scenarios consistent with 2°C . Global Kyoto-GHG emissions still peak before 2020 in most cases (Figure 8.1). The latter finding is biased by the setup of the original scenarios (Rogelj et al., 2011b) to mainly look at least-cost pathways over the 21st century (see Rogelj et al. (2012a) for a more elaborate discussion).

8.2.2 BC-related sensitivity analysis

To further explore the influence of BC-related emission reductions on global mean warming, we develop four sensitivity cases (Table 8.1): (a) a 20-year delay case of moderate-cost BC-related emissions (Shindell et al., 2012), (b) a case with SO₂ emission reductions consistent with a low-carbon development path and/or stringent air-pollution controls (van Vuuren et al., 2011b) in addition to the moderate cost BC-related measures, (c) an 'accelerated action' case in which moderate-cost BC-related emission reductions are applied on top of the original emissions (Supplementary Figure B.4), and (d) a case in which we explore the influence of the uncertainty surrounding BC forcing, by amplifying its direct warming effect by two.

We find that about 85% of the effects of the moderate-cost BC-related measures on 2°C -consistent emission levels of Kyoto-GHGs in 2020 is also obtained when BC-related measures

are delayed by 20 years. This is because emission reductions of SLCFs are most effective in terms of limiting maximum global-mean warming around the peak in warming (Smith et al., 2012), which only occurs in the second half of this century at the earliest in 2°C-consistent scenarios.

The original scenarios from the Gap Report had virtually no variation in its SLCF assumptions. The SLCF Reports provide this dimension. However, whereas the SLCF Reports assess a large range of mitigation measures for BC-related emissions, its SLCF scenarios did not include measures beyond 2030 (a constant extrapolation was applied), while their CO₂ scenarios were provided up to 2070 (Shindell et al., 2012). The largest fraction of SO₂ emissions are co-emitted with the burning of fossil fuels. SO₂ emissions are therefore strongly coupled to CO₂ emission reduction strategies, and would decrease significantly in a low-carbon world along with CO₂. A coupling also exists between NO_x and CO₂ emission reductions, although not so strong. By contrast, the coupling with CO₂ reductions is weak for BC-related emissions, as only roughly a third of present-day BC direct forcing is fossil-fuel related (Bond et al., 2013), while another third is linked to biofuel burning (Bond et al., 2013) that can also be expected to be replaced by modern energy sources in a low-carbon scenario in the long term (Riahi et al., 2012; McCollum et al., in press), or any scenario that projects access of the rural poor to modern forms of energy (electricity or LPG) for poverty eradication at some point in the future (Pachauri et al., 2012) (see also Supplementary Figure B.9).

Alternatively, even in a scenario with high CO₂ emissions, both SO₂ and BC-related emissions can be reduced importantly by end-of-pipe technologies or other measures induced by air-pollution control policies (Riahi et al., 2011). Historical emission inventories provide us with real-world illustrations of this possibility. For example, the historical decoupling observed between rising CO₂ and declining SO₂ emissions in Western Europe and North America since the 1970s (Stern, 2005; RCP Database, 2009; Smith et al., 2011), and the recent stabilization and possibly marked decline in SO₂ emissions in China (Granier et al., 2011; Klimont et al., 2013) despite their steeply increasing CO₂ emissions up to 2011.

SO₂ emissions result in a cooling effect on the climate, but also contribute to the formation of acid rain and have adverse local public health effects by forming secondary aerosols, in particular regarding the respiratory system (Sandstrom, 1995) and birth outcomes (Shah et al., 2011). Local public-health concerns can therefore also be a driver for policies aiming at further reducing SO₂ emissions. We find that the short-term climatic cooling benefit obtained by lower BC-related emissions could offset some, but not all, of the short-term unmasking of GHG warming by reduced SO₂ emissions due to air-pollution control policies and/or CO₂ mitigation (required to stabilize the climate over the medium to long term; Case 5 in Supplementary Table B.1 and Figure 8.1). Note that based on the same argumentation the exercise above could be repeated with NO_x emissions. However, given their current estimated forcing is a factor 4 smaller than the SO₂ forcing (IPCC, 2007d), we are confident that our sensitivity cases with SO₂ mitigation illustrate the main effect.

The SLCF Reports did not explore BC emissions changes after 2030. As we analyze emission scenarios over the entire 21st century, we also explore the effect of continuing action on these species beyond 2030. Our 'accelerated action' sensitivity cases (numbers 6 and 7 in Table 8.1) therefore apply the moderate cost BC-related emission reductions on top of the overall low SLCF trajectories in the original scenarios (Case 0, effectively accelerating the re-

duction of these species by a few decades and continuing reduction post-2030, Supplementary Figure B.4). Assuming lower SO₂ emissions consistent with stringent action on CO₂ and/or stringent air-pollution control policies (see earlier), these 'accelerated action' scenarios do not show a net influence on emission levels of Kyoto-GHG in 2020 that are consistent with staying below 2 °C (Figure 8.1, Supplementary Table B.4).

Our climate model setup is consistent with the uncertainty assessment of the IPCC AR4 report (IPCC, 2007d) (see section 8.4). However, large uncertainties remain, and recent assessments (Bond et al., 2013) suggest a 50% higher direct forcing effect of BC and a higher total forcing of BC (not explicitly provided in the IPCC AR4). In line with the SLCF Reports and recent assessments, we explore the influence of an amplification of the direct forcing effect of BC by a factor of two (all other effects kept the same). We find that these simple sensitivity assumptions would allow for a median increase of the 2020 range of GHG emissions in line with 2 °C (>66% probability) of approximately 1 GtCO₂e/yr. This still implies that the peak in most pathways consistent with 2 °C remains before 2020 in scenarios that minimize mitigation costs over the 21st century.

8.2.3 The temperature impact of methane

The scenarios included in the original analysis of the Gap Report assume a very wide range of methane emissions (Supplementary Figure B.2, panel A). However, only those assuming strong methane mitigation action throughout the century are able to stay below 2 °C (Supplementary Figure B.3). The SLCF Reports did not explore methane emission changes after 2030, and instead kept emissions constant. Therefore, even their 'Reference' case is much lower than a baseline with unmitigated, increasing methane emissions during the 21st century (Supplementary Figure B.2, panel A). Lowering emissions from a high baseline to the SLCFs Report's 'Reference' (with constant extrapolated post-2030 values) lowers temperatures by about 0.3 °C from a global-mean warming of about 5.5 °C above preindustrial due to all forcers. Assuming the methane mitigation potential from the SLCF reports throughout the century could lower these with an additional 0.2 °C. The methane emission levels resulting from these measures are then in line with the family of the 2 °C-consistent scenarios from our set (yellow range in Supplementary Figures B.2, panel A, and B.3). While these measures thus form an integral part of stringent 2 °C scenarios in our set, limiting warming to below 2 °C will only be achieved together with strong mitigation action on long-lived GHGs, particularly CO₂. Reducing methane can however help hedging against the risk that the CO₂ mitigation potential in the long term would be lower than current best estimates (Rogelj et al., 2012a).

8.2.4 Rate of temperature change

Reducing SLCFs can slow the near-term rate of climate change (Shindell et al., 2012). Here we assess the influence of BC-related SLCF measures, methane, and other Kyoto-GHG mitigation on the near-term rate of temperature change (see Figure 8.2). We assess both the change in rate of temperature increase in the 2010-2030 and in the 2010-2050 period.

We find that during the 2010-2030 period, BC-related SLCFs measures can cancel out the temperature increase resulting from SO₂ co-control due to CO₂ reduction measures in line with

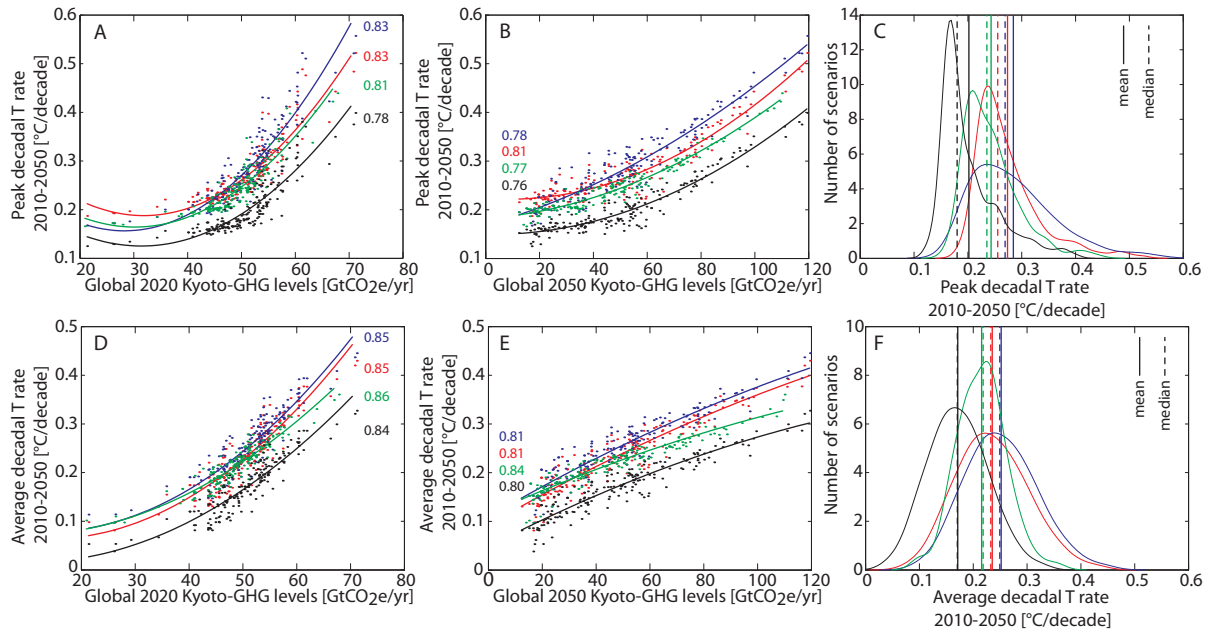


Figure 8.2: Influence of short and long-lived forciers on near-term rates of temperature change. Peak (A,B) and average (D,E) decadal rate of temperature increase between 2010 and 2050 as a function of to the level of total Kyoto-basket greenhouse gas (GHG) emissions in the year 2020 and 2050, respectively. Frequency distributions of peak (C) and average (F) rates of temperature increase between 2010 and 2050, together with mean and median estimates over the entire ensemble (vertical solid and dashed lines). Cases 1, 6, 7, and 8 defined in Table 1 of the main text are color-coded in red, blue, green, and black, respectively. Solid lines in panels A-D are quadratic fits for each case. Numbers in panels A, B, D, and E are R^2 values for the respective fits.

a 2 °C limit and air-pollution policies. Therefore, median peak and average decadal rates of temperature change between 2010 and 2030 are only reduced by about 0.01 °C/decade between our Case 1 and Case 6. Moreover, for the 2010-2050 period this effect is reversed and BC-related SLCF measures do not provide enough cooling to counteract the effect of decreased SO₂ emissions. Note that this case is mainly academic, as the effect of reducing CO₂ emissions was not included in the number above (see below).

These shifts in temperature rates are smaller than anticipated from earlier studies (Shindell et al., 2012) because (1) we here account for a larger unmasking effect of CO₂ warming due to a lower SO₂ emission path (see earlier), and (2) our BC-related forcing is relatively small compared to the one used in the SLCF Reports. In the sensitivity case where the direct BC warming effect is doubled, both peak and average rates of temperature change are reduced by an additional 0.04 °C/decade.

Methane reductions are generally included in the reductions of both Kyoto-GHG and SLCFs, and play an important role in tempering the rate of near-term temperature change. In most mitigation scenarios from the literature, stringent action on methane is taken together with stringent action on CO₂ (Weyant et al., 2006). However, for clarity we here assess the influence of reducing emissions from methane and the other Kyoto-GHG (excluding methane) separately.

Reducing methane emission in 2030 from their reference level to a level consistent with the mitigation measures assessed in the SLCF Reports (see Supplementary Figure B.2, panel A), shows a clear tempering effect on the rate of temperature rise. In the 2010-2030 period, peak and average rates of temperature change are reduced by 0.02 and 0.03 °C/decade, respectively. In the 2010-2050 period, these reductions amounts to 0.02 and 0.04 °C/decade, respectively.

Not only BC-related SLCF and methane emission reductions influence the near-term rate of temperature change until 2050. From our large scenario set, we find that changes in Kyoto-GHG emission levels in 2050 (independent from methane and BC-related SLCFs), also have a robust, and possibly even larger effect on both peak and average rates of temperature change from 2010 to 2050.

The range of Kyoto-GHG emissions scenarios in our ensemble is very large, however, with changes during the 2010 to 2050 period ranging from a 70% decrease to a more 150% increase (Supplementary Figure B.1). Over these same 40 years, BC reductions range from about 5% (Case 1) to 50% (Case 3). The magnitude of such changes is comparable, however, when looking at the costs to bring them about per tCO_{2e}. The above-mentioned BC reductions are implemented at a marginal cost of <75US\$/tCO_{2e} (note that this cost metric is derived assuming a global average forcing as proxy basis for comparing the strongly spatially heterogeneous BC effects with long-lived GHGs following Bond and Sun (2005), and that the uncertainty in BC forcing (Bond et al., 2013) has an important effect on this marginal cost, see section 8.4). With the same marginal cost range, Kyoto-GHG emissions in 2050 can increase by about 110% or decrease by about 70% relative to 2010, taking into account a full portfolio of mitigation technologies and a range of energy efficiency improvements (Rogelj et al., 2013b). For reasons of consistency, we therefore limit the discussion below to the ranges of Kyoto-GHG emissions described above (39-61 GtCO_{2e}/yr in 2020, and 16-101 GtCO_{2e}/yr in 2050), as a first order proxy for a comparable range.

Depending on 2050 Kyoto-GHG emission levels within the above-defined comparable range but with methane emissions not allowed to change, both average and peak rates of temperature change between 2010 and 2050 vary by 0.16 °C/decade, an influence several times larger than the maximum BC-related SLCF and methane influence with measures of comparable cost (Figure 8.2 panels B and E). Due to the long life-time of Kyoto-GHGs (excluding methane) this influence is less for the temperature rate between 2010 and 2030, with average and peak rates of temperature change varying by 0.07 and 0.09 °C/decade, respectively.

For each 10 GtCO_{2e}/yr reduction of Kyoto-GHG emissions excluding methane in 2050 (starting from the high-end of our comparable range), both average and peak rates of temperature change between 2010 and 2050 decline by about 0.02 °C/decade.

Because of path dependency due to lock-in of carbon-intensive infrastructure and limits to attainable emission reduction rates (Rogelj et al., 2012a), 2020 Kyoto-GHG emission levels are also informative about emissions paths until 2050 (Meinshausen et al., 2009; Rogelj et al., 2011b). Therefore, we also find strong correlations between 2020 Kyoto-GHG emission levels and rates of temperature change. For instance, limiting Kyoto-GHG emissions in 2020 from their estimated baseline emissions (about 58 GtCO_{2e}/yr; UNEP (2012)) to levels consistent with 2 °C (about 44 GtCO_{2e}/yr; UNEP (2012)) by exclusively reducing non-methane Kyoto-GHGs reduces both average and peak rates of temperature change between 2010 and 2050 by about 0.1 °C/decade.

The marked influence of both SLCFs and Kyoto-GHG mitigation on the rate of temperature change calls for attention. Accelerating short-term action on SLCFs and methane (see Table 8.1, Case 7, 'accelerated BC-related SLCFs with SO₂ and methane mitigation') has the potential to reduce peak rates of near-term temperature change in our scenarios by 0.05 and 0.02 °C/decade during the 2010-2030 and 2010-2050 period, respectively. At the same time, total Kyoto-GHG emissions rising — due to GHGs other than methane — until 55 GtCO₂e/yr by 2020 (or stabilizing at 50 GtCO₂e/yr) instead of decreasing to 45 GtCO₂e/yr, would point towards a relative increase of these rates by 0.04 (0.02) °C/decade between 2010 and 2030, and by 0.06 (0.04) °C/decade between 2010 and 2050, and thus offset the decrease in rate of temperature change by BC-related SLCFs and methane. Higher 2020 Kyoto-GHG emissions would also be more consistent with a higher absolute temperature increase over the entire 21st century.

In summary, both accelerated action on BC-related SLCFs and mitigation of methane and other Kyoto-GHGs influences the rate of near-term temperature change. These results show the joint benefits both BC-related and Kyoto-GHG mitigation can achieve in terms of global mean warming, but also highlights an important pitfall. If accelerated short-term action on both BC-related SLCFs and methane would come at the expense of rapid reductions of other Kyoto-GHGs (like CO₂), the aim of limiting the near-term rate of temperature change between 2010 and 2030 might well be unsuccessful, and rates until 2050 could be higher overall. Conversely, failure to address methane and BC-related emissions in the near-term could lead to accelerated short-term warming and millions of preventable deaths from poor air quality.

8.2.5 Long term importance of new HFC projections

A connection to the HFC Report remains the only missing link in this exercise. The projected increase in HFC emissions is primarily due to their increasing use as replacements for ozone-depleting substances. Post-2020 HFC emissions are projected to grow, especially in countries with emerging economies and increasing populations (UNEP, 2011b). They will have, if not abated, a noticeable influence on the climate system (UNEP, 2011b). Three studies (TEAP, 2009; Velders et al., 2009; Gschrey et al., 2011) provide updated projections for HFCs. To quantify the impact of the upper literature range, we here use the highest available estimates (Velders et al., 2009) (Supplementary Figure B.10).

HFCs are part of the Kyoto-GHG basket (see section 8.4). Therefore, when emission reduction proposals are defined relative to a fixed historical base year — as put forth by developed countries (UNFCCC, 2010a) — their total future emissions are effectively limited to an absolute value. Higher projections of HFCs for developed countries will hence imply stronger mitigation efforts in developed countries but should, given a robust international emission accounting framework, not result in an increase in absolute GHG emissions.

However, the most pronounced increase in HFC emissions is projected in developing countries (UNEP, 2011b; Velders et al., 2012). Developing countries provide their GHG emission reduction pledges not relative to a fixed base year, but relative to projected future emissions (UNFCCC, 2010a). These 'no climate policy' baselines will increase in line with higher HFC projections and therefore the stringency and absolute level of developed country pledges would change without balancing repercussions elsewhere. If developing countries would update their

baseline HFC projections from earlier (Nakicenovic and Swart, 2000) to the new estimates (Velders et al., 2009; UNEP, 2011b), this would increase the aggregate baseline emissions of developing countries in 2020 by 0.3 to 0.4 GtCO₂e/yr.

The impact on keeping mitigation action by 2020 in line with 2 °C is therefore limited. However, as HFC emissions in developing countries could increase more than tenfold from 2020 levels by 2050 in our upper range scenario (Velders et al., 2009), sustained mitigation of these species is required to minimize their influence on global warming. If the projected increase in HFC emissions in developing countries is not abated, temperatures are projected to increase an additional 0.1-0.3 °C (for the range of emissions in Velders et al. (2009), representing the high end of the literature, see Supplementary Figure B.10) and only four scenarios remain below 2 °C (with >66% chance) compared to 26 in the original set.

8.3 Conclusions

Our study shows that mitigation measures for BC-related emissions influence the window for Kyoto-GHG emissions in the year 2020 that would be consistent with 2 °C limit only to a very limited degree. Average global emissions of Kyoto-GHGs in our 'ensemble of opportunity' (Tebaldi and Knutti, 2007) still peak and embark on a downward trajectory by 2020, under all BC-related SLCF scenarios assessed here. Consistent with earlier literature (Berntsen et al., 2010; Myhre et al., 2011; Smith et al., 2012), the timescales of the climate system, and the inertia of global CO₂-emitting energy infrastructure (Davis et al., 2010), our results indicate that mitigation of long-lived GHGs, like CO₂, cannot be traded for mitigation on BC-related SLCFs when global temperature increase is to be limited to below 2 °C in the long run. An early timing of BC-related emissions reductions, as well as methane reductions in absence of stringent CO₂ mitigation, is relatively unimportant for the question whether 2 °C warming is exceeded during this century, because phasing in these emission reductions early versus late has little effect on the temperature peak value. To keep global mean temperature increase to below 2 °C in the long term, stringent and sustained reductions of long-lived GHG emissions, in particular CO₂, remain the first and most crucial climate protection strategy.

Complementing reductions of long-lived GHGs with reductions in BC-related SLCF and methane emissions will have local public-health benefits, influence crop yields, and can further reduce the rate of near-term warming. These near-term benefits are additional to the benefits of reducing CO₂ emissions only. However, reductions in the rate of near-term warming resulting from actions on SLCFs could be cancelled out by the effect of not substantially reducing Kyoto-GHG emissions by 2050. Our results show that SLCF mitigation does not buy time for actions on CO₂ and other long-lived GHGs.

Integrated assessment modeling exercises looking further into the multiple benefits of joint short and long-lived forcer mitigation, including the preferred mitigation timing windows for each of these respective forcings and the interactions between them, would be an area of important further research and could provide timely, and highly policy-relevant insights.

8.4 Methods and materials

We use the original scenario ensemble (Rogelj et al., 2011b) and the reduced-complexity carbon-cycle and climate model MAGICC (Meinshausen et al., 2011a,b) in a probabilistic setup (Meinshausen et al., 2009) updated such that the marginal climate sensitivity distribution is consistent with the IPCC AR4 findings (Rogelj et al., 2012b). In our discussion we distinguish between methane and other SLCFs (aerosols). The 'other SLCF' group refers to BC-related measures and their impacts on co-emitted species, such as CO, BC, OC, NO_x, and NMVOC. We modify the emissions for methane and other SLCFs in the original scenarios, consistent with the SLCF Reports' '450 scenario' cases. Originally, SLCF emissions were from RCP3-PD (van Vuuren et al., 2011b). The SLCF reports provide estimates for all sectors excluding savannah and forest burning, and international transport. The latter contributions were taken from RCP3-PD. For each multi-gas pathway, the probability of limiting temperature increase to below 2 °C relative to pre-industrial (1850-1875) is computed by computing a probabilistic set of 600 ensemble members. The used setup is closely in line with historical radiative forcing (RF) uncertainty estimates of the IPCC AR4 (Table 2.12 in IPCC (2007d), and Supplementary Figure B.7), but does not contain an as sophisticated implementation of aerosol interactions and indirect forcing effects as global composition-climate models (GCMs), for example, sulfate-aerosol formation being dependent on the tropospheric oxidation capacity in the NASA-GISS model (Shindell et al., 2006).

Checking consistency, we find that total RF changes simulated by MAGICC are broadly consistent with, yet smaller than, those of the NASA-GISS model (Supplementary Figure B.8). Important differences in historical BC and OC forcing assumptions partially explain this difference (Supplementary Figure B.7). The median direct BC and OC RF in 2005 in our model, consistent with the IPCC AR4, is only about 50% and 75% of the RF applied in the NASA-GISS model (UNEP, 2011c), respectively. Some recent observations might lower earlier model-based estimates (Cappa et al., 2012), while others suggest that values should be even larger (Chung et al., 2012; Bond et al., 2013). These discrepancies illustrate the uncertainty surrounding SLCFs, particularly their RF. While the BC forcing assumed in our central case is in the lower range suggested by recent assessments (Bond et al., 2013), we address this RF uncertainty with a dedicated sensitivity case with higher BC forcing.

Costs for reducing BC emissions in terms of US\$/tCO₂e are also influenced by the forcing uncertainty and hinge on the assumption that spatially heterogeneous and short-lived effects are comparable to the more spatially homogeneous and long-lived effects. The SLCF reports used estimates for conversion factors which only included the direct BC forcing effect (Bond and Sun, 2005). Recent estimates that include all BC forcing effects (Bond et al., 2013) would shift the 'moderate cost' threshold value of <75 US\$/tCO₂e to <56 US\$/tCO₂e, with an uncertainty range of 28 to 425.

The influence of updated HFC projections is modeled under the conservative hypothesis that baseline projections in developing countries are adjusted so that no additional absolute emission reductions would be necessary despite the higher projections. This is achieved by computing the difference between the old (Nakicenovic and Swart, 2000) and new (Velders et al., 2009) 'A1' baseline projections, and adding this difference to the scenarios from the original set (Rogelj et al., 2011b), starting from zero in 2010, increasing linearly to the full difference

in 2015, and keeping emissions constant after the last data point. Developed and developing countries are grouped following the UNFCCC Annex I/non-Annex I split. Our approach does not assess how developing countries may actually cope with the increased projections in the real world. For HFC-23 (emitted during the production of HCFCs) no new projections were computed (Velders et al., 2009).

The Kyoto-GHG basket is defined in Annex A to the Kyoto Protocol (UNFCCC, 1997a) and contains carbon-dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆). NF₃ is not included in our calculations. Contributions are combined using 100-year global warming potentials from the IPCC (IPCC, 2007d), consistent with UNFCCC 2002 reporting guidelines (UNFCCC, 2002).

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Author Contributions J.R., M.S., D.S., and W.H. designed the research; M.M. developed the setup of the MAGICC model; J.R. carried out the research, performed and further improved the analysis in close collaboration with M.S., D.S., and M.M.; all authors contributed to writing the paper.

Chapter 9

Probabilistic cost estimates for climate change mitigation

Probabilistic cost estimates for climate change mitigation

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Abstract

Not part of the final submission

Limiting climate change requires global action under deep uncertainty, ranging from the geophysical uncertainties of the Earth system's response to greenhouse gases (GHG), to uncertainties of technological, social, and political nature. The interplay of these factors and their relative importance is only poorly understood or quantified. In a probabilistic analysis, we use a detailed modeling framework with a technology-rich representation of GHG-emitting sectors, and explore the implications of these uncertainties for the costs to stay below various temperature limits, like 2 °C. We quantify probabilistic relationships between the risks of exceeding temperature limits and the mitigation costs required to reduce these risks. We find that political choices that delay mitigation have the largest effect on the cost-risk distribution, followed by geophysical, future energy demand, and mitigation technology uncertainties.

9.1 Introduction

For more than a decade, the target of keeping global warming to below 2 °C has captured the international climate debate (Randalls, 2010). In response, the scientific community has published a number of scenario studies that estimate the costs of achieving such a target (Clarke et al., 2009; O'Neill et al., 2009; Edenhofer et al., 2010; UNEP, 2011a). Producing these estimates remains a challenge, particularly because of relatively well-known, but poorly-quantified uncertainties, and owing to limited integration of scientific knowledge across disciplines (IPCC, 2007b). The integrated assessment community, on one side, has extensively assessed the influence of technological and socio-economic uncertainties on low-carbon scenarios and associated costs (Clarke et al., 2009; Edenhofer et al., 2010; Riahi et al., 2012; UNEP, 2011a). The climate modelling community, on the other side, has spent years improving their understanding of the geophysical response of the Earth system to emissions of greenhouse gases (Meehl et al., 2005; Friedlingstein et al., 2006; Meehl et al., 2007; Archer et al., 2009; Meinshausen et al., 2011b) (GHG). This geophysical response remains a key uncertainty for the cost of mitigation scenarios but has only been integrated with assessments of other uncertainties in a rudimentary manner, i.e., for equilibrium conditions (IPCC, 2007b; Schaeffer et al., 2008). Here, we bridge this gap between the two research communities by generating distributions of the costs associated with limiting transient global temperature increase to below specific temperature limits, taking into account uncertainties in four dimensions: geophysical, technological, social and political. We find that political choices that delay mitigation have the largest effect on the cost-risk distribution, followed by geophysical uncertainties, social factors influencing future energy demand, and mitigation technology uncertainties. Our information on temperature risk and mitigation costs provides crucial information for policy making, since it helps to understand the relative importance of mitigation costs, energy demand, and the timing of global action to reducing the risk of exceeding 2 °C, or other temperature limits like 3 °C or 1.5 °C, across a wide range of scenarios.

We generate cost distributions by combining mitigation cost estimates of emissions scenarios with probabilistic temperature projections. Importantly, our cost estimates do not account for any avoided climate damages as a result of emission reductions. This information is obtained from a large set of scenarios created with an integrated assessment model (Rao and Riahi, 2006; Riahi et al., 2007) (IAM), for which the temperature increase has been computed with a probabilistic climate model (Meinshausen et al., 2011a,b; Rogelj et al., 2012b) (Figure 9.1 and Supplementary Figure 1, Methods and Supplementary Information¹ — SI). Each modelling framework has inherent limitations. For example, while incorporating state-of-the-art uncertainty quantifications of the Earth system, tipping points remain underexplored in our model, and similarly our energy-economic emissions scenarios map a wide range of possible futures (Supplementary Figures 7 and 8), but are not exhaustive of all potential outcomes (for a discussion see SI).

¹Supplementary online information is available at: <http://www.nature.com/nature/journal/v493/n7430/extref/nature11787-s1.pdf>. A dedicated spreadsheet tool to query the results of this study has been made available at: <http://www.nature.com/nature/journal/v493/n7430/extref/nature11787-s2.xlsx>

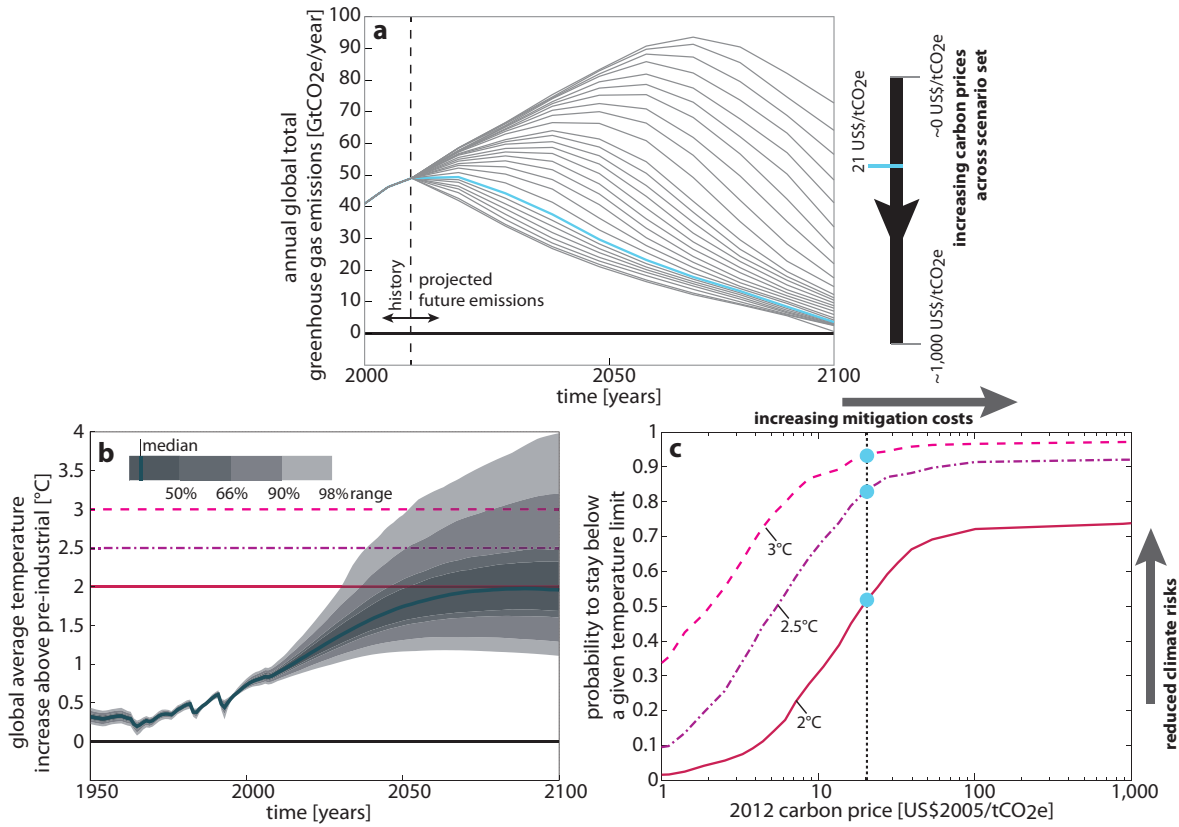


Figure 9.1: Methodology for creating cost-risk relationships for a given temperature limit. **a**, Illustrative set of emission scenarios with carbon prices increasing from 0 to 1000 US\$/tCO₂e. The arrow indicates the direction of increasing carbon prices across the illustrative set. The highlighted scenario has a global carbon price discounted back to 2012 of 21 US\$/tCO₂e; **b**, Probabilistic temperature projections for the light-blue trajectory in panel **a**. Horizontal lines at 2, 2.5, and 3°C show possible target temperature limits. In this illustrative scenario, median (50% probability) warming is 2.0°C. A slim (<5%) chance exists that temperatures remain below 1.3°C, and a large (>90%) that they remain below 3.0°C; **c**, Cumulative distributions of carbon prices consistent with limiting warming to below 2, 2.5, and 3°C, respectively. Light-blue dots indicate points defined by the cost information of the scenario highlighted in panel **a** and the probabilistic temperature projection in panel **b**.

9.2 Results and discussion

Temperature projections for any given pathway have a spread due to geophysical uncertainties (Figure 9.1b, (Knutti et al., 2008)). In the absence of any serious mitigation efforts (global carbon prices <1 US\$ per metric tonne of carbon-dioxide-equivalent emissions — US\$/tCO₂e), the likelihood of limiting warming to below 2 °C is essentially nil ($<1\%$, Figure 9.1c). However, imposing a carbon price of about 20 US\$/tCO₂e in our model would increase the probability of staying below 2 °C to about 50%, while carbon prices of >40 US\$/tCO₂e would achieve the 2 °C objective with a $>66\%$ chance ('likely' by the IPCC's definition (Mastrandrea et al., 2010)). Similar trends hold for other cost metrics (see SI). For example, a carbon price of 20-40 US\$/tCO₂e translates in our model to cumulative mitigation costs (2012-2100; discounted) on the order of 0.8-1.3% of gross world product of 0.8-1.3% (Supplementary Figure 10).

A marked feature of the mitigation cost distribution (Figure 9.2) is that the 2 °C probability levels-off at high carbon prices. This occurs because beyond a given carbon price, nearly all mitigation options that can significantly influence emissions in the medium term have been deployed in our model. Higher carbon prices help further reduce emissions later in the century, but only affect temperatures after peaking (Smith et al., 2012). Hence, the probability of staying below 2 °C during the 21st century reaches an asymptote.

Geophysical uncertainties shed light on only one dimension of mitigation costs, however. To gain insight on how assumptions regarding technological and social uncertainties influence our cost distribution, we create a large set of sensitivity cases (Table 9.1), in which we vary some salient features of the scenarios, namely (a) the availability and use of specific mitigation technologies, (b) future social development and, by extension, global energy demand, and (c) the international political context surrounding climate mitigation action, specifically delays in the implementation of a globally-comprehensive mitigation response (see Riahi et al. (2012)) and SI). Note that population and economic growth do not vary in our scenarios; we therefore cannot assess their relative importance with our ensemble (see SI for further discussion). Given its policy relevance (UNFCCC, 2010a), we focus most of our discussion on 2 °C (Supplementary Figures 4 and 5 illustrate the results for 2.5 and 3 °C, respectively).

Our results can be framed in two ways (Figure 9.2): first, in terms of how probabilities for achieving the 2 °C objective change for a fixed cost (black arrows), and second, in terms of how the cost consistent with the 2 °C goal varies for a given probability level (orange arrows). Whether or not a carbon price of about 40 US\$/tCO₂e restricts global warming to less than 2 °C with $>66\%$ likelihood depends on the future availability of key mitigation technologies (Figure 9.2a). In our worst-case technology sensitivity assumption — where capture and geological storage of carbon (CCS) is entirely unavailable — the probability of staying below 2 °C at a carbon price of 40 US\$/tCO₂e decreases to around 50%. On the other hand, with no such constraints and further breakthroughs in the technology portfolio (Table 9.1), the likelihood of limiting warming to 2 °C could be higher than 66% at the same carbon price.

The cost distributions also show how changes in the technology portfolio affect the economics of mitigation given a fixed probability level. For example, in most cases the 2 °C objective can be achieved with $>66\%$ probability as long as the carbon price is high enough (Figure 9.2a). There are certain instances, however, where the unavailability of mitigation options (such as renewable technologies, nuclear power, or limited biomass and afforestation

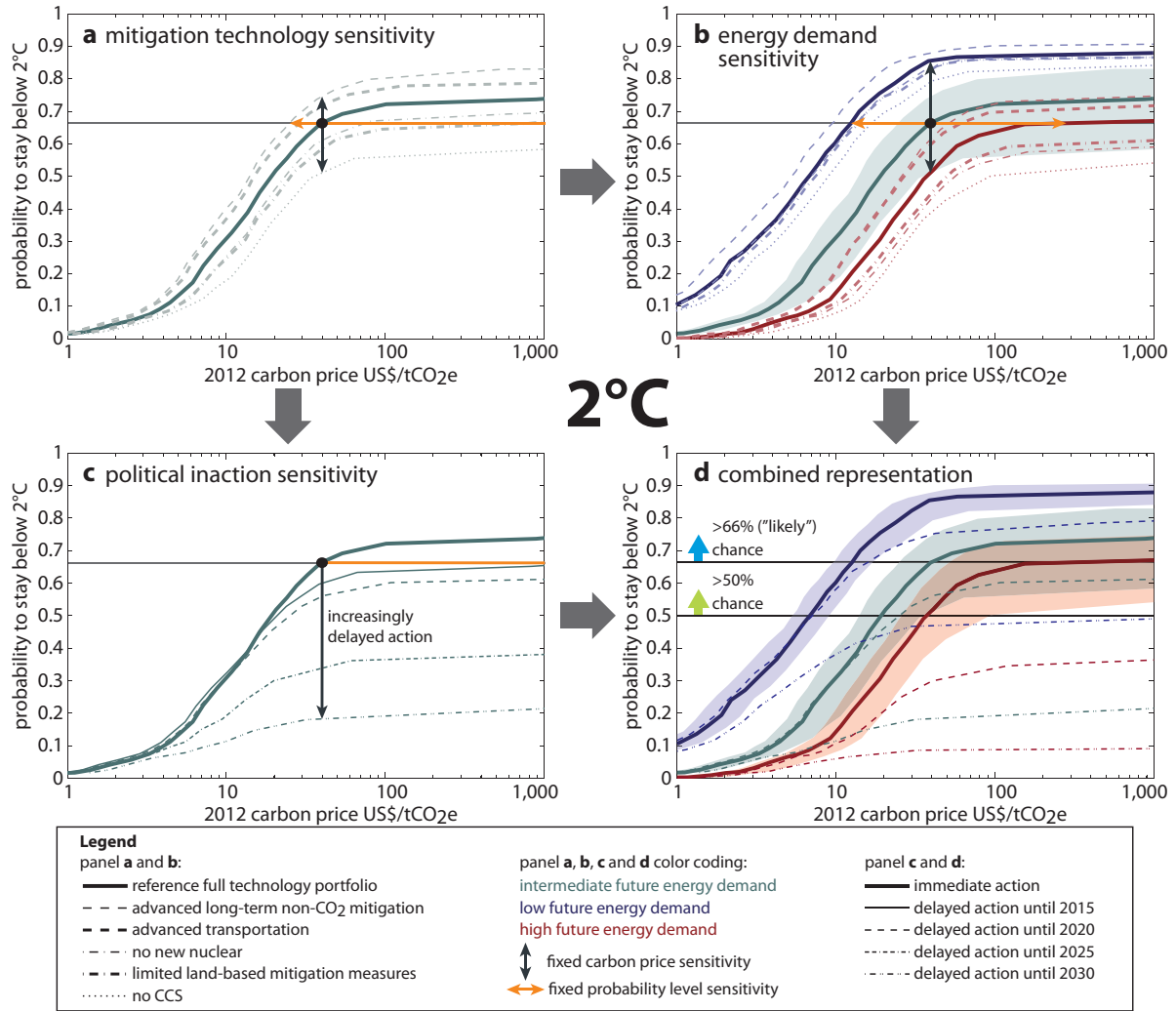


Figure 9.2: Analysis of influence of mitigation technology availability, energy demand, and political inaction on the mitigation cost distribution for staying below 2°C. Cost distributions for six cases with varying future availability of specific mitigation technologies (panel a), and three sensitivity cases for future energy demand (panel b, thick solid lines). Shaded areas and dashed lines in panel b (d) represent technology (technology and political) sensitivity cases comparable to those shown in panel a (a and b); c, Illustration of the impact of delayed global mitigation action; d, Overview figure combining all sensitivity cases. The horizontal line in panels a-c is the 66% line. Similar figures for 2.5 and 3°C are provided in Supplementary Figures 4 and 5. A comparison to 91 scenarios from the literature (Clarke et al., 2009) is provided in Supplementary Figure 7.

Table 9.1: Overview of sensitivity cases. Detailed descriptions and background are provided in Supplementary Information and Riahi et al. (2012).

Mitigation technology sensitivity cases	
<i>Technological limits</i>	
No new nuclear	From 2020 onwards, no new investments are made into nuclear power, leading to a full phase-out of existing plants by 2060.
Limited land-based measures	The mitigation potential from biomass, land use and forestry is limited.
No CCS	Technology to capture and geologically store CO ₂ (CCS) from fossil fuel and/or biomass energy never becomes available at a globally significant scale.
<i>Technological breakthroughs</i>	
Advanced transportation	Fundamental changes in transportation infrastructures (e.g., for electric transport) or major breakthroughs in transportation technology (e.g., in hydrogen fuel cells) lead to increased decarbonization of the transportation sector.
Advanced non-CO ₂ mitigation	The mitigation potential of non-CO ₂ greenhouse gases is assumed to improve continuously, beyond the level of current best practice.
Energy demand sensitivity cases	
Intermediate demand	The development of energy demand and efficiency improvements is broadly consistent with (only slightly faster than) what is observed historically.
High demand	Energy efficiency improves slower than historically observed, leading to a high future energy demand.
Low demand	Energy efficiency improves radically in all end-use sectors (buildings, industry, transport) leading to low future energy demand.
Political inaction sensitivity cases	
Delayed action	Globally concerted mitigation action is postponed from today until 2015, 2020, 2025, and 2030, respectively.

potential) could require substantially higher carbon prices in order to keep the same target in play. At the limit is CCS: the wholesale elimination of this mitigation option — either for technological reasons or due to social and political concerns — would put the 2 °C objective (with >66% probability) out of reach in our model, no matter how high the carbon price.

The future availability of energy supply technologies (e.g., renewables, CCS) tells only one side of the story; a strong finding from our analysis is that social developments influencing energy demand (i.e., efficiency of energy use) are even more important. This is evidenced in Figure 9.2b by the differences between three distinct scenario families whose future energy demands vary greatly (low, intermediate and high; see Table 9.1 and Riahi et al. (2012) for details). In the low demand scenarios, end-use efficiency measures and conservation-minded energy and urban planning policies are instituted ubiquitously throughout the industrial, buildings, and transportation sectors in all countries. This leads to global energy demand in 2050 that is about 25% lower than in our intermediate baseline, which broadly applies historical patterns of efficiency improvement (Riahi et al., 2012). Such demand reductions could play a crucial role in keeping the 2 °C objective in play, independent of what happens on the energy supply side.

For example, in our scenarios the availability of nuclear power has an almost negligible effect on overall mitigation costs compared to a switch from an intermediate to a high energy-demand scenario. Low-demand strategies would ensure a higher likelihood of staying below 2 °C for the same carbon price (from 66% to >80% likelihood at 40 US\$/tCO_{2e}), or viewed in a different way, would dramatically reduce the cost of reaching the 'likely' (Mastrandrea et al., 2010) probability level (from 40 US\$/tCO_{2e} to around 10-15 US\$/tCO_{2e}). In stark contrast, a high energy-demand future — about 20% greater in 2050 than in the intermediate baseline, resulting from more energy-intensive lifestyles and less efficiency and conservation-focused policies — would require far higher carbon prices (>150 US\$/tCO_{2e}) and make it far less likely, if not impossible, to reach the 2 °C objective with a >66% chance.

Overall, Figure 9.2b indicates that geophysical uncertainties currently have a comparable influence on the spread in mitigation costs to achieve the 2 °C objective as the uncertainties arising from different future pathways for social development and technological changes and choices. The maximum difference in probability of staying below 2 °C between the least (blue dashed) and the most costly (red dotted) distribution is slightly above 60 percentage points. This roughly matches to the range of probabilities one sees when taking into account the Earth system uncertainty under the same supply and demand assumptions (e.g., 0-70% in the reference portfolio, intermediate demand case between the lowest and highest carbon prices). Such a finding is broadly consistent with earlier studies comparing the relative contributions of geophysical and technological factors (Smith and Edmonds, 2006) using a non-probabilistic approach.

Yet, despite all of the uncertainty in the geophysical, social and technological dimensions, our analysis shows that the most dominant factor affecting the likelihood and costs of achieving the 2 °C objective appears to be, perhaps not surprisingly, politics. Here, we model political uncertainties by varying the timing of concerted global mitigation efforts. Although studies of the implication of delays in climate action are not new (Bosetti et al., 2009; Clarke et al., 2009; Krey and Riahi, 2009; Vaughan et al., 2009; den Elzen et al., 2010b), our results show how geophysical uncertainties interact and compare with political inertia: if global tempera-

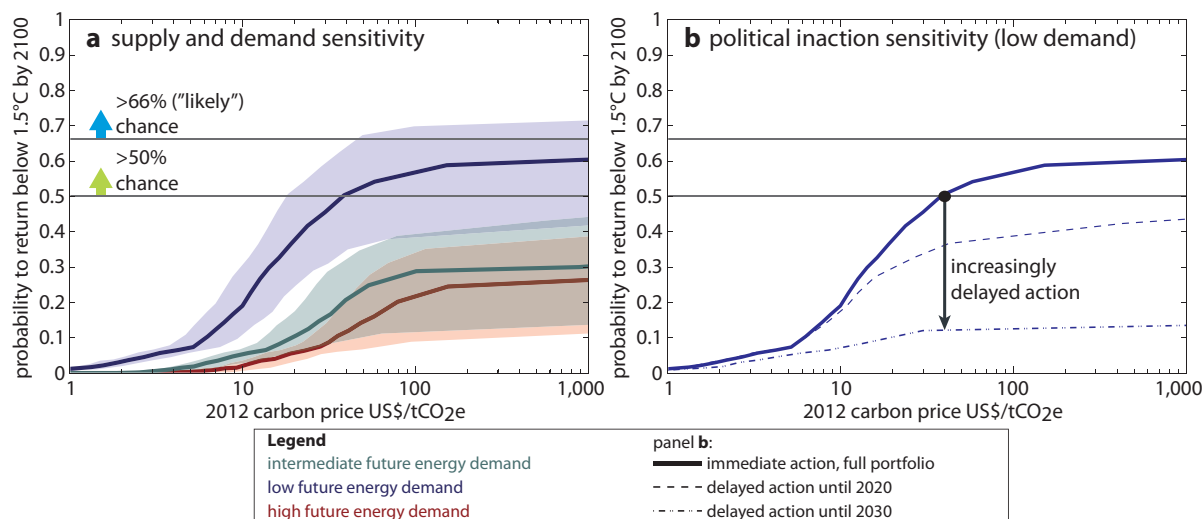


Figure 9.3: Analysis of influence of mitigation technology, energy demand, and political inaction on the mitigation cost distribution for returning temperature increase to below 1.5°C by 2100. **a**, Cost distributions for 3 cases of varying future energy demand (solid lines in red, green, and blue) and varying future availability of specific mitigation technologies (shaded ranges around solid lines). Ranges show the variation over all assessed technology sensitivity cases; **b**, Illustration of the influence of global mitigation action delayed from now until 2030.

ture rise is to be kept below 2°C with >66% probability under central technology and energy demand assumptions, our scenarios show that immediate and globally-coordinated mitigation action is necessary (Figure 9.2c; SI provides an explanation of 'immediate'). Only under low energy demand pathways can global mitigation action be delayed until 2020 (2030) and the 2°C objective still be achieved with a >66% (50%) chance (Figure 9.2d).

In conclusion, we find that the impact of global mitigation action delayed by two decades is much more pronounced than the uncertainty surrounding mitigation technology availability and future energy demands, and even renders the geophysical uncertainties almost irrelevant for the 2°C objective (Figure 9.2d, Supplementary Table 2, Supplementary Figure 9). Furthermore, we find asymptotic limits to increasing the probability of reaching a given temperature objective in our model: if mitigation action is delayed, simply throwing more money at the problem in the future will not increase this probability beyond certain limits imposed by the Earth system.

Our mitigation cost distribution methodology can also be applied to other temperature objectives, for example, a weaker 3°C or stricter 1.5°C limit, the latter of which has already been discussed in the policy arena (UNFCCC, 2010a). We find that unless energy demand is low, CCS technology is available, and global climate action is undertaken immediately, holding temperature increase to below 1.5°C by 2100 with at least a 50% probability is already an infeasible prospect (Figure 9.3a). In terms of costs, this would require the immediate introduction of global carbon prices >40 US\$/tCO₂e (rising over time with the discount rate). When global mitigation action is delayed by 10 to 20 years, a carbon price of 40 US\$/tCO₂e would yield probabilities of 10–35% only, and even under higher prices, a 50% probability could no longer be reached under central technology and low energy demand assumptions (Figure 9.3b). On the other hand, the same 40 US\$/tCO₂e carbon price would prevent a rise in warming beyond

3 °C with a high probability (>90%) across all supply-demand combinations, contingent upon immediate introduction of the pricing instrument globally (see Supplementary Figure 5).

Our findings have important implications for the on-going international climate policy discussions (UNFCCC, 2011), which foresee a global agreement coming into effect only in 2020. For such a strategy to be successful, national and local governments would need to put a far greater importance on concurrent demand-side solutions to climate protection (thus lowering energy demand growth), as well as voluntary or revised near-term mitigation policies and measures that anticipate and are consistent with a future stringent climate agreement. Our model results show that robustly safeguarding the future achievement of the oft-discussed 2 °C objective requires that society embarks on a higher-efficiency, lower energy demand course well before 2020 in the context of sustained, concerted and coordinated mitigation efforts.

9.3 Methods summary

We create a large ensemble ($n > 700$) of emission scenarios with MESSAGE (Rao and Riahi, 2006; Riahi et al., 2007), a global integrated assessment modelling framework with a detailed representation of GHG-emitting sectors, by imposing cumulative GHG emission constraints (for all GHGs: carbon-dioxide, methane, nitrous oxide, halocarbons, and fluorinated gases) of varying stringencies for the full 21st century, and by changing salient features in the underlying scenario assumptions (SI, Supplementary Figure 1, Supplementary Table 1, and Riahi et al. (2012) for a full set of assumptions). Our scenarios assume 'middle-of-the-road' assumptions for socio-economic development from the scenario literature: population peaking at 9.7 billion later in the century (UN median projection (United Nations, 2009)), and gross world product increasing more than seven-fold by 2100 (updated SRES B2 scenario projection (Nakicenovic and Swart, 2000; Riahi et al., 2012)).

We then compute probabilistic estimates of global temperature increase for each scenario with the MAGICC climate model (Meinshausen et al., 2009, 2011a,b). These estimates are based on a 600-member ensemble of temperature projections for each scenario, which together closely represent the carbon-cycle and climate uncertainties as assessed by the IPCC AR4 (described Rogelj et al. (2012b)). Additionally, our temperature projections are also constrained by observations and estimates of hemispheric temperatures and ocean heat uptake (see SI). The probability of staying below a given temperature threshold is computed over the entire 21st century and relative to pre-industrial levels. In contrast to the 2 °C objective, 1.5 °C is referred to as a long-term goal (UNFCCC, 2010a), meaning we allow a small, temporary overshoot and assess the probability of returning warming to below 1.5 °C by 2100.

We present our results using carbon prices as the cost metric. For the illustration of our results using other cost metrics like total mitigation costs see the SI (Section 1.4 and Supplementary Figures 2 and 3). The carbon price shown is the price at the time action starts, discounted back to 2012 with a discount rate of 5%/year (see SI Section 1.4 and Supplementary Figure 6).

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Author Contributions All authors were involved in designing the research; J.R. performed the research in collaboration with D.L.M.; all authors contributed to writing the paper.

Part VI
Epilogue

Chapter 10

Conclusions and outlook

10.1 Conclusions

The primary objective of this doctoral thesis was to explore and quantify uncertainties related to the very low end of emissions scenarios. For the study of these uncertainties analyses were carried out in four main dimensions: (1) uncertainties in short-term emission trends, (2) scenario comparability for climate and impact assessments, (3) uncertainties in pathways to limit global temperature increase, and (4) the integration of uncertainty assessments across disciplines. This section provides synthesized conclusions for each part, respectively, and while doing so attempts to link back to the calibrated language on uncertainty that was introduced in Chapter 1.

- **Short-term emission trends and uncertainty** Chapter 2 and 3 described the influence of emission inventory imprecision and the ambiguity in the short-term evolution of society and policies on emission levels in 2020 consistent with limiting warming to specific limits. In particular, the consistency of projected 2020 emission levels with limiting global temperature increase to below 2 °C during the 21st century was assessed. The analysis found that emission reductions and limitations pledged by countries under the Copenhagen Accord (and by extension, under the Cancún Agreements) still imply rising emissions from now until 2020 under all ambiguity and indeterminacy considerations assumed, and that, using a simple scenario approach, these high 2020 emission levels imply that only low probability options remain for limiting warming to below 2 °C. The uncertainty dominating this assessment is the ambiguity of various emission reduction pledges and the indeterminacy surrounding the environmental integrity governments will exhibit in achieving their pledge. Furthermore, an important discrepancy was found between top down estimates and officially reported bottom up inventories of global greenhouse gas (GHG) emissions. This discrepancy due to measurement imprecision and ambiguity systematically increases the gap between where emissions are heading and where they ought to be in 2020 to be on a pathway consistent with limiting warming to below 2 °C.
- **Scenario comparability for climate and impact assessments** With both scenarios and models differing between the IPCC Fourth and Fifth Assessment Reports, comparability between earlier and newly published studies is difficult. Chapter 4 described an effort to

consolidate insights of equilibrium climate sensitivity, climate and carbon cycle uncertainty assessments (related to imprecision, intractability, and unawareness) by the IPCC Fourth Assessment Report (IPCC, 2007d) in a single framework, and provides probabilistic estimates of global mean temperature increase for the scenarios used in both the latest and the forthcoming IPCC Assessment Report. Three pairs of 'old and new' scenarios are found with similar global mean warming: *SRES B1* and *RCP4.5*, *SRES B2* and *RCP6*, *SRES A1FI* and *RCP8.5*. These similarities can be used to link earlier impact studies to more recent assessments. Importantly, due to its peak and decline in global mean radiative forcing, the lowest of the 'new' scenarios (*RCP3-PD*) shows very distinct temperature response characteristics in our model setup and is not comparable to any of the previous scenarios. Combining the results for this scenario — designed to be representative of scenarios limiting warming to below 2 °C during the 21st century — with insights from both 'old' and 'new' scenarios used in the IPCC Assessments therefore allows for an unprecedented, explicit assessment of which climate impacts could potentially be avoided under a stringent global climate protection regime.

- **Pathways for limiting global temperature increase** A vast range of possible scenarios manages to potentially keep global mean temperature increase to below a given temperature limit. The two studies presented in Chapters 5 and 6 have assessed this question from two different angles: (1) given a very large set of emissions scenarios from the literature, what are the robust features of the subset of scenarios that limit warming to below a particular temperature limit? And (2) under which emission levels in 2020 does it still remain technologically and economically feasible in a particular modelling framework to limit warming to below 2 °C with a certain probability? Chapter 5 found that median global annual GHG emissions of published scenarios that limit global temperature increase to below 2 °C with a greater than 66% chance are 44 billion tons of carbon-dioxide equivalence (GtCO₂e/yr) in 2020, with a 15-85% quantile range of 31 to 46 GtCO₂e/yr. Important to note is that the large bulk of these scenarios assume immediate climate action to minimize the discounted costs of mitigation over the entire century. Using a fundamentally different approach, Chapter 6 found that while a relatively wide range of emissions in 2020 — from 41 to 55 GtCO₂e/yr — may preserve the option of meeting a 2 °C target, the size of this 'feasibility window' strongly depends on the prospects of key energy technologies, and in particular on the effectiveness of efficiency measures to limit the growth of energy demand. A shortfall of critical technologies — either for technological or socio-political reasons — would narrow the feasibility window, if not close it entirely. Targeting lower 2020 emissions levels of 41-47 GtCO₂e/yr would allow the world to stay below 2 °C under a wide range of assumptions, and thus help to hedge against the risks of long-term uncertainties related to the ambiguity of future societal preferences, the current intractability of aspects of the Earth system's response to GHG emissions, and also the indeterminacy of the adequacy of the here assumed 2 °C limit.
- **Integration of knowledge across disciplines** Many drivers influence the amount of GHG emissions and other radiatively active species over time that are ultimately emitted by human activities. These drivers, as well as the climatic impacts resulting from the actual emissions, are studied by often very distinct scientific disciplines. Integrating

knowledge across these disciplines can therefore provide valuable insights. For example, the analysis in Chapter 7 showed that simultaneously achieving the three energy-related objectives of the UN's 'Sustainable Energy for All' initiative can provide an important entry point to climate protection in terms of limiting global mean warming to below 2 °C, but highlights that this initiative cannot be considered a robust substitute for a global climate treaty that would explicitly limit anthropogenic GHG emissions. Sustainable development, poverty eradication, and stringent climate protection are shown to be able to go hand in hand. In Chapter 8, our results showed the joint benefits mitigation short and long-lived forcings can achieve in terms of global mean warming, but also highlighted an important pitfall. If accelerated short-term action on both BC-related short-lived climate forcings (SLCFs) and methane would come at the expense of rapid reductions of other Kyoto-GHGs (like CO₂), the benefits of reducing SLCFs in terms of global mean warming might be offset by the effects of other GHGs. Even limiting the near-term rate of temperature change might well prove unsuccessful under such a scenario, and the long term warming is likely to be higher. Chapter 9 then assessed the relative importance of various uncertainties for climate protection. Limiting climate change requires global action under deep uncertainty, ranging from the geophysical uncertainties (i.e., the imprecision and intractability) of the Earth system's response to GHG emissions, to uncertainties of technological, social, and political nature (i.e., the ambiguity, intractability, and indeterminacy of the evolution of our global society). Here we showed that the impact of global mitigation action delayed by two decades is much more pronounced than the uncertainty surrounding mitigation technology availability and future energy demand, and even renders the geophysical uncertainties almost irrelevant for the 2 °C objective. Furthermore, we find asymptotic limits to increasing the probability of reaching a given temperature objective in our setup, in particular for the 2 °C limit: if mitigation action is delayed, simply throwing more money at the problem in the future will not increase this probability, because of the long time scales of the Earth system's response to GHG emissions.

10.2 Outlook

You cannot think without abstractions; accordingly, it is of the utmost importance to be vigilant in critically revising your modes of abstraction. It is here that philosophy finds its niche as essential to the healthy progress of society. It is the critic of abstractions. A civilization which cannot burst through its current abstractions is doomed to sterility after a very limited period of progress.

Alfred North Whitehead in 'Science and the Modern World' (1925)

By means of Alfred North Whitehead's almost one-century-old quote, our attention in this section is first focussed to what might be the essence of the scientific method: the intellectual questioning of hypothesis, notion, and principle. Applied to the context of this thesis this questioning can materialise in a variety of ways, be it a straightforward expansion of the study horizon, or a critical contemplation of implicit assumptions, approaches, and concepts. Given

the policy-relevance and societal importance of many of the questions raised by the climate change issue, arguably both will prove to be essential in the long run. A few ideas for how this could be put into practice with regard to this thesis are suggested below.

Towards an impact-centred analysis approach In the introduction section (Chapter 1, Figure 1.2), four simplified analytical approaches to assess the link and implied uncertainties between emissions and their societal impact were presented. Already there, the suggestion was made that a shift of the main anchor point of such analytical approaches to the impact-side of the system would be desirable (see Figure 10.1, panel a and b). Looking at the issue at hand, and acknowledging the policy and societal interest in such exercise, it becomes abundantly clear why analyses that are centred around geophysical or, even more so, societal impact limits are beneficial to the science-policy dialogue. In this way, policy makers can relate more closely to actual impacts their societies are projected to experience in the future. They can then proceed with defining a maximum limit for such tangible and understandable impacts, instead of on a global mean physical variable. The policy makers' concerns are thus truly centrally positioned in this approach. A geophysical impact could, for example, be the avoidance of a particular tipping point or the protection of the habitat for coral reefs; a more societal impact could be a maximum allowable limit on agricultural yield losses due to climate change. Following the definition of geophysical or societal impact limits, consistent climate forcings (possibly geographically explicit) are computed from which then consistent emission scenarios are derived (see Figure 10.1, panel a and b). Such an approach would require massive computational resources for the inverse modelling of a huge amount of climate model realisations. This aspect would be only one of the current limitations for a large-scale application of such an approach. Other limitations to this approach are the difficulties to quantify some of the impacts or the issue that some impact might not be identified as important because of unawareness about certain physical linkages. In that case, it is well-possible that no societal limit would be defined for such an impact or the assessment would lead to overconfidence about the level of protection. The current efforts to assess the impacts of the RCPs with state-of-the-art coupled Earth System Models are therefore of extreme importance to explore possible causal chains between forcings and impacts.

Towards the inclusion of climate society feedbacks As already illustrated in Figure 1.1 in Chapter 1, a full-fledged analysis approach would ideally include policy-impact-scenario feedbacks, for example, taking into account the impacts of climate change on the global society or societal adaptation to projected changes. Such a full coupling would also allow to elicit the possible unavoidable losses due to climate change on time scales relevant to human society. Figure 10.1, panel c, shows an alternative representation of how such a feedback loop could look like. However, the perpetual multiplication of uncertainties in this kind of setup complicates its practical application. Also the difficulties in appropriately modelling adequately '*intelligent*' actors (Becker, 2006; Christen, 2013) — which should include various types of intelligence and also include irrational or paradigm shifting behaviour — and the massive assumptions involved in defining the motivations of such actors, raises important questions about whether such a fully-integrated approach will be able to produce ground-breaking new insights in the foreseeable future. Therefore, a simplified compromise setup is suggested in Figure 10.1,

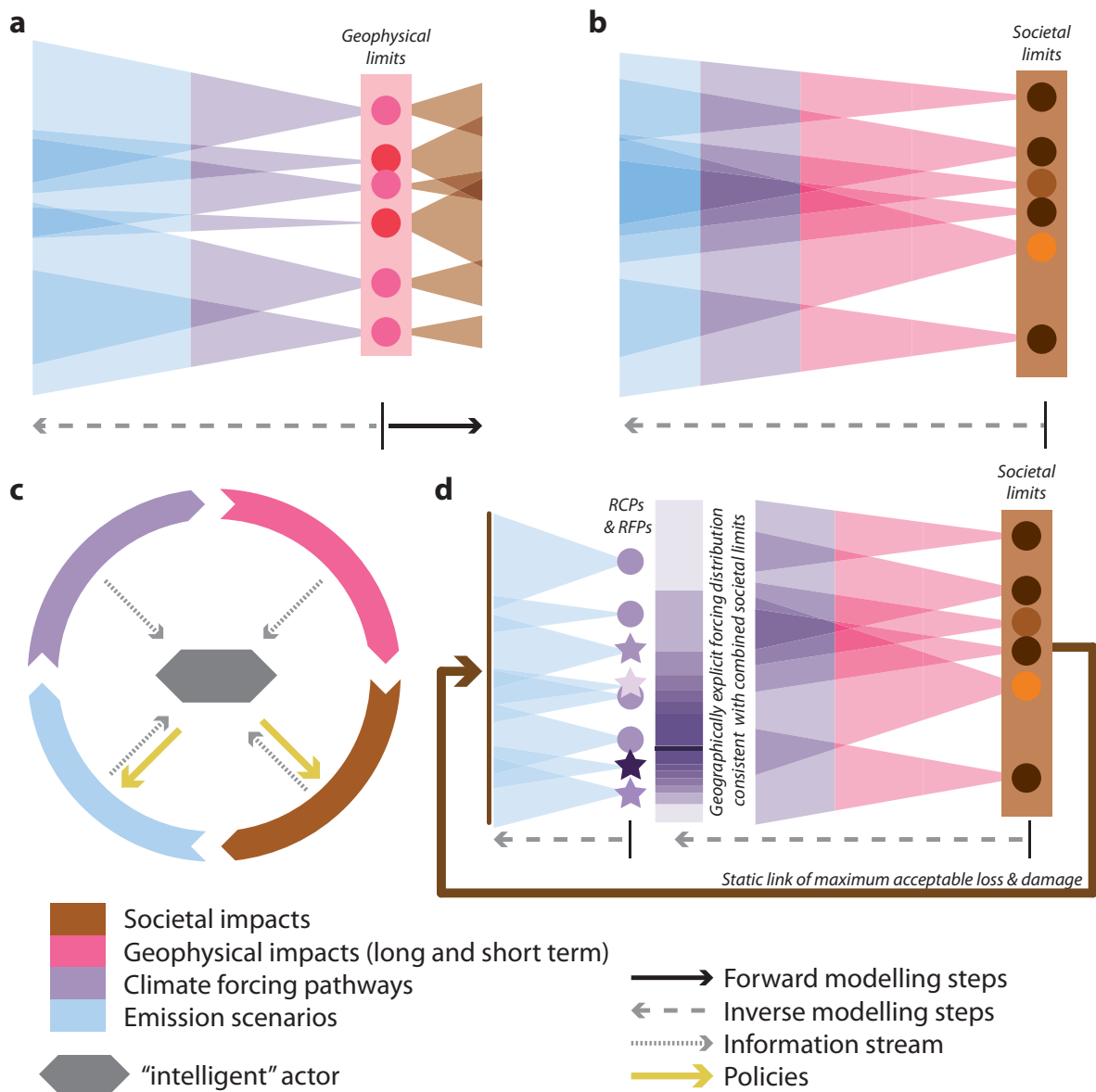


Figure 10.1: Analytical approaches to assess the links and implied uncertainties between emissions and their societal impacts. Panels **a** and **b** have geophysical and societal limits at the center, respectively. Panel **c** depicts the most complete representation of the links shown in Figure 1.1. Because of the impracticality of the approaches in panels **a-c**, panel **d** presents a compromise approach consisting of two inverse modelling blocks, starting from representative concentration or forcing pathways (RCP and RFP), and from societal or geophysical impact limits, respectively.

panel d, which positions society more at the center of the exercise but at the same time keeps the required value judgements in the hands of real people. Starting from a set of limits on societal (or alternatively geophysical) impacts, consistent evolutions of climate forcing are being calculated through inverse climate modelling (Figure 10.1d, right-hand side). Depending on computational constraints, these consistent forcing evolutions can even be geographically explicit, a characteristic that might be of importance when also short-lived climate forcers are targeted because of their local societal impacts, like public health. At the same time, a scenario exercise similar to the shared socioeconomic pathways exercise (SSPs, Kriegler et al. (2012)) is carried out (Figure 10.1d, left-hand side). However, the SSP approach would now be extended with the inclusion of additional boundary conditions that define static maximum amounts of societal loss and damage. These amounts are defined by the limits set on societal impacts at the onset of the exercise and once defined would not change (Figure 10.1d, bottom brown arrow). As such, the value judgements about acceptable loss and damage are not being taken by the modelling framework but are explicitly in the hands of the modeller or model user. The end result of the scenario exercise part of this setup would be a large set of possible societal evolutions consistent with a particular set of climate forcings, all taking into account the maximally allowed damage. In the end, this set could then be combined with the results in terms of allowable climate forcing evolutions (Figure 10.1d purple stars/dots and range), to define which emission scenarios could ultimately be compatible with the desired societal impact limits. Currently technological limitations inhibit carrying out such inverse analysis for a large ensemble of realisations, and therefore models of reduced complexity could be applied in a first phase. However, with the passing of time, also the most advanced global circulation models could become available to carry out the many runs required for this society-centred approach. An important limitation to this approach is that societal impacts can be reduced by both mitigation and adaptation. The suggested approach would put more emphasis on the mitigation than on the adaptation side of the problem.

Towards the exploration of societal alternatives The many, sometimes tacit assumptions surrounding the representation of societal mechanisms in integrated assessment models (IAMs) define to a very large extent — not to say entirely — the world view that will drive the global development simulated by the model. This does not only influence how IAMs project the future, but also how impact studies assess damage and the potential for adaptation. Often, this implies a globalized market growth model with free trade and technology exchange, perfect foresight, yet high time preference, and rational behaviour (or irrational that can be overcome by financial incentives), amongst many other assumptions. While not being *a priori* wrong, only investigating this singular societal setup would be a very limited approach, which should not escape scientific questioning. Particularly in case pre-defined limits on societal or geophysical impacts would infer that forcing would need to return to much lower levels than achievable under the assumptions of the tacit world view model, alternative narratives need to be explored by scholars. In absence of concrete examples of how this idea could be put to practice, this last suggestion is without any doubt the most ambitious, complex, and intellectually challenging to implement. Yet, as long as one of the motivations of our research is to inform and inspire a transformation of the global society towards long-term sustainable modes of living, also the structure of that very society should not be exempted from critical scientific scrutiny.

Part VII
Appendices

Appendix A

National GHG emissions reduction pledges and 2 °C: comparison of studies

National GHG emissions reduction pledges and 2 °C: comparison of studies

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Abstract

This article provides further detail on expected global GHG emission levels in 2020, based on the Emissions Gap Report (UNEP, 2010b), assuming the emission reduction proposals in the Copenhagen Accord and Cancún Agreements are met. Large differences are found in the results of individual groups owing to uncertainties in current and projected emission estimates and in the interpretation of the reduction proposals. Regardless of these uncertainties, the pledges for 2020 are expected to deliver emission levels above those that are consistent with a 2 °C limit. This emissions gap could be narrowed through implementing the more stringent conditional pledges, minimizing the use of 'lenient' credits from forests and surplus emission units, avoiding double-counting of offsets and implementing measures beyond current pledges. Conversely, emission reduction gains from countries moving from their low to high ambition pledges could be more than offset by the use of 'lenient' land use, land-use change and forestry (LULUCF) credits and surplus emissions units, if these were used to the maximum. Laying the groundwork for faster emission reduction rates after 2020 appears to be crucial in any case.

A.1 Introduction

In December 2010, at the annual conference under the United Nations Framework Convention on Climate Change (UNFCCC) in Cancún, Mexico, the international community agreed that further mitigation action is necessary. The conference

recognizes that deep cuts in global greenhouse gas emissions are required according to science, and as documented in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, with a view to reducing global greenhouse gas emissions so as to hold the increase in global average temperature below 2 °C above pre-industrial levels, and that Parties should take urgent action to meet this long-term goal, consistent with science and on the basis of equity; Also recognizes the need to consider, in the context of the first review [. . .] strengthening the long-term global goal on the basis of the best available scientific knowledge, including in relation to a global average temperature rise of 1.5 °C (UNFCCC, 2010a).

One year earlier, the Copenhagen Accord of 2009 (UNFCCC, 2009b) had already referred to a 2 °C target and encouraged countries to submit their emission reduction proposals and actions for the year 2020. Following that conference, 42 industrialized countries submitted quantified economy-wide emission targets for 2020. In addition, 43 developing countries submitted Nationally Appropriate Mitigation Actions (NAMAs) for inclusion in the Appendices to the Accord. These pledges have since become the basis for analysing the extent to which the global community is on track to meet long-term temperature goals. They have not changed significantly since early 2010 and were 'anchored' in the Cancún Agreements (UNFCCC, 2010f,g,b) in December 2010, which is the date of this analysis.

In the preparation for the Cancún conference, the United Nations Environment Programme (UNEP), together with the European Climate Foundation and the National Institute of Ecology (Mexico), presented the Emissions Gap Report (UNEP, 2010b), which summarizes the scientific findings of recent individual studies on the size of the 'gap' between the pledged emissions and levels consistent with the temperature limits.

In this article, selected authors of the Emissions Gap Report provide further detail on expected global GHG emission levels in 2020, assuming the emission reduction proposals in the Copenhagen Accord and Cancún Agreements are met. Details on the other questions raised in the Emissions Gap Report are included in a separate journal article (Rogelj et al., 2011b).

Estimating 2020 emissions, based on countries' pledges or submissions to the Cancún Agreements, is not a simple task. It involves, inter alia, information on the historical, current and future development of countries' emissions; interpretation of the pledges in the cases in which countries have submitted a range of pledges; assumptions on the precise meaning of those pledges where countries have not been specific, including the exact accounting rules; and uncertainties in the underlying data used by modelling groups. Accordingly, the various modelling groups that have prepared such analyses have arrived at substantially different results.

The focus of this article is the analysis of global emissions in 2020, because the pledges of the Cancún Agreements are only given for this year. However, it is acknowledged that 2020

emissions are only an approximate indicator for determining the probability of reaching the 2 °C climate target (Meinshausen et al., 2009; UNEP, 2010b).

This article provides an overview of the results of those studies that were available in August 2010 projecting the global GHG emissions in 2020, explains the differences in the results, and derives a range over the different cases based on the same assumptions.

A.2 Method

For this assessment, the analyses of 13 modelling groups were reviewed (see table A.1). Further studies are available but do not include new original estimates (Fee et al., 2010; WWF, 2010). Nine of the 13 groups performed a global analysis, and four focused on either Annex I, or a subset of other, countries. The various estimates were adjusted in order to facilitate a meaningful comparison. Details of this method are described in this section.

Four different pledge cases were established, which aimed to reflect a range of possible outcomes in 2020 as a result of the climate change negotiations. The four pledge cases are combinations of the following two interdependent factors: unconditional versus conditional pledges, and 'lenient' versus 'strict' rules.

A.2.1 Unconditional versus conditional pledges

Several industrialized countries have made pledges that are contingent on the actions of other countries or the passing of domestic legislation. Developing countries' pledges are often contingent on finance or technology transfer. Such conditional pledges were analysed separately to unconditional pledges. Common assumptions were made as to whether a country's pledge should be deemed conditional or not. These were applied consistently to all modelling groups' estimates.

The classification of the different pledges is detailed in tables A1 and A2 in the Supplementary Online Information. If a country only provided a conditional pledge (e.g. Canada, Japan, the US and South Africa) the business-as-usual (BAU) estimate for that country was assumed for the unconditional case. Given that these countries are implementing and/or are planning some domestic policies, this is a conservative assumption (e.g. for the US, see Bianco and Litz (2010)).

A.2.2 'Lenient' versus 'strict' rules

International accounting rules for achieving emission reduction targets by 2020 have yet to be defined. Rules for Annex I countries exist under the Kyoto Protocol until 2012. Rules for developing countries are not available, as they have no commitments to reduce emissions under the first commitment period of the Kyoto Protocol. The future international climate regime may apply central rules to all countries or move to decentralized rules country by country.

Table A.1: Overview of studies assessed in this paper

Organisation	Publication	Date	Coverage		Reference
			Annex I	Non-Annex I	
AVOID programme (UK Met Office, project lead)	Are the emission pledges in the Copenhagen Accord compatible with a global aspiration to avoid more than 2 °C of global warming?	Mar 2010	Yes	Yes	http://ensembles-eu.metoffice.com/avoid/ (Lowe et al., 2010)
Climate Action Tracker (Ecofys, Climate Analytics & PIK)	Climate Action Tracker (CAT) website	Aug 2010	Yes	Yes	www.climateactiontracker.org (Ecofys and ClimateAnalytics, 2010; Rogelj et al., 2010a,b)
Climate Interactive (C-ROADS)	Climate Scoreboard website	Aug 2010	Yes	Yes	www.climateinteractive.org/scoreboard
Climate Strategies	Analytic Support for Target-based Negotiations (paper 5)	May 2010	Yes	China and India	www.climatestrategies.org/research/our-reports/category/59.html
Fondazione Eni Enrico Mattei (FEEM)	Beyond the Copenhagen Pledges: Realistic Climate Policy in a Fragmented World	Oct 2010	Yes	Yes	www.feem.it/ (Carraro and Massetti, 2012)
IIASA (GAINS model)	Analysis of the proposals for GHG reductions in 2020 made by UNFCCC Annex I Parties: Implications of the economic crisis	Nov 2009 (data as of Apr 2010)	Yes	No	http://gains.iiasa.ac.at/index.php/gains-annex-1
Grantham Research Institute, London School of Economics & UNEP	What do the Appendices to the Copenhagen Accord tell us about global greenhouse gas emissions and the prospects for avoiding a rise in global average temperature of more than 2 °C?	Mar 2010	Yes	Yes	(Stern and Taylor, 2010)
OECD	Costs and effectiveness of the Copenhagen pledges: Assessing global greenhouse gas emissions targets and actions for 2020	Jun 2010	Yes	Yes	(Dellink et al., 2011)
PBL Netherlands Environmental Assessment Agency	Evaluation of the Copenhagen Accord: Chances and risks for the 2 °C climate goal	May 2010	Yes	Yes	(den Elzen et al., 2010c, 2011b)
Peterson Institute for International Economics (PIIE)	Evaluating Copenhagen: Does the Accord meet the challenge?	Feb 2010	Yes	Yes	(Houser, 2010)
Project Catalyst (Climate Works Foundation)	Taking stock: the emissions levels implied by the pledges to the Copenhagen Accord	Feb 2010 (data as at Sept 2010)	Yes	Yes	www.project-catalyst.info
UNEP Risø Centre	Climate Pledges website	Data as at Sept 2010	Yes	Yes	www.unep.org/climatepledges/
WRI	Comparability of Annex I Emission Reduction Pledges	Feb 2010	Yes	No	(Levin and Bradley, 2010)

Note: Some of the studies used in part the same datasets, which could lead to some bias, no attempt was made to correct for this. For example, Climate Interactive and PIIE both use C-ROADS data, which they have adapted to their own needs. CAT and PBL use similar data for some countries. UNEP also uses some of the Grantham data.

The results of the modelling groups were adjusted to take into account the maximum impact of two of the unresolved accounting issues for developed countries in the negotiations: accounting rules for land use, land use-change and forestry (LULUCF) and the use of surplus emissions units. These issues have the potential to displace mitigation action in other sectors and hence to lead to higher actual global emissions in 2020 than those pledged. The two 'lenient' pledge cases reflect an upper bound of applying such lenient accounting rules. The 'strict rules' cases assume the impact to be zero (see Section A.4.1 for details).

A.2.3 Completed data sets with missing country/sector emissions

or studies with less than global coverage the median estimate of the other modelling groups' findings for any missing countries or sectors was added to ensure a consistent comparison across studies. For the studies that estimated global emissions but did not include estimates for international transport emissions, the median estimate of other modelling groups for those emissions (2020 emissions of about 1.3 GtCO₂e) was added. Some modelling groups included such emissions in the individual country emissions data, which explains part of the range between modelling groups in emission estimates at a regional and country level.

A.2.4 Harmonized emissions data

To ensure consistent comparison of the present work with the results of recent emission pathways, the historical emissions data from the pledge analysis needed to be harmonized. The emissions data used in the nine global studies were harmonized around consistent 2005 levels of 45 GtCO₂e, as was done with the global emission pathways in UNEP (2010b). The harmonization included an absolute adjustment for each study's data set for 2005, which was kept constant for all subsequent years. (For further work on harmonization see Rogelj et al. (2011a)) The results of the harmonization led to changes in 2020 of between -0.3 GtCO₂e and +1.0 GtCO₂e (median, BAU and four cases) but larger adjustments for individual studies (-2.8 GtCO₂e to +1.5 GtCO₂e).

A.3 Results

The results for global emissions as provided by the modelling groups and adjusted, as described above, are provided in figure A.1.

As a reference point, without pledges, global GHG emissions may increase from 45 GtCO₂e in 2005 to around 56 GtCO₂e in 2020 (with a range¹ of 54-60 GtCO₂e) according to BAU projections.

- *Case 1 - 'Unconditional pledges, lenient rules'*. This case occurs if countries implement their lower-ambition pledges that are subject to 'lenient' accounting rules. Annex I countries could maximize the use of surplus emission units and 'lenient LULUCF credits' to meet their targets. In this case, the median estimate of emissions in 2020 was 53 GtCO₂e per year, with a range of 52-58 GtCO₂e.
- *Case 2 - 'Unconditional pledges, strict rules'*. This case occurs if countries keep their lower-ambition pledges and are subject to 'strict' accounting rules. The effect of the use of surplus units and 'lenient LULUCF credits' on resulting emissions is assumed to be zero. In this case, the median estimate of emissions in 2020 was 52 GtCO₂e, with a range of 50-55 GtCO₂e.
- *Case 3 - 'Conditional pledges, lenient rules'*. This case occurs if countries move to their higher-ambition pledges (as conditions are either met or relaxed), but are subject to 'lenient' accounting rules. This case was included because some of the more ambitious pledges of Annex I countries are conditional on some use of these credits or carry-over of surplus units (e.g. Member States of the EU, Russia, Ukraine). In this case, the median estimate of emissions in 2020 was 52 GtCO₂e, with a range of 50-54 GtCO₂e.
- *Case 4 - 'Conditional pledges, strict rules'*. This case occurs if countries move to their higher-ambition pledges and are subject to 'strict' accounting rules. In this case, the median estimate of emissions in 2020 was 49 GtCO₂e, with a range of 47-51 GtCO₂e.

Real global emissions in 2020 could be higher, if international offsets are counted towards both industrialized and developing countries' pledges (the so-called 'double counting' of offsets). In some countries, the impact of existing domestic policies or national plans could lead to lower emissions than the conditional pledges submitted under the Copenhagen Accord and the Cancún Agreements. International climate finance could also leverage further mitigation and lower emissions. All these issues were analysed and found to have a significant effect on 2020 emissions. However, they were not included in any of these cases and are discussed as additional factors in Section A.4.3.

From the analysis of these four cases it is important to note that the international policy options being discussed in the UNFCCC negotiations, and inherent in these cases, can significantly reduce the level of emissions in 2020. The most ambitious of the cases (case 4) is expected to be 7 GtCO₂e lower than BAU emissions (a range of 6-9 GtCO₂e lower).

Note also that the impact of 'lenient' or 'strict' rules on the resulting emissions in 2020 is potentially very sizeable. In fact, the use of 'lenient LULUCF credits' and surplus emission

¹Ranges in this chapter reflect the 20th to 80th percentile range of results, unless otherwise stated.

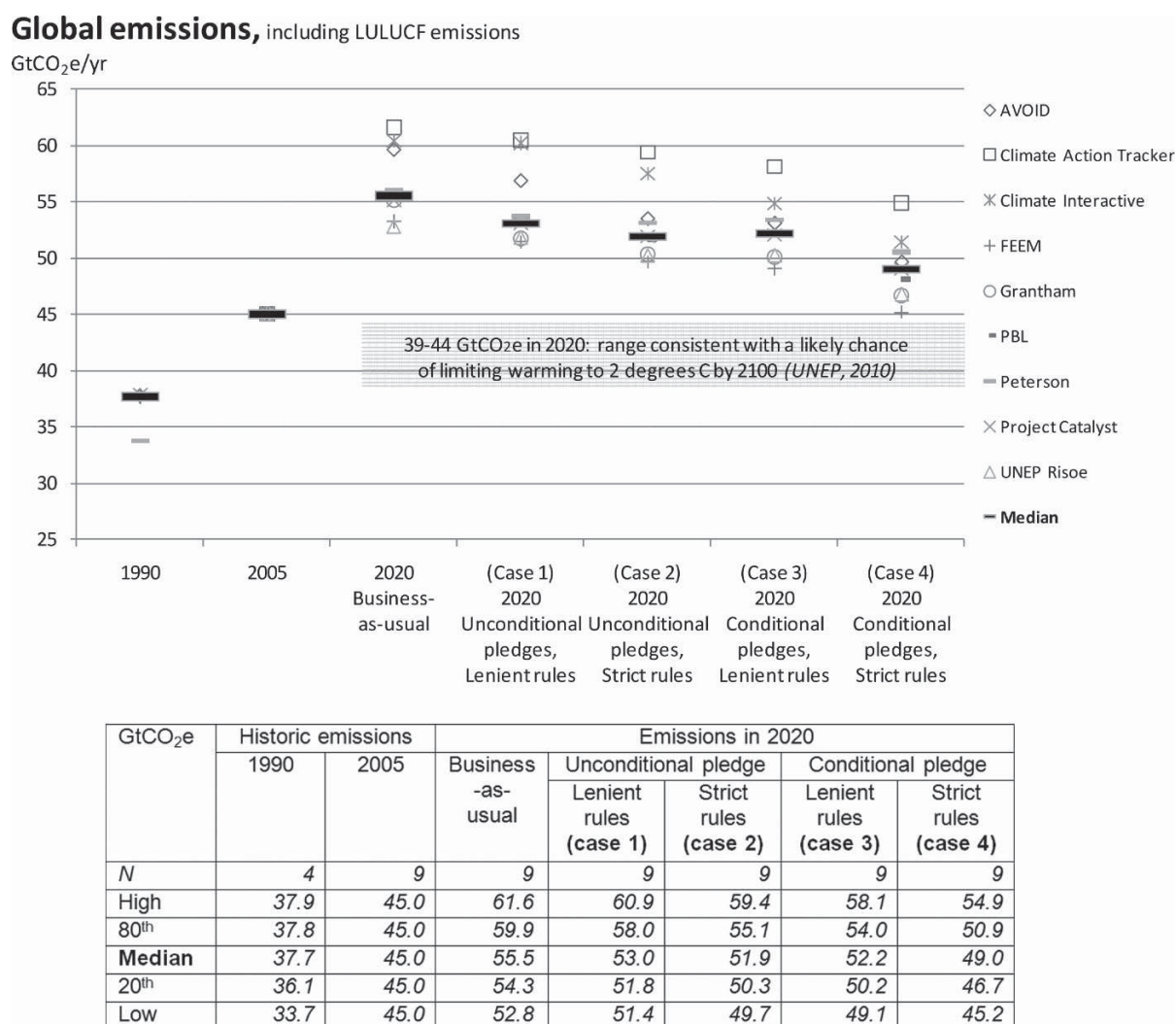


Figure A.1: Global GHG emissions, adjusted as found by different modelling groups. All emissions in this figure and article refer to GtCO₂e (gigatonnes or billion tonnes of CO₂ equivalent) the 1995 global warming potential-weighted sum of the six Kyoto GHGs, that is, CO₂, CH₄, N₂O, HFCs, PFCs and SF₆, including LULUCF CO₂ emissions. N = number of studies; High = maximum of full range; Low = minimum of full range; 20th-80th = 20 and 80 percentile values of the range. In the set of studies examined in this article, the nine modelling groups analysed the impact of pledges at the global level, while four analysed only a subset of countries. The data presented in the table have been harmonized to a common emissions level in 2005 (45 GtCO₂e). The range in 1990 emissions stems from the use of different data sources and assumptions, especially relevant for non-Annex I countries. For more details see table A3 in the Supplementary Online Information.

Table A.2: Annex I pledges compared with 1990 and BAU emission levels.

Annex I	Percent below BAU emission levels ^a		Percent below 1990 emission levels ^a	
	Median	Range ^b	Median	Range ^b
Case 1 Unconditional pledges, lenient rules	0.0	(0.0 to 0.0)	+6.3	(+11.9 to +1.6)
Case 2 Unconditional pledges, strict rules	-6.3	(-5.1 to -8.3)	-0.2	(+3.4 to -4.8)
Case 3 Conditional pledges, lenient rules	-2.6	(0.0 to -8.1)	+2.1	(+0.5 to +2.5)
Case 4 Conditional pledges, strict rules	-20.4	(-16.5 to -26.4)	-15.8	(-15.1 to -17.9)

^a Negative numbers reflect a decrease relative to the comparison year; positive numbers, an increase.

^a Range is the 20th-80th percentile range.

units could completely cancel out the impact of the Annex I pledges in the unconditional (low pledge) case, and significantly reduce their impact in the conditional (high pledge) case. Although a maximum possible impact of these two issues in the two 'lenient' pledge cases was deliberately assumed, it is important to note this finding as the rules surrounding these two issues are expected to be finalized over the course of 2011-2012.

Box: Comparison with IPCC benchmarks

For Annex I countries, in the least ambitious case ('unconditional pledges, lenient rules'), emissions are estimated to be 2-12% above 1990 levels or equivalent to BAU emissions in 2020. In the most ambitious case, Annex I emissions in 2020 are expected to be 15-18% below 1990 levels (see table A.2).

For non-Annex I countries, in the less ambitious cases emissions are estimated to be 6-8% lower than BAU emissions, and in the ambitious cases 8-9% lower than BAU (see table A.3).

This implies that the aggregate Annex I countries' emission goals are less ambitious than the 25-40% reduction by 2020 (compared with 1990) suggested in the IPCC's Fourth Assessment Report (IPCC, 2007b). Similarly, the non-Annex I countries' goals are, collectively, less ambitious than the 15-30% deviation from BAU, which is also commonly used as a benchmark (den Elzen and Höhne, 2008, 2010). While these values are helpful as a benchmark, they have to be regularly updated with the latest knowledge (see e.g. UNEP (2010b)).

Table A.3: *Non-Annex I pledges compared with BAU emission levels.*

Non-Annex I	Percent below BAU emission levels ^a	
	Median	Range ^b
Case 1 and 2 Unconditional pledges	-6.9	(-6.2 to -7.8)
Case 3 and 4 Conditional pledges	-8.9	(-7.7 to -9.3)

^a Negative numbers reflect a decrease relative to the comparison year; positive numbers, an increase.

^a Range is the 20th-80th percentile range.

Several options exist for policy makers to influence the final global 2020 emission level by delivering on their highest announced ambition and ensuring that accounting rules do not displace mitigation, and by finding ways to deliver further ambition either domestically, through finance, or in sectors not currently covered.

In the Emissions Gap Report it was shown that emission levels of 44 GtCO₂e in 2020 (range of 39-44 GtCO₂e) are consistent with a 'likely' chance of limiting global warming to 2 °C. The calculated scenarios for emissions in 2020 result in a median estimate of 49-53 GtCO₂e and therefore leave a gap of 5-9 GtCO₂e in 2020. The lowest gap of 5 GtCO₂e is approximately equal to the annual global emissions from all the world's cars, buses and transport in 2005. However, this is also almost 60% of the way towards reaching the 2 °C target.

The Emissions Gap Report showed that pathways that keep the increase in temperature to 1.5 °C in the long term are currently under-investigated in the Integrated Assessment Model literature. However, their preliminary assessment indicates that reaching 1.5 °C would be physically possible with similar 2020 emission levels as for the 2 °C target, but with a significantly faster decrease in emissions afterwards.

However, having a 'likely' chance of reaching the 1.5 °C target requires higher rates of emission reductions after 2020 (and correspondingly high rates of technological development and deployment) than those reported in the Integrated Assessment Model literature.

If a 'medium' (50-66%) rather than a 'likely' chance of staying within the 2 °C limit were assessed, the 2020 emission levels are only relaxed slightly: emissions in 2020 could be 1 GtCO₂e higher (median, 45 GtCO₂e; range, 42-46 GtCO₂e) and therefore the gap would be 4-8 GtCO₂e in 2020.

A.4 Discussion

The range of results from the modelling groups' estimates can be grouped into three categories:

- 1 Differences between the four pledge cases
- 2 Differences between estimates for the same pledge case
- 3 Other factors that could affect emissions

Figure A.2 summarizes the impact of these differences on the emissions of the four pledge cases, together with the further uncertainties described in this section. Note that because the uncertainties in this section are interconnected, they are not additive.

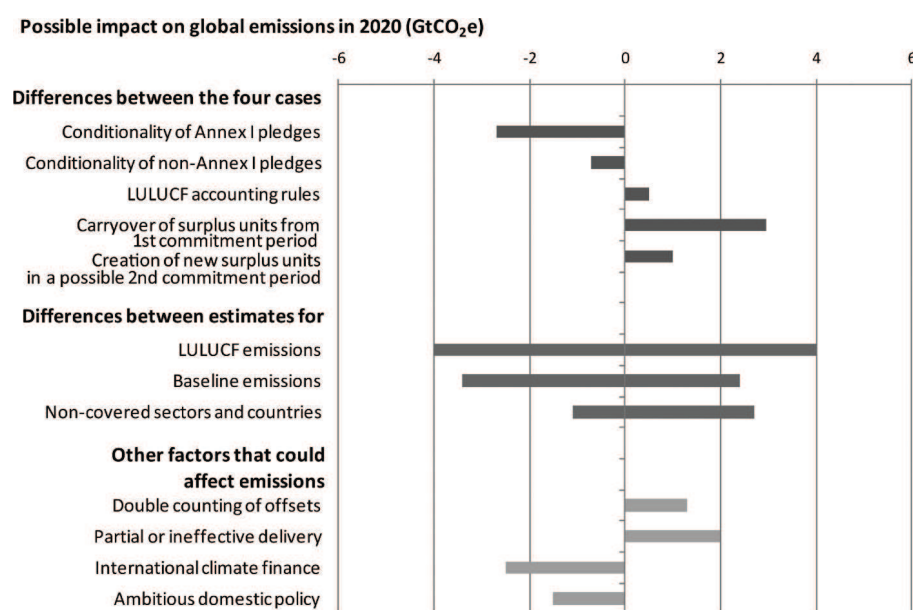


Figure A.2: Summary of the maximum impact of differences and uncertainties on global 2020 emissions (in GtCO₂e). There is a strong interaction between these factors and the effects are therefore not additive. Hence, no estimate of their total impact is given.

A.4.1 Differences between the four pledge cases

The following factors were explicitly taken into account in the construction of the four pledge cases.

Unconditional versus conditional pledges

If all countries were to implement their conditional pledges, emissions could be around 1-3 GtCO₂e lower in 2020, depending on whether 'lenient' or 'strict' rules apply, according to the median global estimate. Details of how these emissions were distributed across industrialized and developing countries are given below. Note that, as explained below, the numbers indicated in the following headings give the range of median changes in emissions as a result of moving from pledge case 2 to 4 (i.e. moving to conditional pledges while 'strict' accounting rules apply).

Conditionality of Annex I (industrialized) countries (up to -2.7 GtCO₂e) A number of Annex I countries' submissions included a range of pledges with conditions attached. For example, Australia, Member States of the EU, and Russia all submitted a range of pledges. Other countries submitted a single target or a list of actions but with conditions associated with delivering them. Canada, Japan and the US had conditions attached to their pledges and no alternative unconditional pledge. In this instance, as described above, BAU emissions were taken in the unconditional pledge cases².

²According to our estimates, if the pledges of these countries were treated as unconditional, rather than conditional, the median emissions would be 2.0 GtCO₂e lower in the unconditional pledge cases.

If Annex I countries were to move from their unconditional to conditional pledges, emissions could be between 0.8 and 3.1 GtCO₂e lower in 2020, depending on the stringency of the rules applied. This reflects the change in the median Annex I estimate in our sample. The median change in emissions across modelling groups (rather than the change in the median) as a result of the unconditional to conditional move was also examined. Modelling groups found that emissions could be between 0 and 2.1 GtCO₂e lower in the 'lenient' cases (i.e. the move from case 1 to case 3), with a median change of 0.5 GtCO₂e, and between 2.2 and 3.6 GtCO₂e lower in the 'strict cases' (i.e. the move from case 2 to case 4), with a median estimate of 2.7 GtCO₂e.

Conditionality of non-Annex I (developing) countries (up to -0.7 GtCO₂e) As is the case for Annex I countries, some non-Annex I countries included a range of pledges with conditions attached that, if fulfilled, would lead them to deliver the top of this range. Others submitted a single target or list of actions but with conditions associated with delivering them (e.g. whether industrialized countries would provide adequate financial support, technology transfer or capacity building).

For non-Annex I countries, this is particularly relevant to the pledges of South Africa, Mexico and Indonesia (for that country's higher-ambition pledge³), which all have conditions attached.

If non-Annex I countries were to move from their unconditional to conditional pledges, emissions would be 0.4 GtCO₂e lower in the median estimate in our sample (shown by the move from case 2 to case 4). The median change in emissions across modelling groups as a result of the unconditional to conditional move was also examined. Modelling groups find that emissions could be between 0.5 and 0.8 GtCO₂e lower in case 4 than in case 2, with a median estimate of the change in emissions of 0.7 GtCO₂e.

'Lenient' and 'strict' rules

'Lenient' rules would result in emissions being around 1-3 GtCO₂e higher than in the hypothetical 'strict' case in which the impact of LULUCF credits and surplus emission units is assumed to be zero.

LULUCF accounting rules for Annex I countries (up to +0.5 GtCO₂e) LULUCF accounting systems should provide credits for proven CO₂ removal or reduced emissions from new or enhanced sinks as a result of further policy intervention (e.g. new forests, different management of existing forests). Such CO₂ removals from the atmosphere could contribute to meeting emission targets. Resulting LULUCF credits could thus be counted as a contribution towards meeting targets in order to incentivize cost-effective mitigation from LULUCF activities.

LULUCF accounting rules are still being negotiated. Most Annex I pledges are based on the accounting approach used for targets in the Kyoto Protocol, which excludes LULUCF emissions from emission targets but allows the use of LULUCF credits to meet those targets. The

³Indonesia's high case commitment of 41% is not included in the Copenhagen Accord but was announced prior to COP 15 by the President of Indonesia. Six of the modelling groups reviewed in this assessment have modelled this.

current debate on reducing emissions from deforestation and forest degradation in developing countries is exploring if and how the LULUCF rules being discussed for Annex-I countries could be applicable to non-Annex-I countries.

The 'strict' rules cases reflect situations in which only those CO₂ removals are credited that occur as a result of new or enhanced sinks, that is, as a consequence of further policy intervention. Only real reduction of emissions in the LULUCF sector would result in new LULUCF credits. If these credits are used to increase emissions in another sector, the net effect would be zero. For calculation purposes, the quantity of LULUCF credits can therefore be set to zero. As the resulting target emissions levels are assumed not to be influenced by the credits, it is not necessary to estimate the extent to which LULUCF credits count towards meeting this goal.

In the 'lenient' case, on the other hand, it is also assumed that those CO₂ removals by the sinks that the climate models predict to occur are credited in the absence of additional policy. Given that these removals are in any case part of the baseline emissions, the use of such credits would increase the 2020 estimate of other emissions. In this assessment such credits are called 'lenient LULUCF credits'.

Recent analysis from PIK PRIMAP (Chen et al., 2011; Nabel et al., 2011) and the Joint Research Centre (JRC) of the European Commission indicates quite a wide range of estimates, depending on the accounting options considered in the international negotiations until mid-2010.⁴ Taking into account these estimates, in the creation of the 'lenient' pledge cases used in this article, maximum LULUCF credits of 0.5 GtCO₂e in 2020 (i.e. this extra amount of emissions will be allowed in other sectors), equivalent to 2.6% of Annex I 1990 emissions, was assumed. This compares to the 0.8 GtCO₂e used in the Emissions Gap Report that was based on earlier estimates.

Even lenient LULUCF rules could potentially lead to a stricter outcome if they represent a pragmatic solution that allows countries to take on more stringent targets or targets that they otherwise would not have taken (Höhne et al., 2007).

Carry-over of surplus units from the first commitment period (up to +3.0 GtCO₂e) Surplus emission units can arise because some countries have over-achieved their targets in the first commitment period of the Kyoto Protocol, either due to ambitious policy or for non-climate policy reasons. Where this has occurred countries could carry over (as most countries with a surplus have argued that they should), or 'bank', this surplus for use in the second commitment period. Surplus emission units from previous commitment periods, if sold or used domestically to displace mitigation activity up to 2020, reduce the stringency of 2020 emissions and hence increase estimates of 2020 emissions. The total surplus by 2012 at the end of the first commitment period is estimated to be 9-13 GtCO₂e of surplus emission units (PointCarbon, 2009; den Elzen et al., 2010a; Rogelj et al., 2010b). If fully purchased this could, therefore, displace up to 3.0 GtCO₂e of mitigation in 2020, assuming that a mid-range estimate of 11.4

⁴The range of LULUCF estimates for 2020 from different studies are as follows: PIK PRIMAP: from a debit of -0.19 GtCO₂e to a credit of 0.46 GtCO₂e; the calculation of Party-preferred options yields 0.42 GtCO₂e. JRC: from a debit of 0.18 GtCO₂e (all activities, forest management with net-net accounting as compared to the first commitment period) to a credit of 0.42 GtCO₂e (all activities, forest management with reference levels and without caps).

GtCO₂e of surplus emission units are carried over into the next commitment period and are used in a wedge-like manner (i.e. increasing linear distribution; (Rogelj et al., 2010a,b)). Such a distribution is close to the upper bound; it could be further increased by distributing even more of the allowances to 2020. This compares to the 1.3 GtCO₂e used in the Emissions Gap Report, which was based on a little less total allowances and an even distribution over the 10 years.

Note that the actual implications for 2020 emissions depend not only on how this surplus is used over the accounting period but, more importantly, on whether there are any countries willing to buy these surplus emissions units to meet their goals, despite questions about their environmental advantages (e.g. den Elzen et al. (2010a); Bosetti et al. (2009)). Just because surplus units exist does not mean they will be used, as demonstrated by the current commitment period in which some countries have emissions significantly below their targets, leading to the carry-over from this commitment period estimated above. In addition, the surplus might not be carried over if a new international regime is adopted that restricts the carry-over of earlier surplus credits. Hence the 'lenient rules' case represents an extreme situation in which countries use all of the available surplus credits by 2020 to displace mitigation efforts.

Creation of new surplus units in a possible second commitment period (up to +1.0 GtCO₂e) Further surplus emission units could arise if countries (such as Russia, Ukraine and Belarus) are allocated emission units significantly above the estimated BAU level in 2020.

Many modelling groups in our sample have not analysed this situation, or they have simply assumed that these new surplus emission units would not have an impact on emissions in 2020 (i.e. would not be traded). The modelling groups Climate Action Tracker, FEEM, IIASA (GAINS), Grantham, PBL and Project Catalyst found that, if emissions remain above BAU, the use of new surplus emission units by Annex I countries in 2020 could lead to an increase in global emissions up to 1 GtCO₂e (for the 'unconditional' pledge case). The full range is 0.3-1.0 GtCO₂e. For the conditional pledge case, global emissions in 2020 could be up to 0.6 GtCO₂e higher (full range, 0-0.6 GtCO₂e). The range reflects different BAU assumptions across modelling groups.

In constructing the 'lenient' pledge cases, the impact of new surplus emission units estimated by the modelling groups themselves was reported, with a range of 0-1.0 GtCO₂e on 2020 emissions depending on the study, which is reflected in the subheading above. The 0 GtCO₂e impact reflects those studies that either did not estimate the impact of new surplus units or judged that these new surplus units would not have an impact on actual emissions (e.g. if other countries do not purchase them).

A.4.2 Differences between estimates for the same pledge case

Section A.3 showed a large range of estimates across studies, even after separating out the different policy options reflected in the four pledge cases. The range in estimates is largely driven by the following uncertainties (numbers in parentheses give the range of 2020 emission estimates that can be attributed to each of these uncertainties).

Global land-use change emissions (± 4 GtCO₂e)

At the global level, emissions from land-use changes are subject to a high level of uncertainty. The Intergovernmental Panel on Climate Change (IPCC) estimates that these emissions in the 1990s amounted to 5.9 GtCO₂e and that uncertainty around these emissions is about ± 4 GtCO₂e (IPCC, 2007d). Assuming that this level of uncertainty of global land-use change emissions will remain in 2020, this accounts for a large part of the discrepancy between the 2020 total emissions estimates of the different modelling groups.

Anthropogenic emissions from peat are particularly uncertain. Current global emissions from peat are estimated to be about 1.7 GtCO₂e, with an uncertainty of around ± 1 GtCO₂e (Joosten, 2010)⁵. Uncertainty in these emissions is a particular issue for Indonesia where peat has been incorporated in the country's BAU emissions and planned mitigation actions. Modelling groups need to avoid double-counting these emissions in both their global estimates and Indonesia's emissions. This uncertainty may be partially reflected in the range of estimates in the pledge cases as different modelling groups have made different assumptions about these emissions.

In addition, the treatment of emissions and sinks from LULUCF in the accounting (i.e. its use for future targets) in Annex I countries is a source of uncertainty that is partially reflected in the range of estimates under each pledge case.

Emissions data tabulated by the Secretariat of the UNFCCC indicate that the LULUCF sector in all Annex I Parties has been a net anthropogenic sink of around 2 GtCO₂e in the last decade. This is attributed mostly to historical forestry policies not undertaken for climate policy reasons. However, it is not always clear which of the LULUCF sinks or sources should be considered as anthropogenic removals or as emissions by climate models. For example, there may be an inconsistency between the emission sources considered by the UNFCCC and other institutions, or inconsistent identification of direct and indirect anthropogenic emissions. Some groups estimate that the Annex I LULUCF sector is a net source of emissions (see also Rogelj et al. (2011a)). This could therefore lead to a range of about 2 GtCO₂e between those groups that assumed a large net sink from LULUCF emissions in 2020 and those that assumed a small net source.

Baseline emissions (-3.4 to +2.4 GtCO₂e)

Many non-Annex I countries submitted pledges that specified a percentage reduction below an emissions baseline but not the baseline itself. This has led to a range of results across modelling groups because different baseline emissions have been estimated. For the developing countries that measured their target against BAU emissions, the estimates of 2020 emission levels after action varies across studies by -1.4 to +0.3 GtCO₂e (around the median estimate) for the unconditional pledges and -0.9 to +0.2 GtCO₂e for the conditional pledges.

Some countries stated their pledges in terms of carbon intensity targets (measured as the improvement in emissions per unit of gross domestic product). This requires further assumptions about future economic growth to determine expected emissions in 2020. For example, if

⁵The uncertainty range is estimate-based on an uncertainty bound of 20% applied to the estimate for drained peatland (± 0.3 GtCO₂e) and the range of estimates of peat fire emissions (± 0.5 GtCO₂e).

economic growth (or the carbon intensity of growth) exceeds the modelling groups' expectations, then emissions will be higher than estimated. Conversely, slower or low-carbon growth patterns will lead to lower emissions. This uncertainty means that 2020 emissions could be significantly higher or lower than the projections from different study teams. There is already a large variation in estimates of the BAU in emerging economies. For example, the difference between the maximum and minimum BAU 2020 emissions of China across studies is 4.2 GtCO₂e and for India is 1.2 GtCO₂e. A variation of $\pm 2\%$ in the economic growth rate assumptions in China and India is estimated by some groups to lead to a variation in emissions of ± 2 GtCO₂e by the year 2020 (Stern and Taylor, 2010; den Elzen et al., 2011a).

Finally, for Annex I countries, there is some uncertainty around the base-year emissions against which targets are set. For some cases it is unclear whether the base year includes LULUCF emissions. This factor can add an uncertainty of around 0.1 GtCO₂e to estimates in this report of Annex I emissions.

Non-covered sectors and countries (-1.1 to +2.7 GtCO₂e)

All categories of anthropogenic emissions matter if the full impact of emissions on the atmospheric concentration of GHGs is to be explored. This means that all sources, gases and countries must be included in any analysis. Where studies were found to exclude a source of emissions, the median estimate from other studies was used. However, considering data scarcity, there is always the risk that studies omit some emissions from some sectors. There is also a risk of emissions being counted twice.

In particular, there are a number of emission categories that are not included in the national targets and therefore not covered by pledges, such as emissions from international aviation and maritime transport (bunkers), following the accounting rules of the Kyoto Protocol. It is important that these are added to the totals, as most studies already do. The median estimate of the different modelling groups was 1.3 GtCO₂e in 2020 with a range from -0.1 to +0.5 GtCO₂e around it.

In addition, emissions from developing countries that did not submit mitigation pledges are found to have a large variation across modelling groups. A range of -1.0 to +2.2 GtCO₂e around the median estimate of BAU emissions in those countries was found.

Collectively, the uncertainties caused by incomplete coverage of sectors and countries and varying estimates of international aviation and marine transport lead to emission estimates from 1.1 GtCO₂e below to 2.7 GtCO₂e above the median estimate in the four pledge cases.

A.4.3 Other factors that could affect emissions, but that are not reflected in the pledge cases

There are a number of other important factors that have not been made explicit in the construction of the four pledge cases, but which could affect emissions in 2020. These are described in detail below (numbers in parentheses give the maximum annual 2020 emissions impact on the four cases).

Double-counting of offsets (up to +1.3 GtCO₂e)

The potential for the 'double-counting' of offsets towards both industrialized and developing country targets could lead to higher emissions in 2020 compared to estimates reported in three of the four pledge cases. The exception is Case 1, 'unconditional pledges, leniently applied', where Annex I emissions were already found to be close to BAU levels, suggesting very little demand for offsets, and hence little opportunities for double-counting.

If Annex I country A uses significant offset credits (such as CDM) from non-Annex I country B to meet its emission target, then actual domestic emissions in A are higher, and actual domestic emissions in B are lower, than the emission target. If the offsets take place in a country B that has no emissions target or if the offsets were additional to the pledges made to the Copenhagen Accord or under the Cancún Agreements, then the global totals reported in the four pledge cases would be accurate even though emissions originated from different countries. If, however, the offset credits were used to meet pledged goals in both the selling and buying countries then there would be double-counting in the estimates of the pledge cases, and hence global emissions would be higher than reported in the four pledge cases.

The extent of this risk remains uncertain, because neither potential buying nor selling countries have specified whether offsets will be used towards the pledges. None of the modelling groups assessed in this article accounted for this risk in their main policy option, and to do so robustly would require modelling of the supply and demand for credits and assumptions on whether the offset projects deliver reductions over BAU. Although some groups attempted to make simple assumptions to quantify the extent of this risk, most groups just assumed that emission reductions resulting from Annex I and non-Annex I pledges would be additive; that is, no double-counting would occur.

A simple estimate of the risk of double-counting can be made by assuming that a given percentage of the Annex I deviation from BAU is met using offsets and that all of those reductions are also used to meet non-Annex I goals. For example, a percentage of 33% would lead to 0.4 GtCO₂e of double-counting in the 'unconditional pledge, strict rules' case and 1.3 GtCO₂e in the 'conditional pledge, strict rules' case (median estimates). For the purpose of this assessment, 1.3 GtCO₂e was assumed to be a reasonable estimate for the maximum potential impact from double-counting of offsets.

It is worth noting that this problem could be exacerbated if the offset credits themselves (e.g. CDM credits) do not represent an 'additional' emission reduction compared to BAU activities in developing countries in the first place. In that case, even counting them once as reduction units would increase global emissions. If offsets were both 'double counted' and 'non-additional', their impact on global emissions might therefore be even greater.

Partial or ineffective delivery (up to +2 GtCO₂e)

All of the studies reviewed here assume that countries will meet their targets. Any failure to do so, however, will lead to higher 2020 emissions, which will push emissions back towards BAU levels. Conversely, well-designed policies that spur innovation and investment could allow goals to be over-achieved.

Assuming, for example, that pledged reductions below BAU are missed by 25%, then global emissions would be about 0.5 GtCO₂e higher in the lowest-ambition pledge case (case 1) and

approximately 2 GtCO₂e higher in the most ambitious pledge case (case 4). Exceeding goals by 25% would lead to a symmetrical reduction in forecast 2020 emissions.

International climate finance (up to -2.5 GtCO₂e)

Industrialized countries pledged in the Copenhagen Accord and Cancún Agreements to provide 'new and additional' financial aid of US\$30 billion for the period 2010-2012, and to mobilize jointly \$100 billion a year by 2020 to address the mitigation and adaptation needs of developing countries. This financial support would be split between adaptation and mitigation. If delivered, resources on this scale have the potential to fund significant mitigation actions in countries that require support. However, it is not clear whether this amount meets or exceeds the funding required to satisfy the conditions of existing pledges contingent on external financing, as these countries have not yet specified the resources they require.

However, the scale of these resources means that they could leverage further reductions beyond existing commitments or deliver mitigation in countries that have not yet specified mitigation actions (representing roughly 20% of global emissions). One study (Carraro and Massetti, 2012) has found that if 25% of the \$100 billion goes to mitigation, this climate finance could reduce emissions by between 1.5 and 2.5 GtCO₂e in 2020. (This study assumed that climate finance only supports additional mitigation actions and that the use of international offsets is limited to 20% of the Annex I target.) Another study (Houser, 2010) estimated that the finance could deliver 1.5 GtCO₂e of mitigation potential.

Ambitious domestic policy (up to -1.5 GtCO₂e)

Another factor affecting emissions in 2020 are domestic policies or goals in national plans that might lead to a reduction in emissions beyond those of the Copenhagen Accord pledges. Three modelling groups (Climate Action Tracker, PBL and Project Catalyst) estimated that domestic climate mitigation plans could lead to global emissions about 1.5 GtCO₂e lower than the four pledge cases.

A.5 Conclusions and policy implications

Various studies that estimate GHG emission levels in 2020 as a result of emission reduction proposals by countries under the UNFCCC negotiations have been compared. Conclusions from this comparison involve two main areas, the accounting of emissions and targets, and the level of ambition.

A.5.1 Accounting of emissions and targets

It is not always clear from country submissions or announcements whether a pledge is conditional or not, which sectors are included, which base year is used and which accounting rules apply. This makes the assessment of pledges difficult. The authors have therefore sometimes had to make a judgement based on discussions with in-country analysts. Further information from countries to help clarify this is welcome.

There are still large uncertainties in current global emissions from forests and peat. The modelling groups discussed in this article have used various estimates or excluded this important emissions source from their analyses. An intensified effort to clarify the differences in the estimates and to narrow the range would help make future analysis of this kind more consistent across modelling groups.

A.5.2 Ambition level

A global emissions gap is probable between expected emissions as a result of the pledges and emission levels consistent with putting the world on an effective trajectory in 2020 to avoid expected global warming above the 2 °C limit. The calculated scenarios for emissions in 2020 result in emissions of 49-53 GtCO₂e (median) and therefore leave a gap of 5-9 GtCO₂e to what would be necessary to be on a credible path towards 2 °C with a high chance of likelihood. Some groups calculated that in the least ambitious case, no reductions beyond BAU would be required from the group of Annex I countries to meet their targets.

However, the analysis of options here for implementing the reduction proposals also shows that the gap could be narrowed through the use of any one of the following five policy options.

First, implement (the more ambitious) conditional pledges. If all countries were to move to their conditional pledges, it would significantly narrow the 2020 emissions gap towards 2 °C. The gap would be reduced by about 1-3 GtCO₂e, with most of the emission reductions coming from industrialized countries and a smaller, but important, share coming from developing countries. This would require that conditions on those pledges be fulfilled. These conditions include expected actions of other countries as well as the provision of adequate financing, technology transfer and capacity building. Alternatively it would imply that conditions for some countries are relaxed or removed.

Second, minimize the use of 'lenient LULUCF credits' and surplus emission units. If industrialized countries applied strict accounting rules to minimize the use of 'lenient LULUCF credits' and avoided the use of surplus emissions units for meeting their targets, they would strengthen the effect of their pledges and thus reduce the emissions gap in 2020 by about 1-3 GtCO₂e (with up to 0.5 GtCO₂e coming from LULUCF accounting and up to 4.0 GtCO₂e from surplus emissions units). Options to limit the use of surplus emissions were discussed in the UNFCCC negotiations.

Third, avoid the double-counting of offsets. Double-counting of offsets could lead to an increase of the gap by up to 1.3 GtCO₂e, depending on whether countries implement their unconditional or conditional pledges (there is likely to be a greater demand for offsets in the higher-ambition, conditional case). Hence, avoiding double-counting could be an important policy option. Options to achieve this include the transparency of all countries on what is counted towards the achievement of their target. Financing countries could make financing of emissions reductions transparent and could specify whether emissions reductions will count towards meeting their own targets.

Fourth, implement measures beyond current pledges and/or strengthen pledges. The mitigation scenarios indicate that it is technically possible to reduce emissions beyond present national plans in 2020. These scenarios show that the gap could be closed, and that emission levels consistent with 2 °C could be achieved through the implementation of a wide portfo-

lio of mitigation measures, including energy efficiency and conservation, renewables, nuclear, carbon capture and storage, non-CO₂ emissions mitigation, hydro-electric power, afforestation and avoided deforestation. Sectors currently not covered by the national pledges, such as international transport, could be included. Additional international climate finance could also induce additional reductions.

Finally, lay the groundwork for faster emission reduction rates after 2020. Emission pathways consistent with a 2 °C temperature limit are characterized by rapid rates of emission reduction post-2020. Such high reduction rates on a sustained time scale would be challenging and unprecedented historically. Therefore, it is critical to lay the groundwork now for faster post-2020 emission reductions, for example, by avoiding lock-in of high-carbon infrastructure with a long lifespan, or by developing and demonstrating advanced clean technologies.

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Appendix B

Supplementary information: Combining short and long-term mitigation efforts to limit global mean warming

Supplementary information: Combining short and long-term mitigation efforts to limit global mean warming

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(in preparation)

Note that this version is not yet formally approved by all contributing authors.

— changes reserved —

B.1 Supplementary tables

Table B.1: Overview of 2020 emission ranges consistent with limiting temperature increase to below 2 °C above pre-industrial during the 21st century. Data is provided for all BC-related sensitivity cases and two probability options: a 'likely' (greater than 66%) or an 'at least fifty-fifty' (greater than 50%) chance. Format: minimum(15% quantile[median]85% quantile)maximum, n = number of scenarios. Cases of this study are provided in the same order as in Figure 8.1.

Case number	label	2020 emission levels consistent with limiting global temperature increase to below 2 °C [GtCO ₂ e/yr]	
		'likely' chance	'fifty-fifty' chance
0	Original scenarios	21(31[44]46)48, n = 26	21(41[45]48)51, n = 44
1	Reference SLCF	21(41[45]47)50, n = 43	21(41[45]49)53, n = 60
6	Accelerated BC-related SLCFs moderate cost with CO ₂ mitigation	21(34[44]46)48, n = 31	21(41[45]48)51, n = 46
7	Accelerated BC-related SLCFs moderate cost with SO ₂ and methane mitigation	21(41[45]48)52, n = 83	21(41[46]49)53, n = 91
2	BC-related SLCF cost-savings	21(41[45]48)51, n = 48	21(41[46]50)53, n = 67
3	BC-related SLCF moderate cost	21(41[45]49)53, n = 56	21(41[46]50)53, n = 79
4	20 year delayed BC-related SLCF moderate cost	21(41[45]48)52, n = 55	21(41[46]50)53, n = 77
8	Enhanced BC warming effect	21(42[46]50)55, n = 84	21(42[47]50)55, n = 90
5	BC-related SLCF moderate cost and SO ₂ mitigation	21(32[44]46)48, n = 27	21(39[45]48)50, n = 41

B.2 Supplementary figures

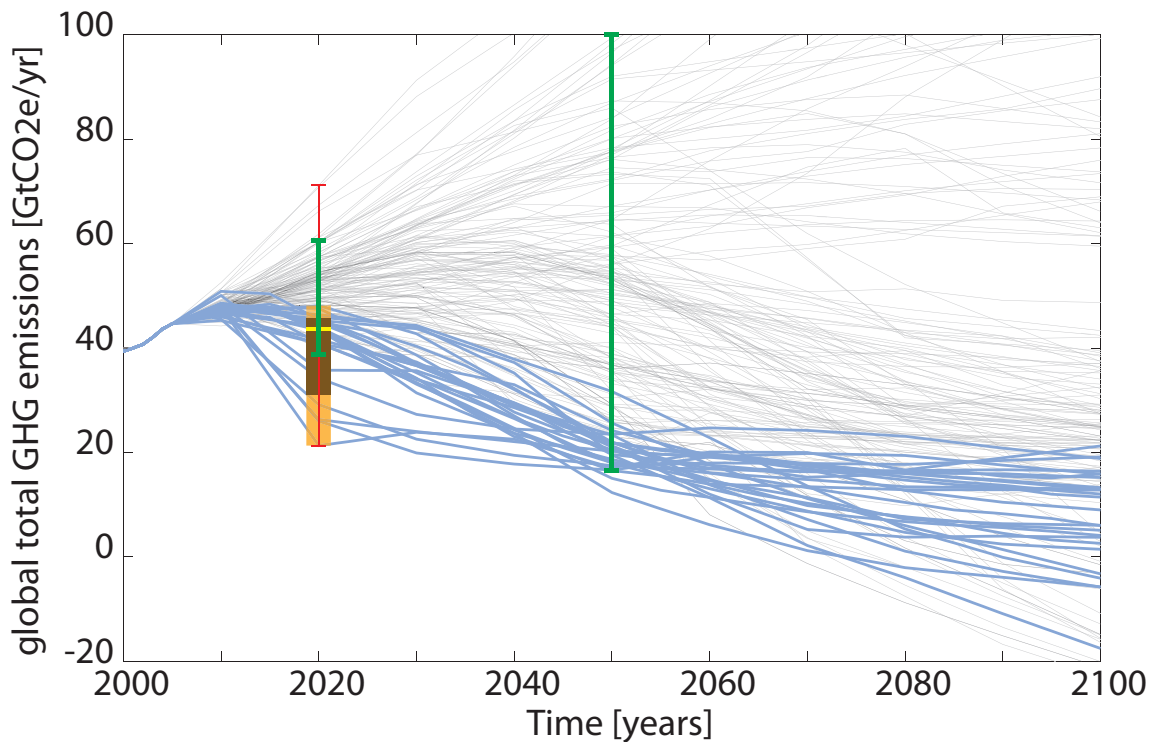


Figure B.1: Ensemble of emission scenarios from the literature and 2°C-consistent 2020 emission range. Global total Kyoto-GHG emissions of all scenarios in our set (grey and light blue lines). Light blue lines show the subset of scenarios that limit global temperature increase to below 2°C during the 21st century with a likely (>66%) chance. The vertical bars show the minimum-maximum (orange) and 15th to 85th percentile (brown) emission range of these scenarios in 2020. The horizontal yellow line shows the median. Red whiskers show the full range of emissions in 2020. Green whiskers show the 'comparable cost' ranges of Kyoto-GHG emissions in 2020 and 2050 consistent with a carbon price of <75 US\$/tCO₂e based on Rogelj et al. (2013b).

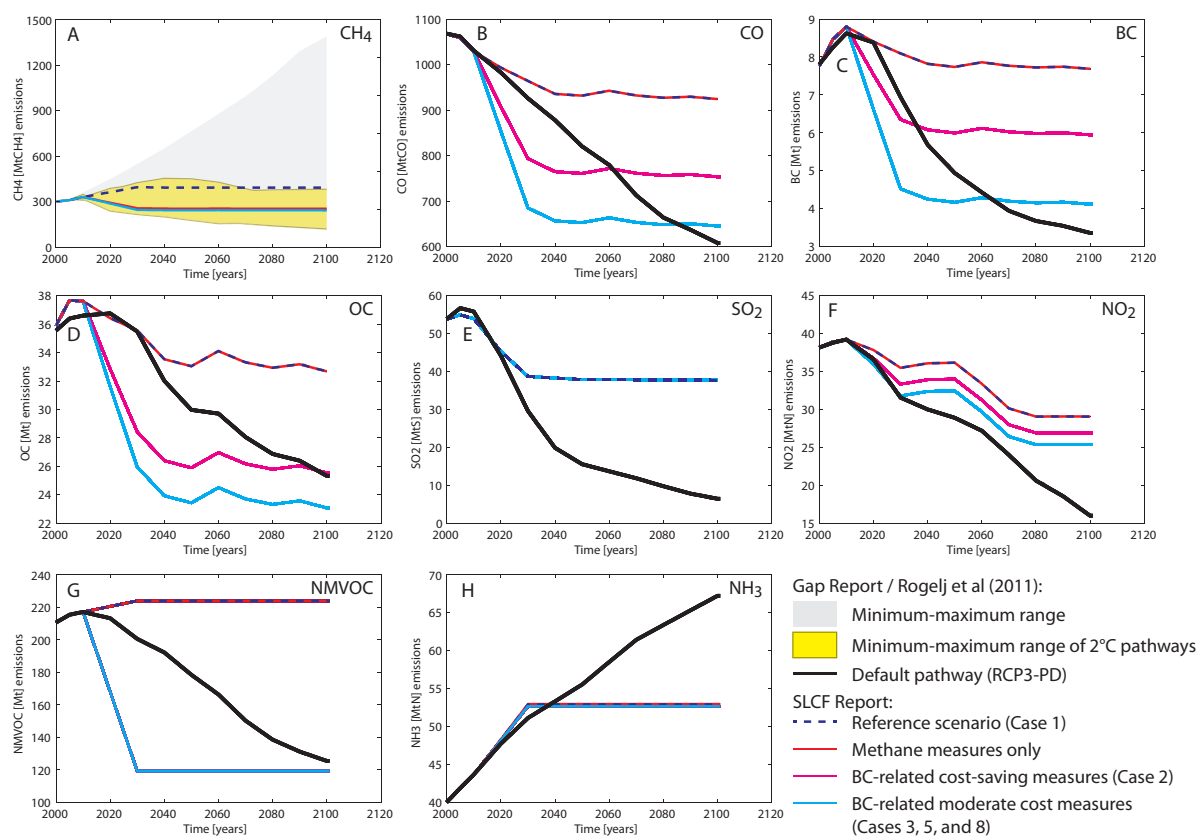


Figure B.2: Emission pathways for short-lived climate forcers (SLCFs). Emissions of SLCFs from the Gap Report and the SLCF Reports for (A) methane, (B) carbon-monoxide, (C) black carbon, (D) organic carbon, (E) sulfur-dioxide, (F) nitrogen oxides, (G) non-methane volatile organic compounds, and (H) ammonia. Black lines are the default emissions used in the Gap Report. The grey range shows the minimum-maximum range of methane emissions of all scenarios used in the Gap Report and of all scenarios staying below 2°C with >66% chance, respectively (details shown in Figure B.3). Dashed blue, and solid red, magenta and cyan lines show reference SLCF, methane mitigation, cost-saving SLCF mitigation and moderate cost SLCF mitigation scenarios of the SLCF Reports, respectively. Note that the SLCF Reports did not examine SLCF emission changes after 2030. Note that the SLCFs Reports extended emissions of the species shown here post 2030 with constant values until 2070. Here they are extended further until 2100.

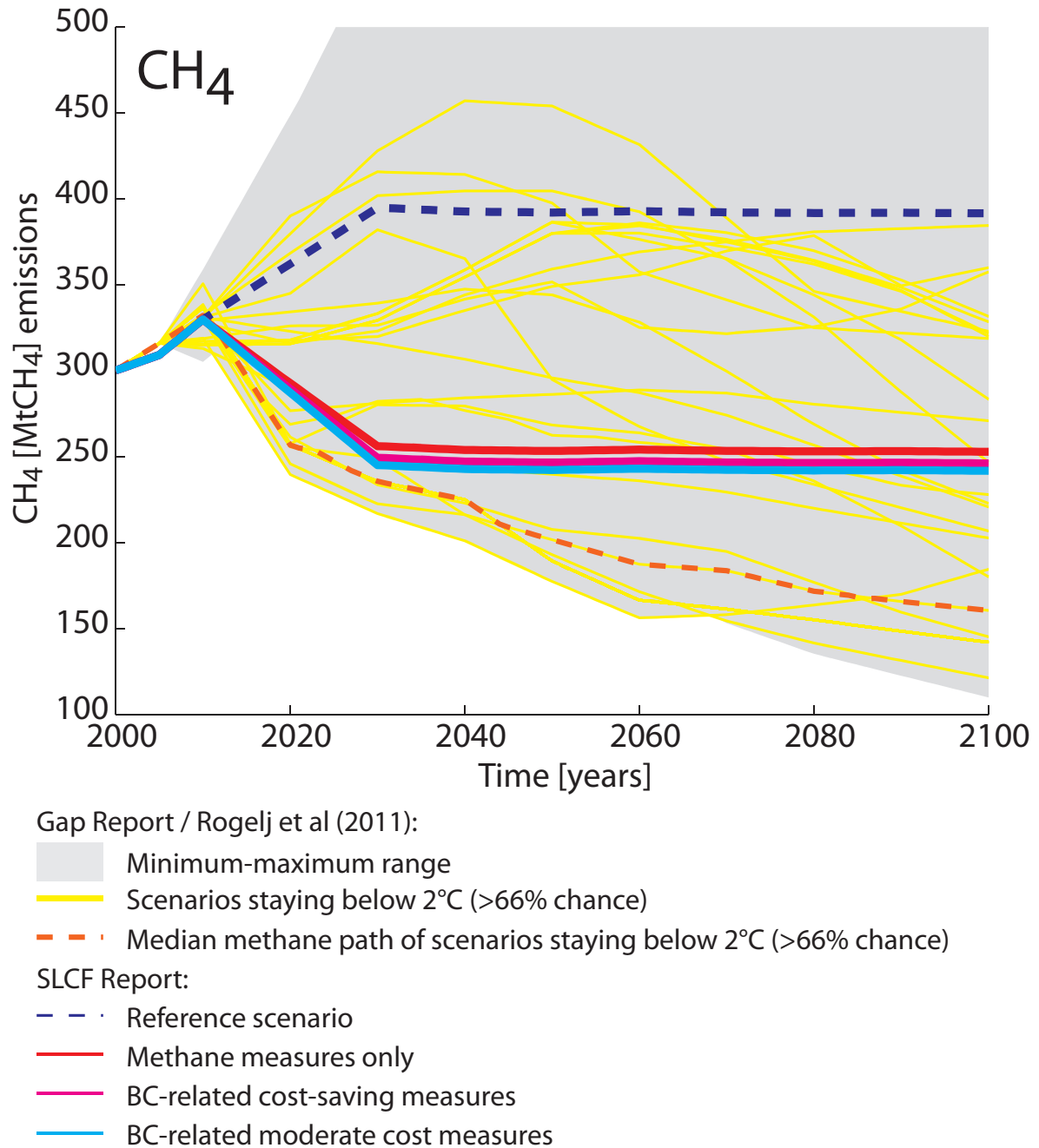


Figure B.3: Analyzed emission pathways for methane. The grey area shows the full range of methane emissions used in the Gap Report. Blue, red, magenta and cyan lines show reference, methane mitigation, cost-saving SLCF mitigation and moderate cost SLCF mitigation scenarios of the SLCF Reports, respectively. Note that the SLCF Reports did not examine SLCF emission changes after 2030. Yellow lines show the methane emission pathways of the 26 scenarios in our original set (Rogelj et al., 2011b) that limit global temperature increase to below 2°C relative to pre-industrial levels with at least 66% probability. Note that by the end of the century more than two thirds of the yellow pathways lie below the lowest methane path assessed in the SLCF reports.

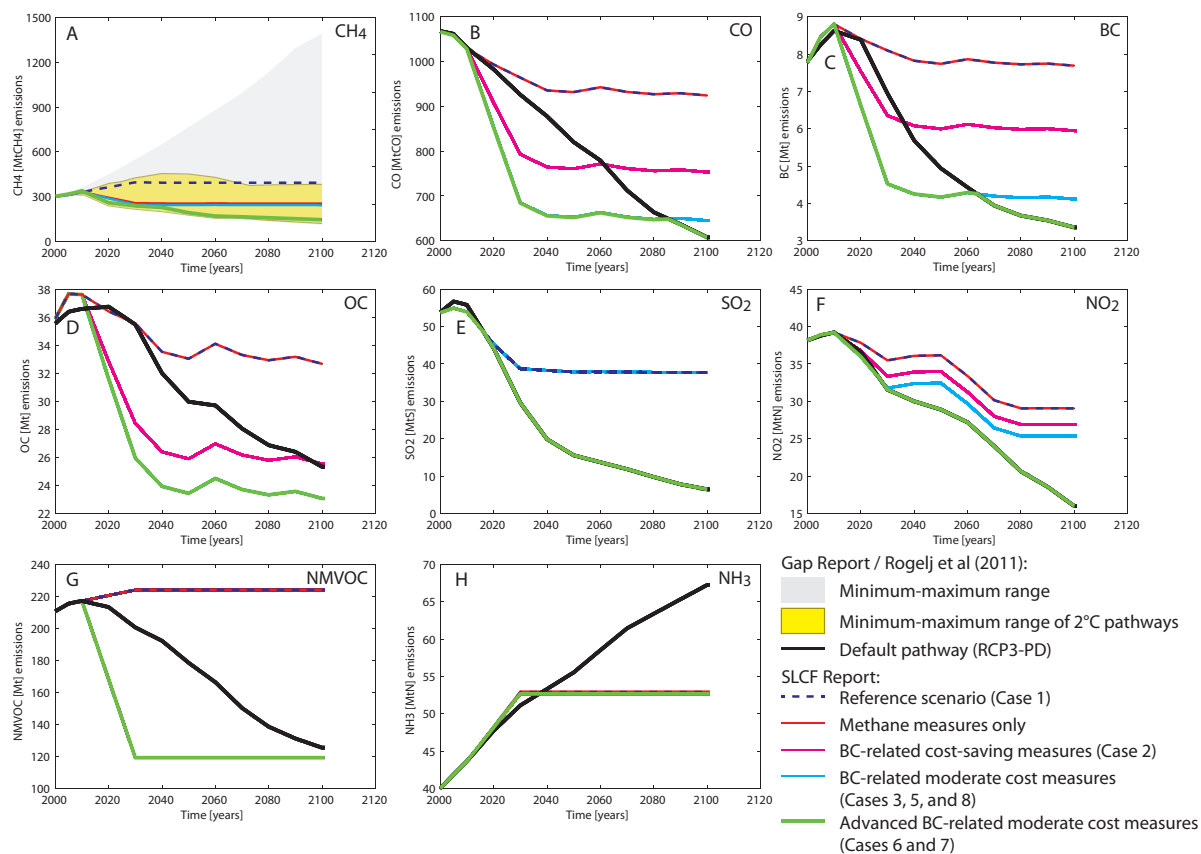


Figure B.4: 'Accelerated action' sensitivity case emissions (Cases 6 and 7, see Table 8.1 in main article). The thick green line represents the emission trajectories for this case. The other lines show the original emission cases as shown in Figure B.2. Note that the SLCF's Reports extended emissions of the species shown here post 2030 with constant values until 2070. Here they are extended further until 2100.

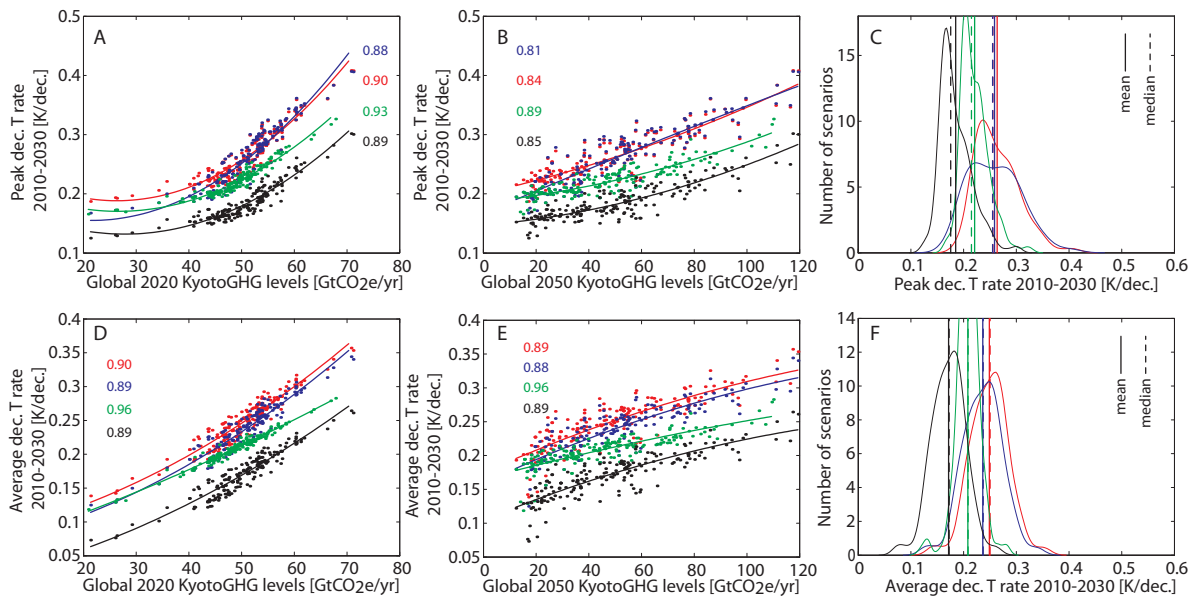


Figure B.5: Influence of short and long-lived forcings on near-term rates of temperature change. As Figure 8.2, but for the 2010-2030 instead of the 2010-2050. Peak (A,B) and average (D,E) decadal rate of temperature increase between 2010 and 2030 as a function of to the level of total Kyoto-GHG emissions in the year 2020 and 2030, respectively. Frequency distributions of peak (C) and average (F) rates of temperature increase between 2010 and 2030, together with mean and median estimates over the entire ensemble (vertical solid and dashed lines). Cases 1, 6, 7, and 8 defined in Table 8.1 are color-coded in red, blue, green, and black, respectively. Solid lines and numbers in panels A, B, D, and E are quadratic fits and R^2 values for each case, respectively.

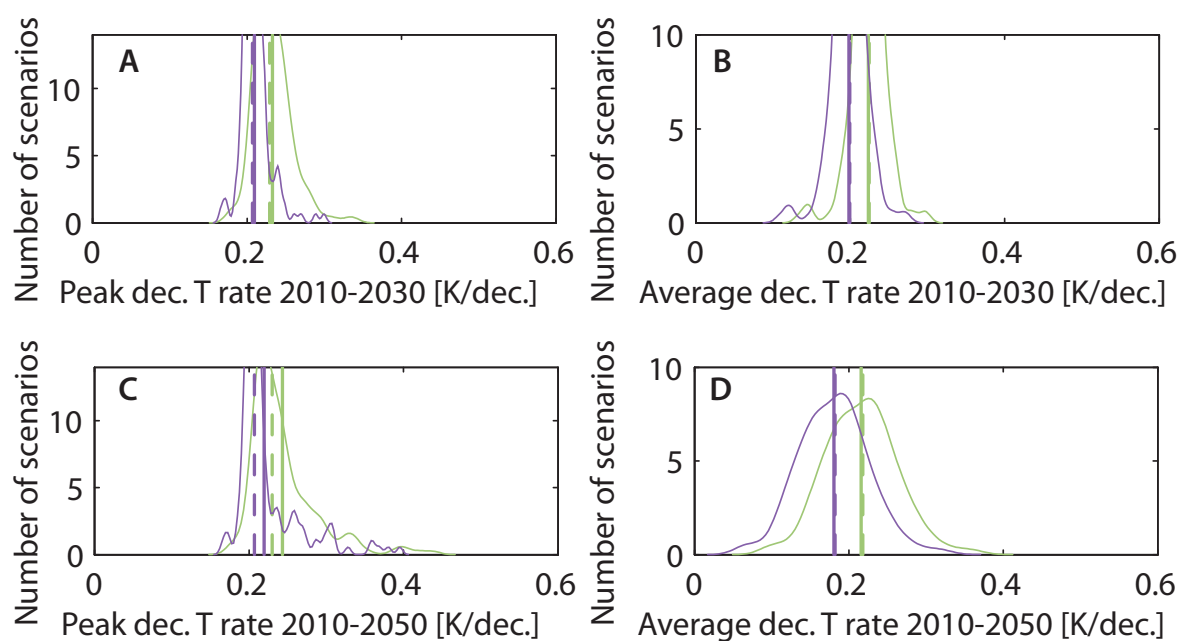


Figure B.6: Influence of methane emission reductions on near-term rates of temperature change. Frequency distributions of peak (A, C) and average (B, D) rates of temperature increase between 2010 and 2030 (A, B) or between 2010 and 2050 (C, D), together with mean and median estimates over the entire ensemble (vertical solid and dashed lines). Methane emissions are changed from their 'Reference' (green, from UNEP (2011c)) to the level implied by the measure assessed in the SLCF Reports (purple). All other forcings are kept the same.

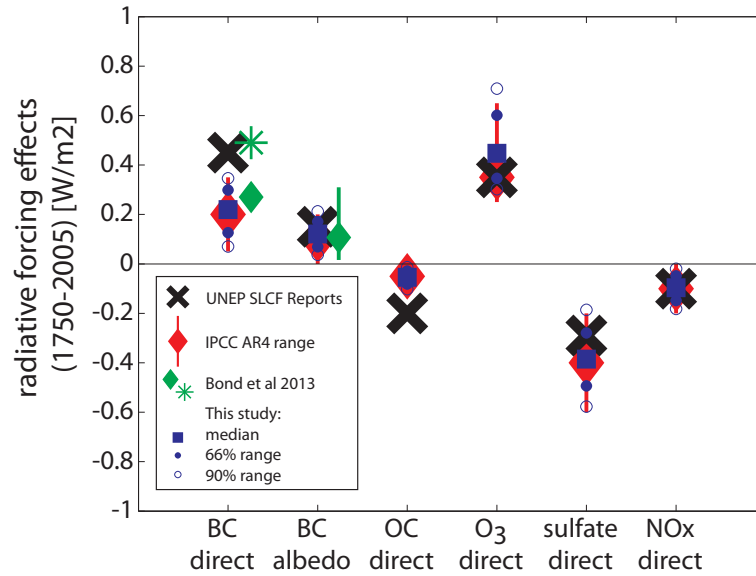


Figure B.7: Comparison of historical radiative forcing (RF). Comparison of the historical RF values SLCFs modified in our cases: the direct RF of black carbon (BC direct), albedo effect of black carbon (BC albedo), the direct effect of organic carbon (OC direct), the direct effect of tropospheric ozone (O_3 direct), sulfates (sulfate direct), and nitrogen oxides (NO_x direct) in the year 2005. Red diamonds and lines show the IPCC best estimates and 5 to 95% confidence range (from Table 2.12 in IPCC (2007d)), respectively. Note that the IPCC Blue squares, filled and empty circles show the MAGICC median, 66% and 90% range, respectively, as used in this study. Black crosses represent the values from the NASA-GISS model as used in the SLCF Reports. Note that the IPCC BC direct estimates are only for fossil fuel, while more recent studies (Bond et al., 2013) also report estimates for the direct effect of the burning of biofuels, amongst other effects. The level marked with * includes the direct BC effect from both fossil fuel and biofuel burning from Bond et al. (2013)

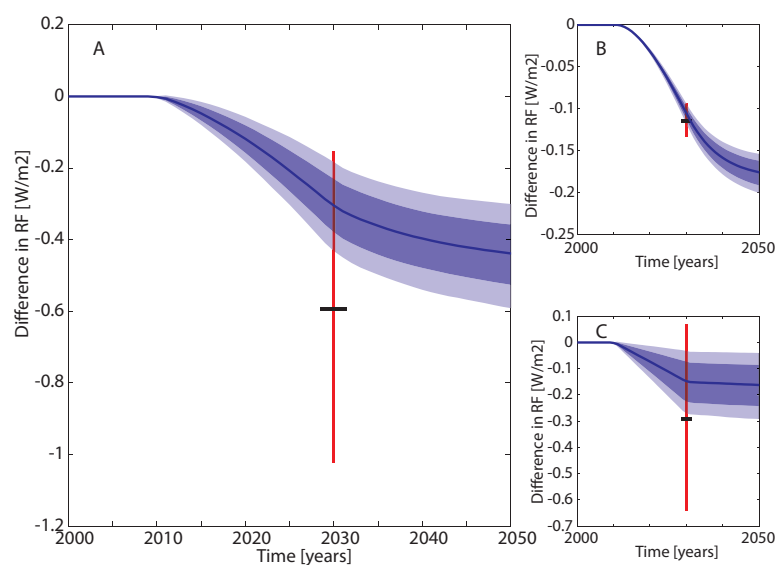


Figure B.8: Comparison of projected radiative forcing (RF). Comparison of the change in total radiative forcing when reducing emissions from their reference level by the moderate cost measures, as assessed by the SLCF Reports. The change is shown for the contributions of (A) all combined forcers, (B) methane only, and (C) all SLCFs excluding methane, respectively. Black horizontal lines show results from the NASA-GISS model used in the SLCF Reports. Red vertical lines show the uncertainty ranges reported in the SLCF Reports. Blue lines and ranges show the median, 66%, and 90% range of the probabilistic results used in this study. This study sees smaller changes in RF due to SLCFs, in part because of its lower historical forcing assumptions (see Figure B.7).

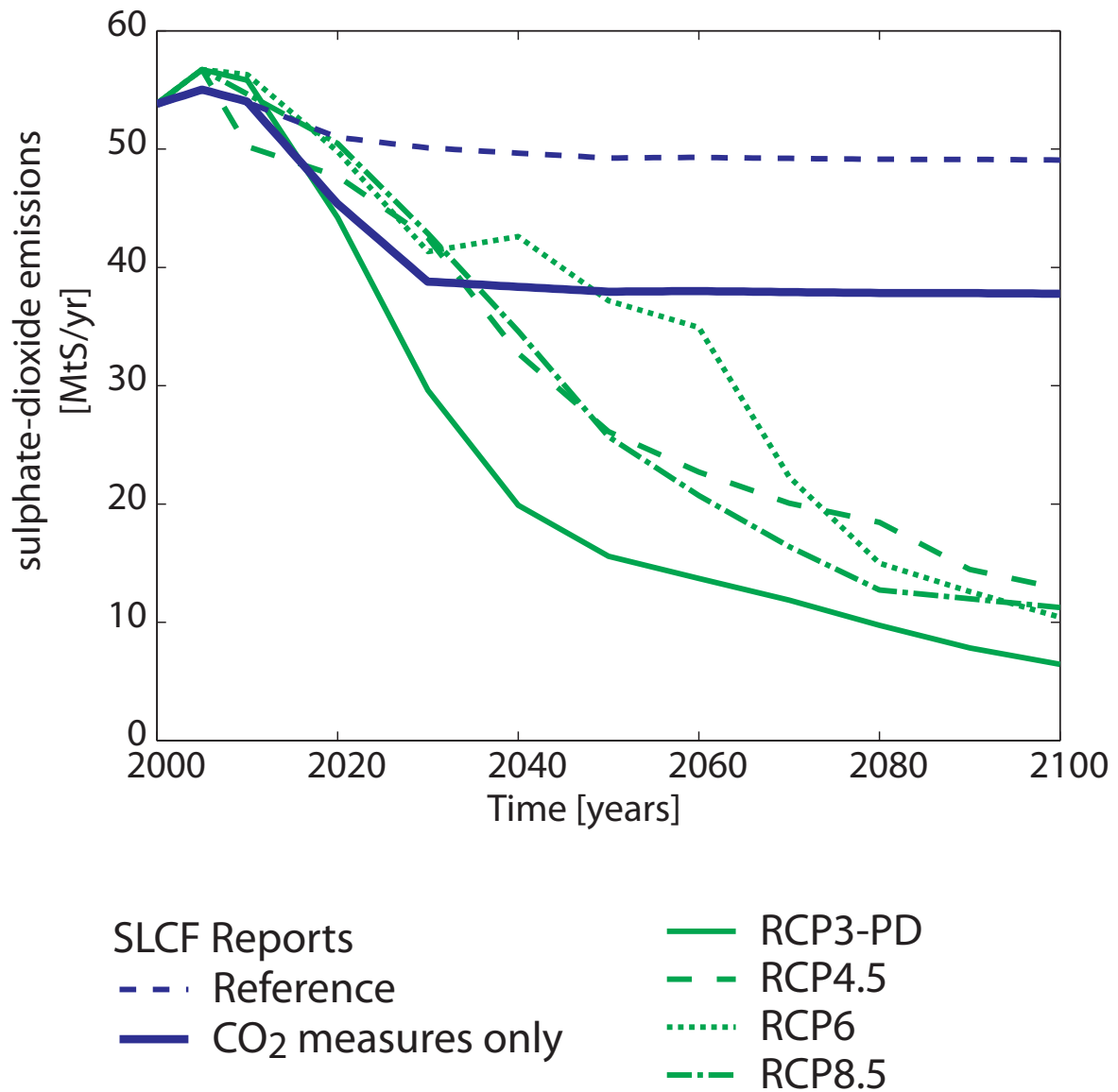


Figure B.9: Comparison of projected sulfur-dioxide emissions. Comparison of projected SO_2 emissions by the SLCF Reports and the four representative concentration pathways (RCPs). SO_2 emissions for the RCPs are described in Lamarque et al. (2011) and available online on <http://www.pik-potsdam.de/~mmalte/rcps/>. The SLCF Reports include a reference SO_2 scenario (dashed blue line) and a scenario for SO_2 emissions when a CO_2 measures are implemented. Because this study particularly looks at low emission scenarios, the '450 scenario' was used here as the SLCF Reports assumptions. In the sensitivity cases which are labeled with 'with sulfur-dioxide mitigation' the RCP3-PD path is assumed.

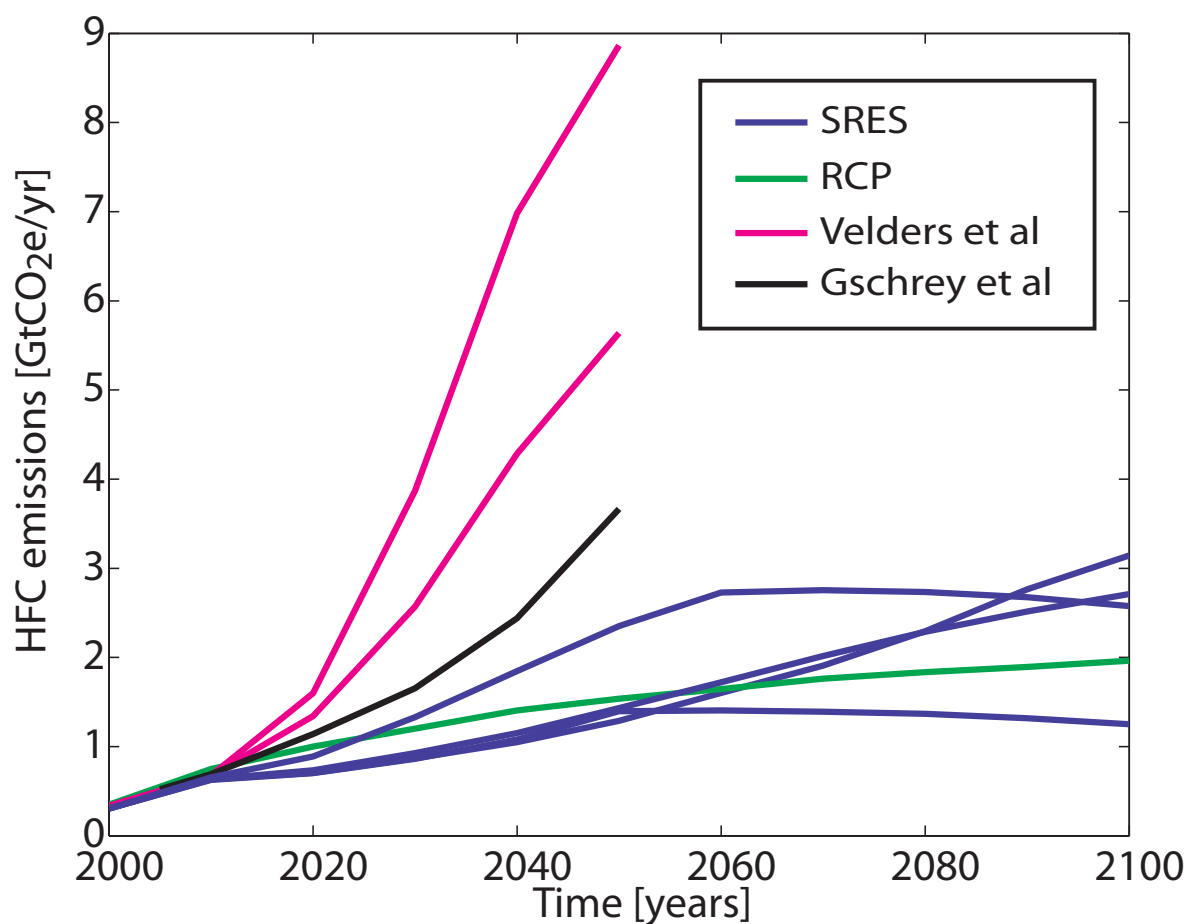


Figure B.10: Comparison of projected HFC emissions. Comparison of projected HFC emissions by Velders et al. (2009) (magenta), Gschrey et al. (2011) (black), the SRES scenarios (Nakicenovic and Swart, 2000) (blue) and the RCP8.5 (Riahi et al., 2011) (green), which, although it is a non-mitigation path, already includes voluntary measures to reduce HFCs.

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