Title

Nuances of Climate Change Mitigation: Four Different Goals and Approaches in the Climate Boxes Framework

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Publication Date

2012

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by

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A dissertation submitted in partial satisfaction of the
requirements for the degree of Doctor of Philosophy
in the
Energy and Resources Group
in the
Graduate Division
of the
University of California, Berkeley

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Fall 2012

Abstract

Nuances of Climate Change Mitigation:
Four Different Goals and Approaches in the Climate Boxes Framework
by
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The Climate Boxes Framework presented in this dissertation provides a structure to discuss and improve the alignment between policy positions and climate goals. I explore the differences in mitigation paths implied by four different mitigation goals ("boxes"): 1) delaying climate change, 2) avoiding a global temperature increase of 1.5-2°C above pre-industrial levels, 3) avoiding a global temperature increase of 3-4°C above pre-industrial levels, or 4) no delay or avoidance of climate change. The topic of delay is particularly under-explored in the literature, and I devote several chapters to calculations of its potential, possible benefits, and arguments for and against different means of achieving it.

Throughout the dissertation, the focus is on identifying the physical and technical constraints that set the bounds on the climate goals that can be achieved via different types of mitigation. For Box 1 (Delay), I calculate that maximum technically feasible reductions of short- and medium-lived pollutants have the potential to delay a given temperature increase by 15 years relative to the current trajectory. Elimination of deforestation would delay a 2°C temperature increase by 20 years relative to the current trajectory. There are many pragmatic reasons for delay, but more research is needed to determine whether there would be lasting climate system benefits from a lower rate of temperature change.

For Box 2 (Avoid 1.5-2°C), I present a broad range of emission trajectories (peak year, target reduction, plateau year) that would avoid 2°C with various likelihoods, demonstrating the option to leverage an early emissions peak to make relatively smaller reductions for the period through 2050. For both Box 2 (Avoid 1.5-2°C) and Box 3 (Avoid 3-4°C), I calculate the cumulative CO_2 budgets that would avoid each temperature increase in the transient and equilibrium time periods. I also highlight the limitations of the carbon budget theory and identify future research needed to make the theory more robust. I find that if CO_2 emissions are consistent with an equilibrium goal of avoiding 2°C, then a transient temperature peak

above 2°C is unlikely (25-40% likelihood even with elimination of cooling sulfates). Maximum technically feasible reductions of short- and medium-lived warming pollutants could further improve the likelihood of avoiding a transient temperature peak by 8-11 percentage points. For Box 3 (Avoid 3-4°C), I propose a novel policy approach (the Point One Approach) that would be based on the increments of 0.1°C temperature increase that are currently experienced every 7-8 years.

Overall, I demonstrate that whether policies are consistent with "addressing climate change" depends materially on *which* mitigation goal is being pursued; most policy choices are only consistent with a sub-set of the boxes. This applies particularly to policies related to CO_2 targets, short- and medium-lived pollutants, offsets, geo-engineering, fossil fuel expansion, forests, and developing world infrastructure.

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Acknowledgements

As is true for most of life's meaningful accomplishments, the creation of this dissertation relied on the support, insights, and lessons provided by a host of wonderful people who I have had the privilege to spent time with over the past five years and over the course of my life.

My first thanks go to my husband Keith, who thoroughly read this dissertation several times, provided countless suggestions for edits, spent too many hours troubleshooting MS Word, cooked dinner for the past several months, and most importantly, has shared so much love and happiness with me over the past twenty years.

My next thanks go to my parents, who raised me to believe that nearly anything can be achieved with sufficient dedication, to have courage to make changes in my life, to listen well and form my own opinions, and to have the discipline required to sit alone in a room for months to finish a dissertation. Their steadfast love and strong values continue to shape the person I am today.

I would not be in graduate school without the support of my former Nike colleagues, Hans, DeeDee, and Paul. After guiding, championing, and supporting my work inside the company, they selflessly encouraged my unconventional decision to pursue a mid-career Ph.D. Instead of dissuading me, they supported my choice with letters and a Cal T-shirt, and I owe the opportunities I've had here to their willingness to help me achieve my goals.

On a final personal note, I want to thank my dedicated workout buddies Sam, Sintana, Diana, and Danielle, who have kept me swimming, running, and cycling for the past five years. In addition to keeping all of us healthy and fit, our workouts have provided structure for my writing days and laid the foundation for lifelong friendships.

I next want to thank the ERG community of faculty, students, and staff. ERG has provided me with extraordinary academic freedom to pursue the questions that interest me and an energizing, supportive, intellectually stimulating environment in which to do my work. It is a joy to spend time with dozens of people who are brilliant and committed to their work, and I look forward to a lifelong source of inspiration within the community of ERG alumni.

My advisors, John Harte and Margaret Torn, have been consistently supportive and selfless. They have guided me to focus on those research ideas that energize me, and their absence of self-interest in my choices has allowed me to shape this dissertation into what I wanted it to be.

They have demonstrated great patience in reading this document multiple times and their flow of insightful, gentle questions has resulted in significant technical improvements and stylistic changes.

I am grateful to Dan Chatman, my outside committee member, for the dedication and seriousness with which he took the task. His insistence on high quality prose and his detailed critique of the content and the structure have led to material improvements in the dissertation.

My fellow students in Climate Lab, Harte Lab, and PhD Seminar have consistently provided insightful, pointed feedback and a forgiving audience for new ideas and hot-off-the-press research results. I give special thanks to John Harte, Mike O'Hare, and Margaret Torn, who gamely agreed to participate as faculty advisors to the student-initiated Climate Lab.

My perspectives on climate policy have been significantly influenced by Holmes Hummel, who advised my master's work and taught climate policy. Her vigor, enthusiasm, and seriousness for the subject made lessons stick and her energy for her work is a source of inspiration.

I would like to thank the community of climate scientists and policy researchers who have done the decades of work upon which this dissertation builds. The EDGAR team and Meinshausen et al. deserve particular credit for providing high-quality, freely available, easily accessible datasets. I also want to specially thank Drew Shindell, Zig Klimont, Harry Vallack, and Malte Meinshausen for being gracious and responsive in answering questions, discussing results, and sharing data.

Finally, my late advisor Alex Farrell told me, "We write in order to think." This phrase has come frequently to mind over the past year, as I have been amazed at how my thoughts have morphed and deepened through the writing process. For this insight and many others, I remember him fondly.

Preface

I entered the M.S./Ph.D. program at UC Berkeley's Energy and Resources Group in 2007 with the intention of researching how to take alternative energy technologies to scale. I had just spent over a decade in the corporate world, mostly working with large companies on finance and strategy, and wanted to see if I could apply what I knew to the challenge of scaling up alternative energy technologies for climate change mitigation.

Two things happened in my first year that changed my research direction into the one reflected in this dissertation. First, I realized that I understood far less about near-term climate change than necessary to be comfortable as a mitigation strategist. My rule #1 of strategic planning is that you first have to understand the problem that you are trying to solve. Second, my advisor on the technology side, Alex Farrell, very sadly passed away. I was fortunate that John Harte and Margaret Torn shared my interests in the intersection of climate science and mitigation and were willing to become my supportive co-advisors on my now-transformed dissertation.

Since then, I have focused most of my research effort on the questions about near-term climate change science and mitigation that I consider important to making decisions at the national and global levels. I have used my science training to venture deeper into climate science territory than most mitigation strategists tend to go, and the dissertation reflects my best attempts to translate and advance state-of-the-art climate science into knowledge that is actionable for mitigation.

Along the way, I have encountered debates about whether we should mitigate short-lived pollutants or focus solely on long-lived carbon dioxide and debates about whether it is better to deploy lower-emission technologies now or zero-emission options later. In this process, I have wrestled with how to put a simple framework around these decisions, and I offer in this dissertation a framework of four boxes that aims to capture many of the nuances of decision-making that come after the step of deciding to "do something" about climate change.

The Climate Boxes Framework presented here revolves around climate outcomes and mitigation approaches and, in its highest use, would lend structure and rigor to broader discussions that integrate cultural norms, values, economics, political power, international relations, structural constraints, and other considerations into the decision-making process.

Chapter 1 Introducing the Four Mitigation Boxes

Nearly 50 years ago in 1965, President Johnson told the U.S. Congress that, "This generation has altered the composition of the atmosphere on a global scale through… a steady increase in carbon dioxide from the burning of fossil fuels." [1] Since then, over 60,000 academic articles have been written on climate change[1], the United Nations (UN) General Assembly in 1988 endorsed the creation of an Intergovernmental Panel on Climate Change (IPCC), 4 international assessment reports have been written by the IPCC, 194 nation states have adopted the UN Framework Convention on Climate Change in 1992 [2], 18 international meetings have been held by the Council of the Parties to the Convention, and over 100 nations have agreed in 2009's Copenhagen Accord [3] to limit global temperature increases to 2°C above pre-industrial levels. In short, the issue of climate change has received a half-century of increasing attention from members of the scientific[2] and political communities, yet global temperatures have steadily increased to ~0.8°C above pre-industrial [4].

Today, distinctly different opinions exist on what to do about mitigating (i.e., slowing, reducing, or stopping) climate change,[3] even among those who agree that something should be done. Some advocate returning to 350 ppm CO_2 [5][4] (the atmospheric concentration of CO_2 in 2010 was 390 ppm [6]), while some advocate aiming for 450 or 550 ppm [7]. Some want to avoid a global temperature increase of 1.5°C above pre-industrial [8], others want to avoid 2°C [3, 9], and others think 3°C would be fine [10]. Some want all renewables and efficiency [11], some want nuclear [12], some want no nuclear [13], and some want natural gas [14]. Some want efforts put into reducing short-lived pollutants [15], and some think that would be a bad idea and that focus should be on CO_2 [16]. Some want binding targets [17], some want more flexible targets [18], some want a bottom-up emergent approach [19], some want only no-regrets actions [20], and some want a Plan B for worst-case outcomes [21]. Additionally, there are those who want no action on climate change mitigation at all [22].

Which policies and approaches make sense from the perspective of a given citizen, policymaker, or organizational leader depends, in part, on the goal that person, their organization, or their stakeholders have for climate mitigation. It also depends, of course, on

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[1] There are 61,193 citations for the topic "climate change" since 1965 in Web of Science as of June 5, 2012.

[2] Scientific history traces back to the 19th century to John Tyndall's discovery that CO_2 is a greenhouse gas and to Svante Arrhenius's discovery that CO_2 from fossil fuels could alter the earth's climate.

[3] The topic of how to adapt to whatever change happens is a separate and important topic that lies beyond the scope of this dissertation.

[4] Atmospheric concentration of CO_2 is measured in parts per million (ppm).

the broader political, social, and economic context in which decisions about climate mitigation are made.

This dissertation focuses specifically on the implications of different climate mitigation goals. Four distinctly different possible goals of mitigation are identified in the Climate Boxes Framework, and the dissertation walks step-by-step through both the climate implications of a given goal and the mitigation requirements for achieving that goal. In the conclusion (Chapter 16), I tie climate mitigation goals back to policy, identifying which energy, technology, and climate policy choices are consistent with which climate mitigation goals. For readers who are primarily interested in policy, it may make sense to read the conclusion first to identify which mitigation goals are implicitly supported by your preferred policy choices and then read the dissertation from the beginning to explore the implications.

1.1 The Climate Boxes Framework

Clarity in the climate discussion requires acknowledging that there exist multiple possible climate goals of mitigation, with only partial overlap of mitigation paths. In Table 1-1, I define the Climate Boxes Framework for four distinctly different mitigation goals, corresponding to different priorities for time horizon (x axis), different climate outcomes (y axis), and different required mitigation actions (box content).

On the horizontal axis is the time dimension describing concern about climate outcomes: concern about the near-term (20-40 years), concern about the long-term (beyond 40 years), or no concern about climate outcomes. I have defined the near-term as 20-40 years to correspond with the lifetimes of today's senior decision-makers.

On the vertical axis is a set of four possible climate outcomes:

- **Delay or slow down climate change**: Slow down the rate of climate change and delay a given climate change outcome by a certain number of years. This box does not include a specific goal for capping the long-term temperature increase.
- **Avoid 1.5C or 2°C**: Avoid ever exceeding a global temperature of 1.5°C-2°C above pre-industrial levels.[5]
- **Avoid 3°C or 4°C**: Avoid ever exceeding a global temperature of 3-4°C above pre-industrial levels.[6]
- **Don't delay or avoid climate change**

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[5] Increases in Fahrenheit: 1.5°C = 2.7°F; 2°C = 3.6°F.

[6] Increases in Fahrenheit: 3°C = 5.4°F; 4°C = 7.2°F.

Climate Outcome	Time Horizon of Concern		
	Most concerned about climate outcomes in the next 20-40 years	Most concerned about long-term climate outcomes	Not concerned
Delay or slow down climate change	Box 1	n/a[a]	n/a
Avoid 1.5°C or 2°C	Box 2		n/a
Avoid 3°C or 4°C	n/a[b]	Box 3	n/a
Don't delay or avoid climate change	n/a	n/a	Box 4

Table 1-1: The Four Boxes of Climate Mitigation[7] [8]

I have chosen the temperature ranges (1.5°C to 2°C and 3°C to 4°C) for Box 2 and Box 3 because of their prominence in the international policy discussion. In 2009's Copenhagen Accord [3], 100+ nations agreed to constrain global warming to 2°C above pre-industrial levels and to consider a 1.5°C goal by 2015. Since then, nations have made voluntary pledges for emission reductions through 2020-2050 that could constrain temperatures to approximately 3-4°C above pre-industrial levels if emissions were to follow a declining trajectory in the second half of the century (section 2.2.a).

Inside each box will sit the mitigation requirements of the box, developed section-by-section throughout the dissertation. The choice of box is analogous to many other decisions in life: What am I or my organization willing to do to achieve a certain result? Is the result we want worth the effort we must put in? Preferences for outcomes are elevated or tempered by perception and knowledge of what is required to achieve them. As scientist L.D.D. Harvey stated, "The acceptable risk depends in part on the cost (or perceived cost) of reducing the risk." [23] Ultimately, the desired outcome must be reconciled with the required action to allow the choice of a single box.

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[7] A) The benefit of delaying is near-term and is only applicable if you are concerned about the near-term (Chapter 6). B) Even high-end emission scenarios are not expected to hit a temperature increase within 40 years of 3°C above pre-industrial levels (likely range for 2050 is 1.4°C to 2.8°C), as we will see in section 2.3. "Likely" is defined as a 66% confidence interval, in line with standards of IPCC AR4 (Working Group I Summary for Policymakers, p.3).

[8] Note, the vertical axis does not include a row for "No climate change". Section 2.4 will show that while it is physically possible to have negligible additional climate change, it would require immediate cessation of all emissions. This option is excluded from the framework due to sheer implausibility.

I do not take a position in this dissertation on which box choice is best. My intention instead is to provide a neutral presentation that acknowledges a wide range of possible goals and a framework within which people with different perspectives can have a discussion. The Climate Boxes Framework could be used by interested citizens, institutional decision-makers, corporations, advocacy groups, negotiators, political leaders, and anyone else who has a personal or professional interest in forming an opinion, evaluating their position, or understanding alternate positions about climate mitigation goals and/or related policies (e.g., energy, public health). Because climate change and the mitigation of climate change have eventual implications for nearly every sector of the economy and many facets of personal and professional life, the range of considerations that someone may bring to this discussion is limitless and an evaluation of the wide range of reasons *why* a given box may be chosen is well beyond the scope of this dissertation. Suffice it to say that among the world's seven billion people, the breadth of perspectives on the widest range of social, political, economic, personal, and other issues ensures that there are those who have reason to support each of the four boxes.

At the global level, the cumulative result of a messy set of individual and institutional actions will be a single aggregated global mitigation path and global climate outcome. Thus, while society as an entity cannot hold values and choose a box, the actions and outcomes at a global level create an implied societal box choice. Based on actions to-date, "society" is currently hovering between Box 1 (delay) and Box 3 (avoid 3-4°C), despite international statements of the desirability of Box 2 (avoid 1.5-2°C).

1.1 Why Box Choice Matters

The subsequent chapters will show that the mitigation options available to achieve each box are different – by atmospheric pollutants, by timeline, and by sectors affected. Pollutants can be categorized into two main groups: 1) long-lived pollutants, most prominently carbon dioxide (CO_2), and 2) short- and medium-lived pollutants, including black carbon (BC), methane (CH_4), and ozone precursors. Lifetime refers to the length of time that an emitted pollutant remains in the atmosphere (see section 4.1).[9] The two categories of pollutants play different roles in

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[9] Pollutants vary in the time they remain in the atmosphere. The time required for the airborne amount to decrease to 37% of original airborne amount (the e-folding time) is on the order of days to weeks for short-lived pollutants (e.g., black and organic carbon, tropospheric ozone, and sulfur dioxide), a decade for medium-lived (e.g., methane and some halocarbons), and a century for long-lived (e.g., nitrous oxide, some halocarbons). CO_2 takes roughly a century to reach 37%, then decays more slowly over millennia.

mitigation, depending on the time horizon (near-term or long-term) and magnitude of change versus business-as-usual, i.e., depending on box choice.

Because mitigation differs between boxes, so do the policies that achieve the goals of a given box. Box choice narrows policy options, and the inverse also applies, as policy choices are only consistent with a subset of box choices (Table 16-3). Boxes thus provide a lens through which to view and discuss on-going policy debates. Examples of policy choices that may be influenced by box choice include: decisions on the extent to which mitigation focuses primarily on CO_2 and other long-lived pollutants versus a mix of long-, medium-, and short-lived pollutants (section 7.2); long-term investment choices regarding expansion of fossil fuel infrastructure (section 10.2 and Chapter 11); decisions to research and /or implement geo-engineering via solar radiation management (sections 5.4 and 7.3);[10] incentives to reduce deforestation (section 5.3.a and 15.1.c); and rules for trading of emissions offsets, including the criteria and trading metrics[11] that apply both domestically and between developed and developing nations (section 10.4 and 16.2.c).

1.2 How the Dissertation is Organized

Throughout the dissertation, the focus is on identifying the physical and technical constraints that set the bounds on the climate goals that can be achieved via different types of mitigation. Analyses are grounded in established analytical climate science methods, scenarios, and inventories. For each box, I analyze the pollutant-level mitigation options, the timeline constraints, and the uncertainties. I also put these scientific results in the context of arguments made for and against each climate goal and the different mitigation approaches.

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[10] Solar radiation management (SRM) includes techniques that would reflect more than the usual amount of sunlight, such as regular injections of reflective particles (e.g., sulfates) into the stratosphere, regular seeding of clouds over oceans (more reflective than water), or the placement of mirrors in space. These techniques could reduce warming temporarily, though preliminary research suggests that precipitation patterns would be altered, ocean acidification would continue to increase, and there would be numerous adverse side effects (e.g., difficulty in doing astronomy) (see section 5.4 and 7.3).

[11] The standard trading metric among warming pollutants is the 100-year global warming potential. Some who are concerned about the near-term have proposed converting to a 20-year global warming potential, which places more weight on short- and medium-lived pollutants.

	Most concerned about climate outcomes in the next 20-40 years	**Most concerned about long-term climate outcomes**	**Both**
In general	Ch 3: Parallel Pursuit of Near-Term and Long-Term Climate Mitigation		Ch 2: Climate Change Projections Ch 16: Applying the Climate Boxes Framework to Decision-Making
Delay or slow down climate change	Ch 4: Mitigation Potential and Progress on Short- and Medium-Lived Pollutants Ch 5: Potential for Delaying Climate Change Ch 6: The Possible Benefits of Delaying Climate Change Ch 7: Issues to Consider Regarding Mitigation of Near-Term Climate Change Ch 8: Scientific Research Needs on the Topic of Mitigating Near-Term Climate Change	n/a	
Avoid 1.5°C or 2°C	Ch 9: Global CO_2 Target Setting to Avoid 2°C Ch 10: Implications for Developing Nations Ch 11: Implications for the Natural Gas Industry Ch 12: CO_2 Mitigation Progress and the Role of Discontinuous Peaks Ch 13: Improving the Likelihood of Avoiding 1.5°C or 2°C via non-CO_2 Pollutants Ch 14: Arguments For and Against Box 2 (Avoiding 1.5°C or 2°C)		
Avoid 3°C or 4°C	n/a	Ch 15: The Point One Approach to Avoiding 3°C or 4°C	

Table 1-2: Mapping of Chapters to the Climate Boxes Framework

The structure of the dissertation maps to the box choices, as illustrated in Table 1-2, and the chapters are grouped into sections as follows:

Section I (chapter 2) provides background on climate change scenarios and projections that are used throughout the dissertation.

Section II (chapters 3-5) discusses the mitigation required to reduce near-term climate change, including why this differs from reducing long-term climate change.

Section III (chapters 6-8) considers the possible benefits of delay, the arguments for and against different means of achieving delay, and the research needs relating to near-term climate.

Section IV (chapters 9-14) explores the mitigation requirements to avoid a 1.5°C-2°C temperature increase above pre-industrial levels and the implications of those requirements.

Section V (chapter 15) discusses the mitigation path required to avoid 3°C or 4°C and policy ideas consistent with that goal.

The dissertation concludes in Chapter 16 by summarizing the themes of the dissertation, reviewing policies consistent with each box, and identifying areas needing further research.

Section I Climate Change in the Near-Term and Long-Term

Section I summarizes the prospective climate changes that will be discussed in the rest of the dissertation. It presents prominent data and modeling results for near-term and long-term climate changes, with temperature projections for a variety of emission scenarios and an examination of what climate changes are already committed. Outcomes are differentiated between what can be expected in the near-term versus the long-term, defined respectively in this dissertation as 20-40 years and 40+ years.

Chapter 2 identifies the approximate timing when the temperature ceilings identified in Table 1-1 (Box 2: 1.5-2°C; Box 3: 3-4°C)) could be reached, establishing the implicit time table for mitigation action.

Chapter 2 Climate Change Projections

This chapter lays the foundation for the rest of the dissertation. In it, I present historical climate observations and projections of climate change that will occur under different future scenarios to answer the following questions:

- What climate changes are projected in the near-term (20-40 year) horizon and in the long-term (40+ year) horizon, under different mitigation scenarios?
- How long of a delay in reaching a given temperature is created by moving from a less aggressive to more aggressive mitigation scenario?
- When will the global temperature hit 1.5-2°C (or 3-4°C) under different mitigation scenarios? Which scenarios avoid 1.5-2°C (or 3-4°C)?
- What climate outcomes are already committed, and how does that differ based on the definition of "committed"?

This chapter compares projections of the most prominent emission scenarios and current emission trends, extracts information about delays and timelines, and compares varying definitions of "committed" climate change. The chapter serves the dual purpose of: a) laying the foundation needed to understand the climate implications of box choice, and b) providing a comparison of emission scenarios and definitions that have not been compared elsewhere. This information will provide the basis for the discussion in the rest of the dissertation.

2.1 The Latest Climate Change Projections

Global surface temperature increased ~0.8°C between the end of the pre-industrial period (1850-1899) and 2001-2005, with a trend of 0.13°C/decade over the 1955-2005 period. [4][12] Temperatures are expected to continue to increase during the 21st century under a wide range of possible emission scenarios, with the magnitude of temperature increase varying widely among scenarios.

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[12] The temperature increase from the first fifty years of the instrumental record (1850-1899, or "pre-industrial") to the 2001-2005 period was 0.76°C (0.57-0.95°C). The linear averaged warming trend from 1955-2005 was 0.13°C per decade. Some data sources compare future temperatures to 1980-1999 or to year 2000 and must be converted to compare to pre-industrial. In the rest of the chapter, I assume that the year 2000 was approximately 0.7°C above pre-industrial (0.76°C – 0.13°C*(2003-2000)/10)=0.72°C) and that the period 1980-1999 was approximately 0.6°C above pre-industrial (0.76°C – 0.13°C*(2003-1990)/10)=0.59°C). Because recent temperature rise has been non-linear (above the linear average of 0.13°C per decade), the estimate of 0.6°C for the period 1980-1999 is high by a few hundredths of a degree. This does not materially affect the analysis or conclusions.

Global average surface temperature change is the most direct manifestation of the extra energy being added to the climate system (see section 6.2.b.ii.i), and temperature is used throughout this dissertation as a proxy for climate change. However, it should not be construed as the only important element of a changing climate. Climate change includes temperature changes, changes in precipitation patterns, changes in ocean and atmospheric circulation patterns, changes in cloud patterns, and much more. [24] The connection between temperature and large-scale climate and ecology outcomes will be discussed in section 6.2.

Changes to the physical climate drive impacts on water supplies, ecosystems, species survival, food, coastal conditions, and health. [25] The relationship between climate variables and impacts is complex, but is often simplified to link to temperature. [25] Impacts that would accompany 2°C are considered severe enough that 100+ nations have agreed in the Copenhagen Accord to the goal of limiting global temperature increase to 2°C above pre-industrial levels (1.4°C relative to 1980-1999). [3] We will see below that temperatures in year 2100 could range from 1.8-7.0°C above pre-industrial levels under commonly modeled scenarios. More information on impacts is discussed in section 6.1.

2.1.a Standard Scenarios and Reference Scenarios

Scenarios describe the future stocks and flows of pollutants, and the most prominent ones provide common reference points that are used throughout the climate science and policy literature and throughout this dissertation. Their emission trajectories and temperature projections are presented in this chapter and in Appendix A. I will discuss them in the categories of standard scenarios and reference scenarios:

Standard scenarios are designed in sets to reflect a range of possible future paths, with no probability provided as to the likelihood of one versus another. The two most frequently referenced sets are the RCP and SRES scenarios:

- **Representative Concentation Pathways (RCPs)** [26, 27]: These scenarios are the latest standard scenarios being run by the major climate modeling groups in preparation for the next Intergovernmental Panel on Climate Change (IPCC) assessment report (AR5). The scenarios are defined by their radiative forcing in year 2100[13] – e.g., RCP 8.5 has a forcing of 8.5 W/m^2 in year 2100. The four scenarios from high to low are: [28] RCP

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[13] Radiative forcing (RF) is a property of the climate at a point in time, and is the extra energy input to the climate system that is attributable to anthropogenic emissions. A more detailed description of RF is provided in section 6.2.b.ii.i. RF from all anthropogenic pollutants in year 2005 was ~1.6 W/m^2 (90% confidence interval: 0.6-2.4 W/m^2), per IPCC AR4.

8.5, RCP 6.0, RCP 4.5, and RCP 3-PD. The middle two scenarios (RCP 6.0 and RCP 4.5) are stabilization scenarios, which assume that forcing stabilizes at 6.0 W/m^2 and 4.5 W/m^2 through equilibrium. The highest scenario (RCP 8.5) assumes that forcing hits 8.5 W/m^2 in 2100 and continues to rise (to 12.5 W/m^2 in 2500). In the lowest scenario (RCP 3-PD, with PD meaning "peak and decline"), forcing peaks at 3 W/m^2 before 2100, declines to 2.6 W/m^2 in 2100 (this scenario is also sometimes called RCP 2.6) and then continues to decline (to 1.5 W/m^2 in 2500). [26, 29][14] See Figure 2-1 for the emission trajectories of these four scenarios.

- **Special Report Emissions Scenarios (SRES)** [30]: These were the standard scenarios used as input by the major climate modeling groups for the last two IPCC assessment reports (TAR and AR4). There are 4 scenarios: B1, B2, A1, A2. These four scenarios describe different storylines about future world economic, social, and technological development. Each modeling team defined emissions paths consistent with the storyline; one emission path for each scenario was defined as the "marker" scenario, shown in Figure 2-1. The A1 scenario was further refined as a family of scenarios with varying technology approaches: A1FI (fossil intensive), A1T (non-fossil emphasis), and A1B (balance of fossil and non-fossil).

Three additional sets of standard scenarios that are less frequently referenced in the climate science literature are the CCSP, IEA, and Shell scenarios. These are shown briefly in this chapter to provide a broad picture of the scenarios that are currently in the public discussion:

- **US Climate Change Science Program (CCSP)** [31]: The CCSP assessment reports are based on a reference scenario (no climate policy) and four stabilization scenarios (CO_2 ppm = 450, 550, 650, 750)[15].

- **Royal Dutch Shell scenarios** [32]: These scenarios were published in 2008 and are noteworthy for their publication by a leading industry player. The scenarios include: Scramble (uncoordinated efforts, focused on national energy security), Blueprints (more coherent climate policy), and Blueprints without CCS (carbon capture and sequestration).

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[14] I have calculated the year 2500 radiative forcing for RCP 8.5 and RCP 3-PD using the methodology in section 15.1, based on the year 2500 CO_2 and Kyoto gas concentrations provided in the RCP database.

[15] These scenarios assume an additional 26-31% of radiative forcing from non-CO_2 pollutants, in addition to the forcing from the designated CO_2 concentrations.

- **International Energy Agency's (IEA) World Energy Outlook 2011**: These three scenarios include "Current Policy" (includes only policies enacted or adopted by mid-2011), "New Policy" (also includes commitments, plans, and pledges that have been announced but not enacted as policy to-date; this is their "central" scenario), and the "450 Scenario" (an emission path consistent with 50/50 odds of avoiding 2°C temperature increase above pre-industrial levels). Projections are only done to 2035, limiting their use for climate projections. (see Appendix A)

Reference scenarios are designed as points of departure, against which the standard scenarios, observed emissions, emission pledges, and other proposed mitigation paths can be compared. Five will be discussed in this chapter (section 2.2.b): the no-policy reference scenario from the US Climate Change Science Program (CCSP) [31], the "current policy" scenario from the IEA's World Energy Outlook 2011 [33], the "median" probabilistic projection by Sokolov et al. 2009 [34], the reference scenario presented by the Climate Action Tracker (CAT) website as a comparison to international emission pledges [35], and the reference scenario presented in the UN Environmental Programme's (UNEP) 2011 Integrated Assessment Report on Black Carbon and Tropospheric Ozone [36].

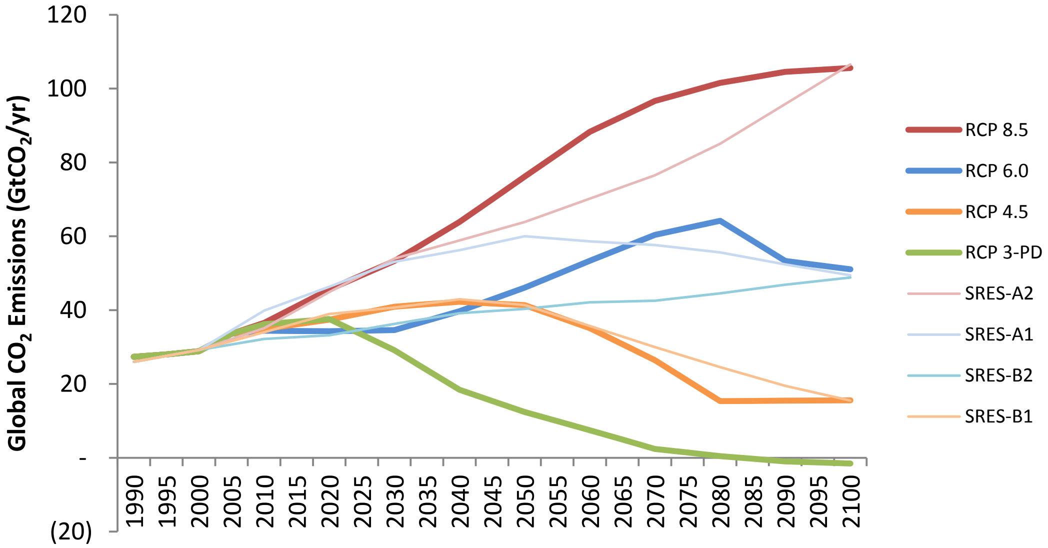

Figure 2-1: Total CO_2 emissions for the SRES marker scenarios and RCP emission-driven scenarios[16]
Data sources: SRES database [30], RCP database [26].

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[16] Note, A1B and A1T are below A2 and A1FI is above A2. (see Figure 2-3)

		2100 Median				2100 Likely[17] Range		
		vs. 1980-1999	vs. 2000	vs. pre-industrial		vs. 1980-1999	vs. 2000	vs. pre-industrial
All SRES:								
	AR4 2007 [28]	1.8 - 4.0 °C		2.4 - 4.6 °C		1.2 - 6.4 °C		1.8 - 7.0 °C
	Rogelj et al. 2012 [37]	1.9 - 4.1 °C		2.5 - 4.7 °C		1.5 - 5.3 °C		2.1 - 5.9 °C
	Prinn et al. 2011 [38]		3.2 - 6.8 °C	3.9 - 7.5 °C				
RCP 3-PD:								
	Rogelj et al. 2012 [37]	1.1 °C		1.7 °C		0.7 - 1.5 °C		1.3 - 2.1 °C
RCP 4.5, RCP 6.0, RCP 8.5:								
	Rogelj et al. 2012 [37]	2.0 - 4.3 °C		2.6 - 4.9 °C		1.5 - 5.5 °C		2.1 - 6.1 °C
Shell:								
	Prinn et al. 2011 [38]		2.4 - 4.7 °C	3.1 - 5.4 °C				

Table 2-1: Projections of Temperature Change in 2100 for Different Scenarios
Data have been visually interpolated from published graphs (Figure 2-2, Figure 2-3, and Figure 2-4) and adjusted to be comparable to pre-industrial. IPCC AR4 and Rogelj et al. are based on multiple climate models; Prinn et al. is based on a single model. Note that Prinn et al. project a 50-60% higher median temperature relative to pre-industrial for the SRES scenarios than projected by IPCC AR4 and Rogelj et al..

2.2 Projections for the Long-Term Horizon (40+ years)

Projections of temperature change by 2100 vary widely, but only the RCP3-PD scenario produces a temperature increase of less than 2°C above pre-industrial levels – the temperature ceiling established in the 2009 Copenhagen Accord. [3]

Figure 2-2, Figure 2-3, and Figure 2-4 show the temperature trajectories to year 2100 for the SRES scenarios (as modeled for AR4), the SRES and RCP scenarios (prepared for AR5), and the Shell, CCSP and SRES scenarios (by Prinn et al. [38]). The results for the SRES, RCP, and Shell scenarios are summarized in Table 2-1.

Excluding RCP3-PD, the range of likely[18] temperatures across these scenarios for year 2100 is 1.8°C-7.0°C above pre-industrial levels (Table 2-1).[19] For a summary of the global and US

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[17] "Likely" is defined as a 66% confidence interval, in line with standards of IPCC AR4 (Working Group I Summary for Policymakers, p.3).

[18] See footnote 17 for definition of likely.

[19] Including RCP3-PD, the likely range is 1.3-7.0°C.

climate change impacts that would accompany these global temperature increases, see [39] and [40][20].

The reasons for the wide uncertainty around the year 2100 temperature can be segmented into uncertainty in the magnitude of temperature change that will be caused by a given forcing (equilibrium climate sensitivity; ECS), uncertainty in the fraction of the equilibrium warming that will be experienced over a given time horizon (the climate response function), and variations in assumptions about the forcing (defined for the RCPs in 2100, variable across models for SRES scenarios).

In Table 2-2, I have calculated the year 2100 temperatures that would result from each RCP scenario under different assumptions about equilibrium climate sensitivity and the fraction of warming experienced in 2100. The results for a high ECS in 2100 versus a low ECS in 2100 can be different by 1.7-4.4°C.[21] The results for a high fraction in 2100 (rapid climate response) versus a low fraction in 2100 (slower climate response) can be different by 0.5-2.1°C.[22]

Comparing the values in this table to the median results from Rogelj et al. 2012 [37], their results are consistent with the best-estimate ECS and a mid- to high-fraction of warming experienced by 2100 (64-71%). Results from IPCC AR4 for the SRES scenarios shown in Table 2-1 were consistent with Rogelj et al., so we can expect that the assumptions were similar. The Prinn et al. [38] results shown in Table 2-1 were markedly higher than the Rogelj et al. results for the SRES scenarios. If I divide Prinn's year 2100 temperature change from Figure 2-4 by the forcing from Figure A-3, I find a transient response in year 2100 of ~2.45°C (per 3.7 W/m^2), which corresponds to an ECS of 4.5 and a fraction of 55%.

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[20] Note, impacts shown in the US Climate Impacts report for 2070 only show SRES scenarios – all of which assume that 2°C is exceeded by then.

[21] The low end of the range is calculated for RCP 4.5 with the 55% fraction (3°C minus 1.3°C). The high end of the range is calculated for RCP 8.5 with the 75% fraction (7.8°C minus 3.4°C).

[22] The low end of the range is calculated for RCP 4.5 with low ECS (1.8°C-1.3°C). The high end of the range is calculated for RCP 8.5 with high ECS (7.8°C-5.7°C).

	Temperature Increase at Year 2100 (°C), above pre-industrial							
	ECS = 2°C		ECS = 3°C		ECS = 4.5°C		Rogelj et al. 2012	
	55%	75%	55%	75%	55%	75%	Median	Fraction of Equil T
RCP 4.5	1.3	1.8	2.0	2.7	3.0	4.1	2.6	71%
RCP 6.0	1.8	2.4	2.7	3.6	4.0	5.5	3.1	64%
RCP 8.5	2.5	3.4	3.8	5.2	5.7	7.8	4.9	71%

Table 2-2: Temperature Change for RCP Scenarios at Year 2100 (relative to pre-industrial) with Different Climate Sensitivity and Transient Response Assumptions

ECS = Equilibrium climate sensitivity (°C per 3.7 W/m^2); note that by convention ECS is typically shown in °C as a shorthand for °C per 3.7 W/m^2. Percentages are the fraction of equilibrium temperature that is realized in year 2100. The calculation is done by multiplying the year 2100 forcing for each RCP scenario (4.5, 6.0, and 8.5 W/m^2) by the fraction of equilibrium temperature realized in 2100 by the equilibrium climate sensitivity (in °C), divided by 3.7 W/m^2. The median values for Rogelj et al. 2012 [37] are visually read from Figure 2-3. The Rogelj et al. fraction of equilibrium temperature is calculated assuming an equilibrium ECS of 3°C. The ECS values chosen are the best estimate (3°C) and 66% confidence interval (2-4.5°C) from IPCC AR4. Fractions of equilibrium temperature chosen are the average transient climate response reported in AR4 [41] and summarized in NRC 2011 [42] (55%) and a more rapid climate response (75%) suggested by Hansen et al. 2011 [43]. RCP 3-PD is excluded from the calculation due to its different emission trajectory shape (peak and decline).

2.2.a Comparison to Historical Trends and Pledges

All scenarios used for projections in the previous section are based on subjective assumptions about the future. In this section, I compare those emission scenarios with objective data from historical trends and government pledges.

Figure 2-6 and Figure 2-7 show the current CO_2 emission trendlines through 2010 compared with the SRES scenarios for fossil fuel only and for all anthropogenic emissions (including land use). In both cases, global CO_2 emission trends fall between the A1 and A2 families. Figure 2-8 and Figure 2-9 show the same trendlines in comparison to the RCP scenario. Fossil fuel trends lie slightly above all RCP scenarios, while total trends lie near or above the highest RCP scenarios.

Looking forward, nations have made pledges of emission constraints to achieve international climate goals and these pledges have been summarized by the United Nations Environment Programme (UNEP) [44] through 2020 and Climate Action Tracker [35] through 2050. Pledge emissions are shown in comparison to the RCP scenarios in Figure 2-10 and Figure 2-11. Emission levels of pledges through 2050 lie above RCP6.0, and well below RCP8.5 (Figure 2-10). If pledge emissions continued on the curve of their trajectory beyond 2050, that emission line would lie somewhere between RCP 4.5 and RCP 6.0 (Figure 2-11). The best estimate temperature outcome of such a trajectory would lie between approximately 3-4°C above pre-industrial levels by year 2300 (see Figure 2-5) and a few tenths above that at equilibrium – falling far short of the reductions that would be consistent with staying below 2°C above pre-industrial levels. We will return to the topic of avoiding 2°C in Chapter 9.

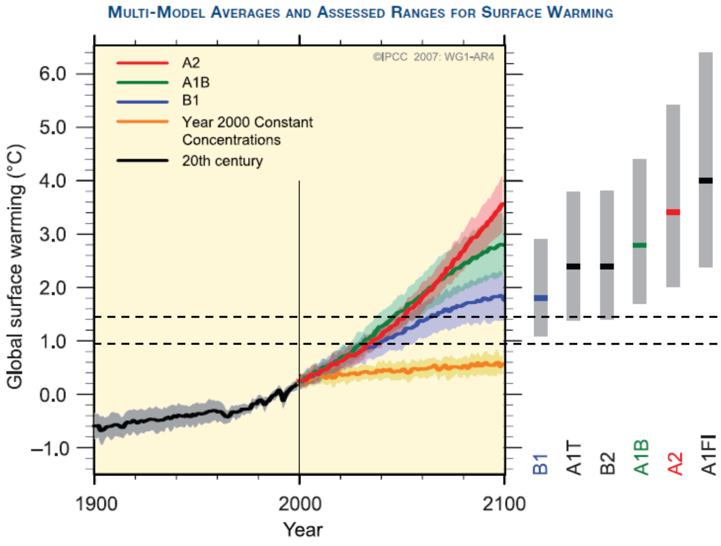

Figure SPM.5. *Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the* ***likely*** *range assessed for the six SRES marker scenarios. The assessment of the best estimate and* ***likely*** *ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. {Figures 10.4 and 10.29}*

Figure 2-2: Temperature Projections for SRES Scenarios, through 2100

Reprinted with blanket permission from IPCC AR4 Working Group I Summary for Policymakers p. 14. [28] Dashed lines are added and mark 1.5°C and 2°C above pre-industrial temperature ($T_{1980\text{-}1999}$ - 0.6°C).

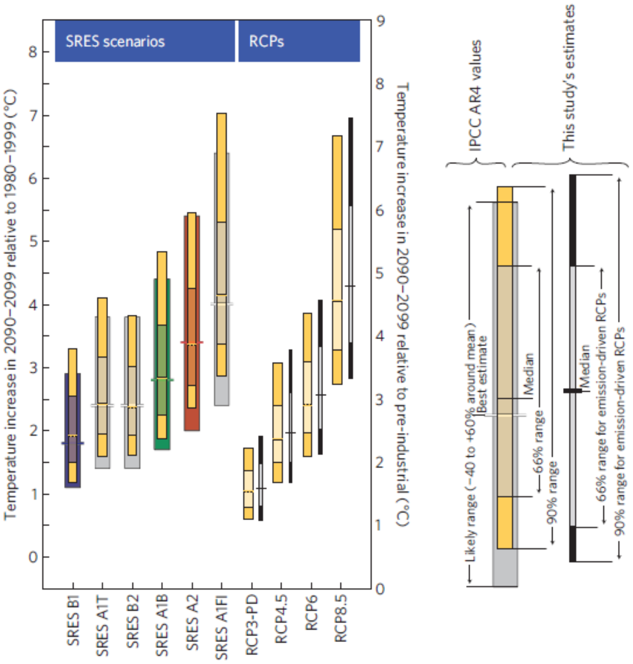

Figure 2-3: Temperature Projections for SRES and RCP Scenarios, 2090-2099[23]

Reprinted by permission from Macmillan Publisherrs Ltd: Rogelj, Meinshausen, and Knutti, Nature Climate Change 2012. [37]

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[23] Includes uncertainty in climate sensitivity (most likely: 3°C; 5% likelihood below 1.5°C; 76% likelihood between 2.0-4.5°C; 14% likelihood above 4.5°C) and carbon-cycle responses (from C^4MIP).

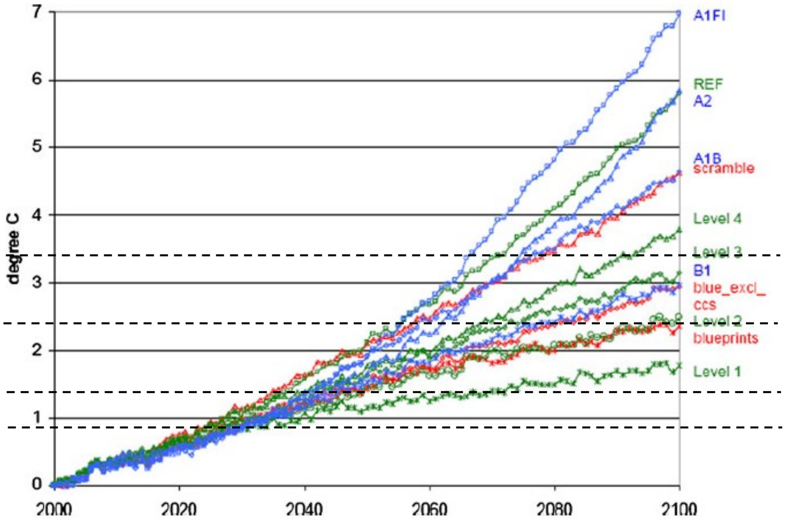

Fig. 9 Increase in the Global Mean Temperature in degrees Centigrade (relative to 2000; Shell in *red*, CCSP in *green*, SRES in *blue*)

Figure 2-4: Temperature Projections to 2100 for SRES, Shell, and CCSP Scenarios

Reprinted with kind permission from Springer Science and Business Media, from Prinn et al., Climatic Change 2011. [38] Dotted lines are added and mark 1.5°C, 2°C, 3°C, and 4°C above pre-industrial temperature (=T_{2000} - 0.7°C).

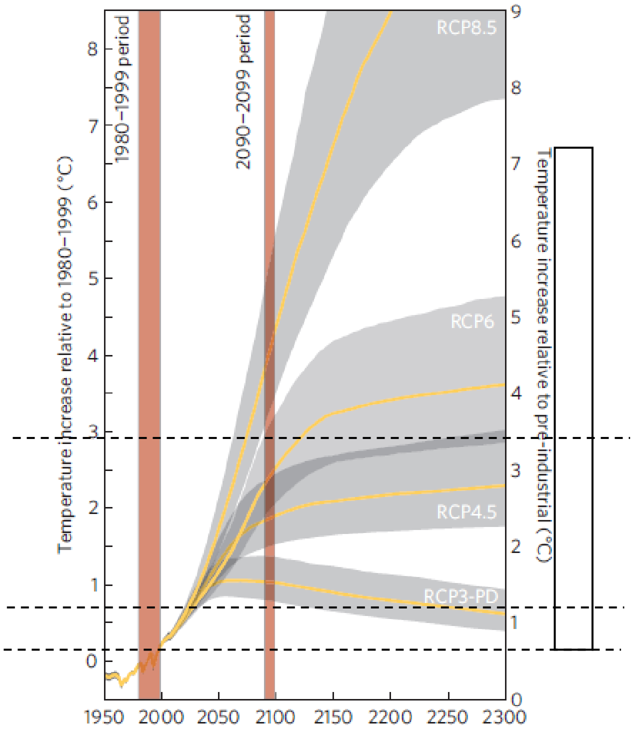

Figure 2-5: Temperature Projections for RCP Scenarios, through 2300

Reprinted by permission from Macmillan Publisherrs Ltd: Rogelj, Meinshausen, and Knutti, Nature Climate Change 2012. [37] Dashed lines are added and mark 1.5°C and 2°C above pre-industrial temperature.

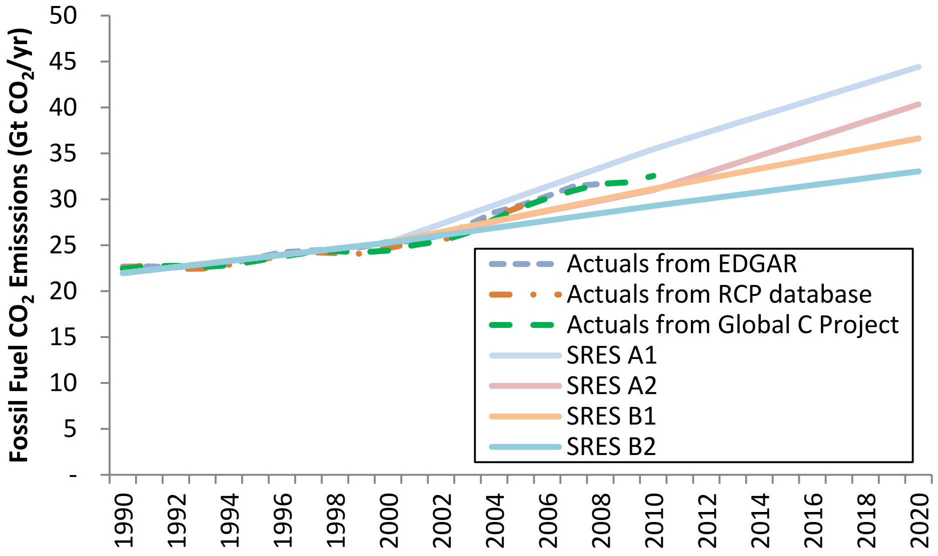

Figure 2-6: Historical CO_2 Emissions and Future Emissions Projected in SRES Scenarios, Fossil Fuel only

Data sources: SRES database [30], RCP database [26], Global Carbon Project [6, 45], EDGAR 4.2 [46]. Global C Project data and EDGAR data include emissions from cement manufacture (3% of total CO_2 emissions).

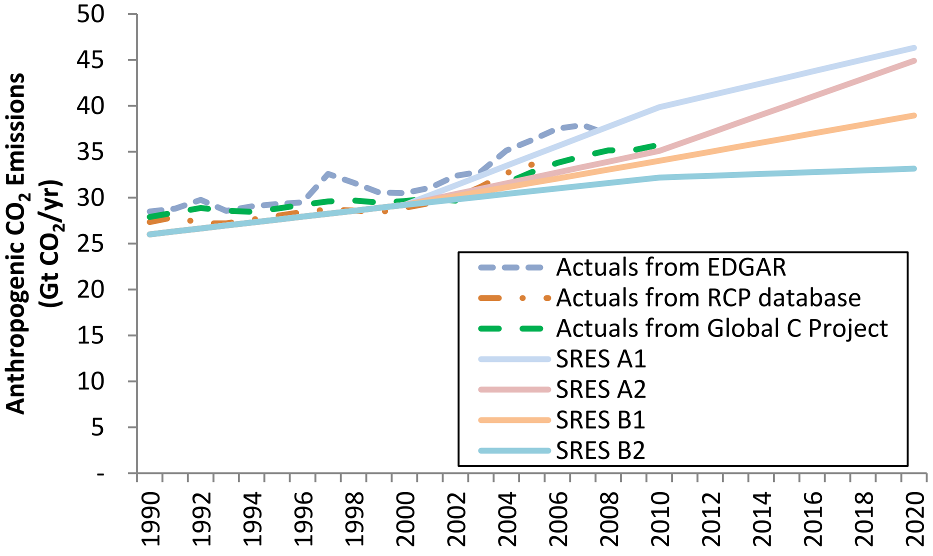

Figure 2-7: Historical CO_2 Emissions and Future Emissions Projected in SRES Scenarios, All Anthropogenic Sources

Data sources: SRES database [30], RCP database [26], Global Carbon Project [6, 45], EDGAR 4.2 [46]. Variation between data sources is due to uncertainties in land use emissions.

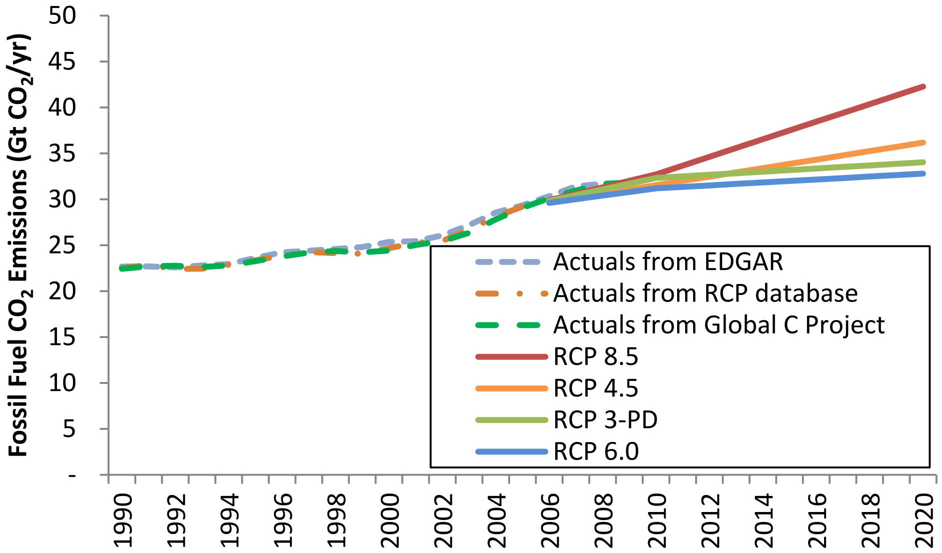

Figure 2-8: Historical CO_2 Emissions and Future Emissions Projected in RCP Scenarios, Fossil Fuel only
Data sources: SRES database [30], RCP database [26], Global Carbon Project [6, 45], EDGAR 4.2 [46]. Global C Project data and EDGAR data include emissions from cement manufacture (3% of total CO_2 emissions).

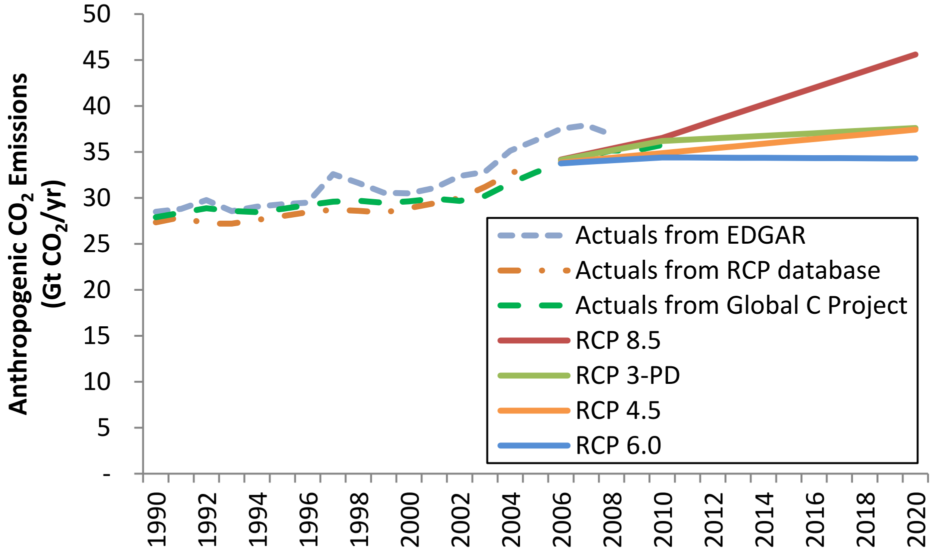

Figure 2-9: Historical CO_2 Emissions and Future Emissions Projected in RCP Scenarios, All Anthropogenic Sources
Data sources: SRES database [30], RCP database [26], Global Carbon Project [6, 45], EDGAR 4.2 [46]. Variation between data sources is due to uncertainties in land use emissions.

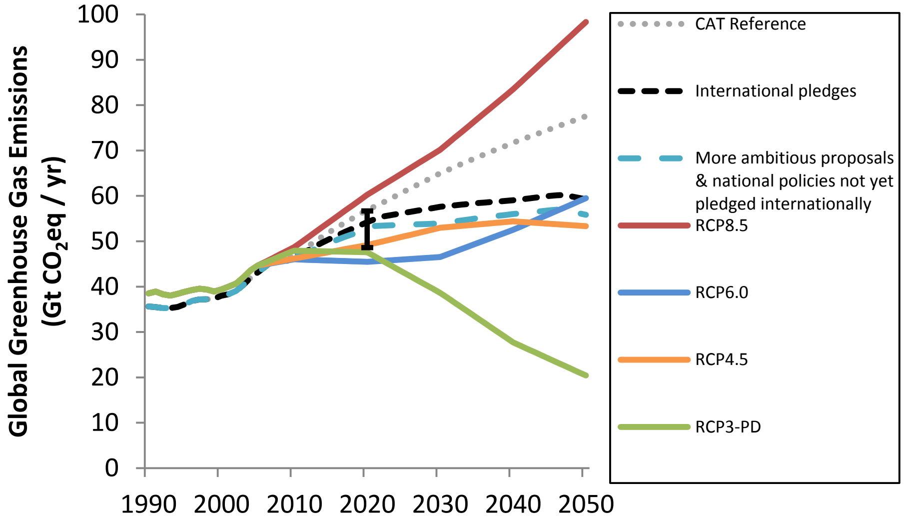

Figure 2-10 International Emissions Pledges, RCP Scenarios, and Climate Action Tracker (CAT) reference
Data sources: Climate Action Tracker website [35], RCP database [26], IPCC AR2 [47], UNEP [44]. Includes the six Kyoto gases[24], in CO_2-equivalent, calculated based on GWP100[25] from the IPCC's Second Assessment Report, consistent with CAT's data and the inventory reporting requirements for the UNFCCC. Pledge lines assume lenient accounting rules for LULUCF[26] and for surplus emission credits, and are estimated by Climate Action Tracker. Black error bar shows the range of estimates from ten modeling groups for 2020 emissions under the international pledges, with lower emission estimates under strict accounting rules and higher emission estimates under lenient account rules [44].

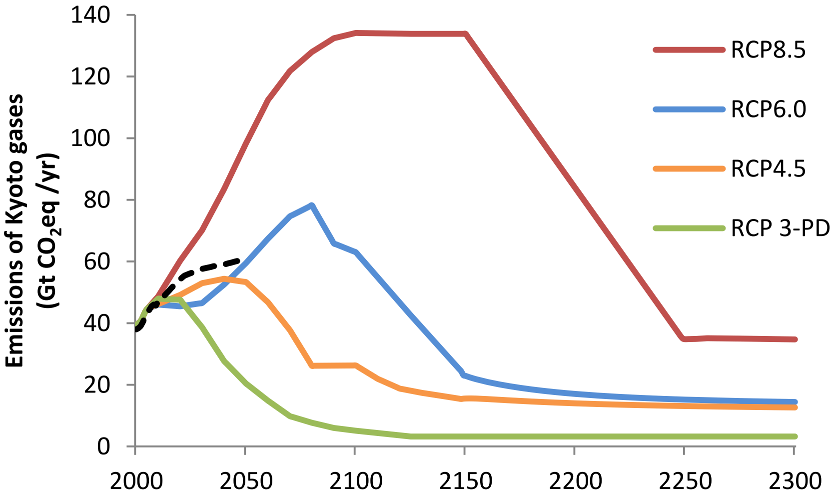

Figure 2-11: International Emission Pledges relative to RCP Scenarios, through year 2300
Replica of Figure 2-10, for an extended time period; same data sources and methods.

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[24] Kyoto gases are those included in the Kyoto Protocol: CO_2, CH_4, N_2O, SF_6, HFCs, and PFCs.

[25] Global Warming Potential (GWP) is the summation of RF over a period of time created by one-time emission of a kilogram of a greenhouse gas, relative to the same calculation for CO_2. GWP-100 is calculated over 100 years.

[26] LULUCF = land use, land use change, and forestry.

2.2.b Reference Scenarios

While international emission pledges lie above emission trajectories that would avoid a temperature increase of 1.5-2°C above pre-industrial levels, they do result in less climate change than would occur under most "reference" scenarios. Reference scenarios are used in the literature as "points of departure" [31] against which mitigation scenarios are compared. Some of these are business-as-usual scenarios, which assume no changes to current policies or behavior (e.g., IEA WEO's "current policy" scenario[27], UNEP reference scenario[28] [48], Climate Action Tracker reference [35, 49]). Some are scenarios with no climate policy (e.g., CCSP reference scenarios).[29] [30] [31] And one is a probabilistic projection of what will happen based on the authors' current understanding of the world economy (Sokolov et al.'s "median" scenario [34]).

In all cases, these reference scenarios are counterfactuals, scenarios that might happen if an aggressive mitigation scenario does not happen. These scenarios are impossible to validate because the future is unknown. Nonetheless, "business-as-usual" / "no policy" / "reference" scenarios are frequently used in the policy discussion in comparison to mitigation paths, making it worth understanding the variation among these reference scenarios and how they compare to the RCP and SRES scenarios.

Results for five reference scenarios are summarized in Table 2-3. Underlying charts are shown in Appendix A and in Figure 2-4. The most complete data are published for the CCSP reference scenario, so the last column compares the other scenarios to CCSP. We see that the emission assumptions range from -13% to -22% relative to the CCSP scenario. Temperature outcomes and radiative forcing also fall within approximately that percentage range.

Table 2-4 presents the reference scenarios in the context of all of the scenarios and observations discussed in the chapter so far. We see that the projected year 2100 global temperature in all of the reference scenarios lies above the temperature in RCP6.0, with Sokolov et al. 2009's "no climate policy" and IEA's 2011 "current policy" roughly equal to A1B, the UNEP reference between A1B and A2, the CCSP reference roughly equal to A2, and Climate

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[27] Includes only policies enacted or adopted by mid-2011.

[28] Per Shindell: The reference scenario was "specifically chosen to only include the impacts of currently agreed policies and legislation applied to projected energy and food usage."

[29] CCSP reference scenarios "assume that in the post-2012 period existing measures to address climate change expire and are never renewed or replaced."

[30] CCSP scenarios were developed by 3 different modeling groups, which produced 3 different reference scenarios. The one discussed in this section is from the MIT IGSM model, which is also the one shown in Figure 2-4.

Tracker reference roughly equal to A1FI and RCP 8.5. Two of the five (CCSP and CAT) lie above current emissions and current pledges.

If we use the ranges for A1B, A2, and A1FI provided in Figure 2-2 and Figure 2-3, we get a likely[31] range for year 2100 (above pre-industrial levels) for the reference scenarios of 2.5°C-5.9°C from Rogelj and 2.3°C-7.0°C from IPCC AR4 (median: 3.3-4.8°C and 3.4-4.2°C, respectively). I will return to these reference scenarios in Chapter 4, Chapter 13, and Chapter 15.

	CCSP REF (Prinn et al. 2011) [38]	Sokolov et al. 2009 "median" [34]	IEA WEO 2011 "current policy" [33]	UNEP 2011 reference [36, 48]	Climate Action Tracker (CAT) 2012 reference [35]	vs. CCSP REF
ΔT in 2100 above pre-industrial	6.5°C	5.7°C				-12%
Radiative forcing (RF) in 2100 (all agents)	10 W/m^2	8 W/m^2				-20%
CO_2 emissions in 2035	55 Gt CO_2/yr		43 Gt CO_2/yr			-22%
CO_2 emissions in 2065 (FF & industrial)	75 Gt CO_2/yr			63 Gt CO_2/yr		-16%
CO_2eq[32] emissions in 2050	90 Gt CO_2e/yr				78 Gt CO_2e/yr	-13%

Table 2-3: Comparison of Forward-Looking Reference Scenarios
Data shown are the data available to compare apples-to-apples across reference scenarios. Prinn et al. has published the most complete data and is used for comparison against the others (see Figure 2-4, Figure A-2, and Figure A-3). Data were visually interpolated from Prinn et al., IEA WEO, and CAT; data from tables were used for Sokolov and UNEP. Temperatures were adjusted from those reported to compare versus pre-industrial (Sokolov et al. reported 5.1°C above 1980-1999 and Prinn et al. reported 5.8°C above year 2000; 0.6°C and 0.7°C were added, respectively). FF = fossil fuel.

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[31] See footnote 17 for definition of likely.

[32] CO_2eq is defined in this table using the 100-year global warming potential.

	Scenarios with comparable year 2100 temperatures			
SRES scenarios (from high to low T)	**RCP scenarios**	**Shell scenarios**	**Reference scenarios**	**Observations and Pledges**
A1FI	RCP 8.5			
A2			CCSP reference	
between A1B & A2			CAT reference UNEP reference	CO2 emissions, 2000-2010
A1B		Scramble	Sokolov et al. median IEA current policy	Current pledges
between B2 & A1B	RCP 6.0			
B2				Pledge trajectory
B1	RCP 4.5	Blueprints excl. CCS		
below B1	RCP 3-PD	Blueprints		Agreement to avoid 2°C temp increase

Table 2-4: Scenarios with Comparable Year 2100 Temperatures
Each row shows a set of emission scenarios that produce approximately the same year 2100 temperature as the SRES scenario in that row. SRES scenarios are ordered from high to low temperature based on Figure 2-4. RCP scenarios are placed on the chart based on their temperature projections in Figure 2-3 relative to the SRES scenarios. Shell scenarios and the CCSP reference scenario are placed on the chart based on their temperature projections relative to the SRES scenarios in Figure 2-4. Sokolov et al. [34] is positioned based on its RF in year 2100, which is comparable to the RF for "scramble" in Figure A-3. This positioning is consistent with its lower temperature and CO_2 concentration relative to CCSP in Table 2-3, but not consistent with the authors' assertion that the Sokolov scenario is comparable to A1FI [34]. IEA WEO 2011's "current policy" scenario is positioned based on its 2035 energy-related CO_2 emissions relative to the comparable emissions in Figure A-2, where it sits between B1 and Scramble (a wide distance in the present table, reflecting the importance of assumptions beyond 2035). I have placed IEA "current policy" alongside Scramble, which is consistent with "current pledges". The UNEP 2011 reference scenario is placed above RCP 6.0 based on its CO_2 emission trajectory (Figure A-4), below CCSP based on 2065 CO_2 emissions (Table 2-3), and above Sokolov and IEA current policy based on their relative comparisons to CCSP (right column of Table 2-3). The Climate Action Tracker (CAT) reference has lower emissions than the CCSP reference (see Table 2-3) and slightly higher emissions than the UNEP reference scenario, so is placed in the same box but above UNEP on this chart. Observed emissions (2000-2010) are placed on the chart between the A1 and A2 families, based on their position in Figure 2-7. Current pledges sit just above RCP 6.0 in Figure 2-10 and are placed accordingly here. The pledge trajectory lies between RCP 4.5 and RCP 6.0 in Figure 2-11 and is placed between them here. The agreement to avoid 2°C implies an emission scenario below B1, since B1 lies above 2°C by 2100 in Figure 2-2 and Figure 2-3.

2.3 Projections for Near-Term Climate Change, Temperature Ceilings, and Delay

Section 2.2 provided information about the long-term, showing that the temperature in 2100 is likely[33] to range from 1.8-7.0°C above pre-industrial levels under commonly modeled scenarios such as SRES and RCP, 2.3-7.0°C above pre-industrial levels under reference scenarios,[34] and 3-4°C above pre-industrial levels if existing international emission reduction pledges are upheld and if emissions beyond the pledge period continue the trajectory.

In this section, I review the current century in greater detail to further inform choices between Box 1 (delay), Box 2 (avoid 1.5°C-2°C), or Box 3 (avoid 3-4°C) (recall Table 1-1). Table 2-5 provides best estimates of the years when the global temperature increase above pre-industrial levels will hit 1.5C, 2°C, 3°C, and 4°C under the SRES, RCP, and Shell scenarios. Data were visually interpolated from Figure 2-2, Figure 2-4, and Figure 2-5 and from Joshi et al. 2011 [50].

The first observation from Table 2-5 is that very few scenarios avoid temperature increases of 1.5C, 2°C, 3°C and even 4°C. Most low-emission scenarios (except for very-low emission scenarios: CC and RCP3-PD) simply delay the arrival at those temperatures relative to the higher emission scenarios.

The next observation to pull from Table 2-5 is the timing when each temperature is reached across a range of scenarios, shown in the next-to-last row of the table. Both 1.5°C and 2°C are projected to be reached in the near-term, with 1.5°C between 2025-2050 and 2°C between 2035-2080. Looking at this observation in more detail, Table 2-6 shows that the temperature increase through 2050 is fairly consistently ~1.5-2.5°C above pre-industrial levels across all analyses and across different scenarios.

Whether the difference between the climate outcomes that accompany a 1.5°C versus 2.5°C increase is considered large or small depends on which impacts are of highest concern, since some impacts differ significantly in this range and others do not. For example, water stress (shortages of freshwater) may affect an additional several hundred million people between 1.5°C and 2.5°C, but the outcome for Arctic summer sea ice may not differ between these temperatures (see Figure 6-1 and Figure 6-2).

Next, a limited number of scenarios do exist that completely avoid 1.5°C (constant concentration (CC)) and 2°C (CC and RCP3-PD). Yet, climate changes of 1.5°C and 2°C are

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[33] See footnote 17 for definition of likely.

[34] Including business-as-usual or no policy scenarios (see section 2.2.b).

already considered “committed” by some authors. [51] Section 2.4 will explore this seeming contradiction.

Next, the higher temperature thresholds (3-4°C above pre-industrial levels) are reached at points beyond the near-term horizon, and some scenarios never cross the 3°C and 4°C thresholds. Those scenarios that hit 3°C reach it between 2060-2100. Those reaching 4°C hit it between 2065-2230. There are four scenarios that never reach 3°C or 4°C: CC, B1, RCP3-PD, and RCP4.5.

Finally, the last row of Table 2-5 provides information about delay. Delay is calculated within each set of scenarios, between the most aggressive and least aggressive scenarios. Only those scenarios that eventually hit a given temperature are included in the delay calculation. A temperature increase of 1.5°C can be delayed for at most 15 years between the modeled scenarios (e.g., from 2035 to 2050). A temperature increase of 2°C can be delayed within the modeled scenarios for 35 years according to Joshi et al. 2011 [50], or at most 20 years according to the other sources (IPCC AR4 [28], Prinn et al. 2011 [38], Rogelj et al. 2012 [37]). Increases of 3°C can be delayed by up to 40 years and increases of 4°C can be delayed up to 150 years within the modeled scenarios. I will return to the concept of delay in Chapter 5 and Chapter 6, calculating the potential for delay beyond the confines of the modeled scenarios and exploring the potential benefits of delay.

		Year that ΔT above Pre-industrial Level will Reach:			
		1.5°C	**2°C**	**3°C**	**4°C**
IPCC AR4 [28]	CC	never	never	never	never
	B1	2035	2060	>2100	>2100 / never
	A1B	2025	2040	2070	>2100
	A2	2030	2045	2070	2095
Prinn et al. 2011 [38]	B1	2030	2045	2080	>2100
	A1B	2030	2040	2060	2075
	A2	2030	2040	2065	2075
	A1FI	2030	2040	2055	2065
Joshi et al. 2011 [50]*	B1		2080	>2100	>2100
	A1B		2045	2085	>2100
	A2		2050	2075	2095
Rogelj et al. 2012 [37]	RCP 3-PD	2050	never	never	never
	RCP 4.5	2040	2060	>2300	never
	RCP 6.0	2045	2060	2100	2230
	RCP 8.5	2035	2045	2060	2080
Prinn et al. 2011 [38]	Blueprints	2030	2045	2095	>2100
	Scramble	2025	2035	2060	2080
RANGE	(excl. never)	2025-2050	2035-2080*	2060-2100	2065-2230
DELAY		0-15	5-35	0-40	~150

🟨 - near-term

Table 2-5: Projected Year that Global Temperature Will Reach 1.5°C, 2°C, 3°C, and 4°C Above Pre-Industrial Levels under Different Scenarios

Data have been visually interpolated to the nearest 5-year increment from published graphs (see Figure 2-2, Figure 2-4, and Figure 2-5) and Joshi et al. [50]. Temperature events that occur between 2010-2050 are highlighted in yellow. *Temperatures may reach a given level up to a decade earlier than the dates provided by Joshi et al. because the underlying models do not include the carbon cycle.[35]

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[35] Per Joshi et al. 2011, “inclusion of the carbon cycle brings forward threshold-crossing times by up to a decade.”

		2050 Median				**2050 "Likely" Range**		
		vs. 1980-1999	vs. 2000	**vs. pre-industrial**		vs. 1980-1999	vs. 2000	**vs. pre-industrial**
All SRES scenarios:								
	IPCC AR4 2007 [28] (multi-model)	1.1-1.6°C		1.7-2.2°C		0.8-1.9°C		1.4-2.5°C
	Prinn et al. 2011 [38]		1.6-2.0°C	2.3-2.7°C				
All RCP scenarios:								
	Rogelj et al. 2012 (multi-model) [37]	1.0-1.7°C		1.6-2.3°C		0.8-2.2°C		1.4-2.8°C
All Shell scenarios:								
	Prinn et al. 2011 [38]		1.5-2.1°C	2.2-2.8°C				

Table 2-6: Projections of Temperature Change in 2050 for Different Scenarios
Data have been visually interpolated to the nearest tenth of a degree from published graphs (see Figure 2-2, Figure 2-4, and Figure 2-5) and converted to be comparable to a pre-industrial baseline. Comparisons versus pre-industrial add 0.6°C to comparisons versus 1980-1999 and 0.7°C to comparisons versus 2000 (see footnote 12). "Likely" is defined as a 66% confidence interval, in line with standards of IPCC AR4 Working Group I. [28]

2.4 Bounding Scenarios

So far, this chapter has focused on projections of future temperatures that would result from a variety of emission scenarios that modelers consider “plausible” (e.g., SRES, RCP) [52]. The actual future, however, may or may not lie within this range.

To understand the limits of what could occur, this section covers bounding scenarios. Physical bounding scenarios situate choices relative to physical extremes and include: burn all fossil fuels (section 2.4.a) or emit nothing starting today[36] (i.e., zero emissions). Some authors have defined scenarios aside from zero emissions as lower bounds on “committed” warming (section 2.4.b, Table 2-8). Aside from zero emissions, the “committed” scenarios do not invoke physical limits.

2.4.a The Fossil Fuel Reserve and Resource Base

An upper bounding scenario for anthropogenic CO_2 emissions is the burning of all fossil fuels. Fossil fuels are divided into historical emissions, reserves, resources, and additional occurrences (Table 2-7). Reserves are defined as sources that are economically and technically recoverable with current technology. Resources are defined as sources that are known or expected to exist based on geological surveys and analyses and may someday become economically and technically recoverable. Resources are expected to be 10 times as large as reserves (see Table 2-7). Additional occurrences are so dispersed or of such low quality that they are not expected to become recoverable. [53]

Reserves and resources of fossil fuels are 50-150% greater than the amount required to produce the highest RCP scenario (RCP 8.5) [29][37] and the highest reference scenarios (see Table 2-7). Thus, it is easily possible to exceed 1.5-2°C (Box 2), to exceed 3-4°C (Box 3), and to exceed higher temperatures with available fossil fuels (see section 15.2 for the relationship between total CO_2 emissions and temperature).

Note that there is wide uncertainty in the size of both the reserve and the resource (Table 2-7). The high estimate for reserves is nearly 2x the low estimate, driven primarily by uncertainty in the unconventional natural gas reserve. The high estimate for resources is more than 50%

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[36] Actually, if negative emissions become possible, “emit nothing” would no longer be a bounding scenario. However, because “emit nothing” is more intuitive and because the bound on negative emissions is not well defined, this dissertation identifies “emit nothing” as a reasonable lower bounding scenario.

[37] RCP 8.5 would involve 7,100 Gt CO_2 emissions over the 21st century and 19,700 Gt CO_2 emissions over the 500 years from 2000-2500.

higher than the low estimate, driven primarily by uncertainty in the coal resource. The natural gas resource, while much smaller than coal, has nearly a 3x spread between the high and low estimates.

Throughout the rest of the dissertation, I will use the averages when referring to the fossil fuel reserves and resource – e.g., a total reserve and resource of 44,500 Gt CO_2.

Gt CO_2	Historical production through 2005	Reserves (low)	Reserves (high)	**Reserves (avg.)**	Resources (low)	Resources (high)	**Resources (avg)**	Reserves + Resources (low)	Reserves + Resources (high)	Reserves + Resources (avg)	Add'l Occurr-ences
Coal	600	1,600	2,000	**1,800**	27,000	40,400	**33,700**	28,600	42,300	**35,500**	-
Natural gas	200	1,300	3,700	**2,500**	2,400	6,600	**4,500**	3,600	10,300	**7,000**	50,300
Conventional	200	300	400	**300**	400	400	**400**	600	800	**700**	-
Unconventional	-	1,000	3,400	**2,200**	2,000	6,100	**4,100**	3,000	9,500	**6,300**	50,300
Oil	500	600	900	**800**	1,100	1,500	**1,300**	1,700	2,400	**2,100**	2,800
Total	**1,200**	**3,500**	**6,600**	**5,000**	**30,500**	**48,500**	**39,500**	**34,000**	**55,100**	**44,500**	**53,100**

Table 2-7: CO_2 Emissions (Gt CO_2) Possible from all Fossil Fuels

Fossil fuel data in EJ were provided by the Global Energy Assessment 2012 [53], which presented the range of estimates (low, high) shown in the literature. I converted from EJ to Gt CO_2 based on the emission factors from EIA 2011 [54]: 0.09 Gt CO_2/EJ for coal (averaged across four types), 0.05 Gt CO_2/EJ for natural gas (US average), and 0.07 Gt CO_2/EJ for crude oil. Numbers are rounded to the nearest hundred.

2.4.b "Committed" Warming

Another way to apply bounding scenarios is to consider how much mitigation is possible versus how much warming is already committed. Table 2-8 shows six definitions of "committed" that are used in the literature, ranging from what is physically committed due to lags in the climate system (Zero Emissions, Constant Concentration)[38] to what is societally committed due to existing infrastructure (Zero New Polluting Infrastructure) to what is societally committed in the form of maintaining today's emissions (Constant Emissions). The widely varying emission assumptions of the six definitions are illustrated in Figure 2-12.

All definitions of committed warming show some rise in temperature relative to warming to-date (see Figure 2-13). The Zero Emission (ZE) definition produces a temporary peak of a few tenths of a degree in the decades following elimination of the cooling aerosols. The constant concentration (CC) definition, which has constant radiative forcing (RF) (see Figure 6-3), shows warming relative to today due to the length of time required for ocean surface temperature to

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[38] Climate changes attributable to today's emissions take many decades to fully appear ("lag"); only a portion of the climate change is evident during the near-term horizon. See description of the warming process in section 6.2.b.ii.i.

rise to a level commensurate with today’s RF (see section 6.2.b.ii.i for a summary of the warming process).

The definition of “committed” that is applied to climate change is important to box choice because some definitions (CC+ZA and CE) imply that a temperature increase above 2°C is already “committed” – which would preclude achievement of Box 2 (avoid 1.5-2°C). Perspectives on which definitions reflect unchangeable constraints on the climate system thus influence whether “committed” climate change places any limits on box choice. It is also important to specify whether the warming commitment is on a century scale (e.g., 2100) or at equilibrium (hundreds of years in the future); this distinction will be discussed at length in Chapter 15. The best estimates of temperature across the definitions of “committed” range widely, from 0.7^{o}C to 2.0^{o}C in 2100 and 0.4^{o}C to 4.1^{o}C in 2400 (Figure 2-13). The full range of uncertainty for each definition is shown in Appendix B.

Name	**What is "Committed"**	**Emission Trajectory**
Zero Emissions (ZE) [55-57]	Historical emissions	All emissions cease, including both long- and short-lived pollutants[39]
Zero CO_2 Emissions (ZCE) [58, 59]	Historical CO_2 emissions	CO_2 emissions cease; for simplicity of calculation, other pollutants are implicitly assumed to be zero in past and future
Constant Concentration (CC) [57, 59-62]	Existing atmospheric concentrations of all radiatively active[40] gases and aerosols	All emissions (of both long- and short-lived pollutants) are held at levels that maintain the existing atmospheric concentrations of each pollutant
Zero New Polluting Infrastructure (ZI) [63]	Existing infrastructure until end of useful life	CO_2 emissions continue at current level from all existing infrastructure until the end of its useful life; [41] all new infrastructure is zero-emission; for simplicity of calculation, other pollutants are implicitly assumed to be zero in past and future [64]
Constant Concentration + Zero Emissions of Aerosols (CC+ZA) [51]	Existing atmospheric concentration of all greenhouse gases (GHGs) [42]	Emissions of greenhouse gases are held at levels that maintain the existing atmospheric concentration of each pollutant; emissions of aerosols cease
Constant Emissions (CE) [57, 60]	Existing emissions level of all radiatively active gases and aerosols	All emissions (of both long- and short-lived pollutants) are held at their current levels

Table 2-8: Six Definitions of "Committed" Climate Change

Definitions are ordered from least climate change committed to most climate change committed, as shown in Figure 2-13. Emission trajectories associated with each definition are shown in Figure 2-12.

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[39] See footnote 9 for atmospheric lifetimes.

[40] "Radiatively active" gases and aerosols are those with absorptive or reflective properties that affect the energy balance of the planet (influence incoming and outgoing radiation).

[41] Davis et al. assumed that "the annual emissions over the remaining lifetime of each power plant…[is] the larger of (i) 2007 plant emissions or (ii) the mean of 2000 and 2007 plant emissions."

[42] Including ozone (O_3) and CFCs, as well as the Kyoto Protocol gases (CO_2, CH_4, N_2O, SF_6, HFCs, PFCs).

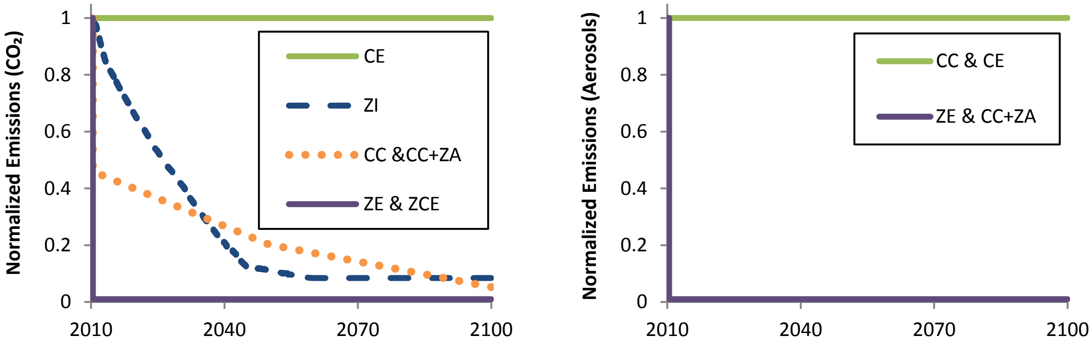

Figure 2-12: a) Normalized CO_2 Emissions and b) Normalized Aerosol Emissions, for Different Definitions of Committed Warming

The six definitions of committed warming shown in these figures are defined in Table 2-8. The chart on the right is intentionally blank in the middle, since any changes occur in a step function. In the Zero Emissions (ZE) definition, emissions of CO_2 and aerosols both fall immediately to zero. In the Zero CO_2 Emissions (ZCE) definition, CO_2 emissions immediately fall to zero; aerosols are implicitly assumed to be zero in the past and future and are not shown in part b. In the Constant Concentration (CC) definition, aerosol emissions remain constant (due to their short lifetimes, constant emission is necessary to maintain constant atmospheric concentration). CO_2 emissions are shown to fall by 54% immediately and then to fall linearly to 80% below 2010 levels by 2050 and then to fall to 95% below 2010 levels by 2100.[43] [42, 65, 66] In the Zero New Polluting Infrastructure (ZI) definition, CO_2 emissions fall by the trend line presented in Davis et al. 2010 [63] through 2060 when all existing energy infrastructure has been retired; remaining (non-energy) emissions are held flat in the current figure from 2060-2100. Aerosols are implicitly assumed to be zero in the past and future and are not shown on in part b. In the Constant Concentration + Zero Emission of Aerosols (CC+ZA) definition, the CO_2 emissions follow the CC trajectory and the aerosols drop immediately to zero, following the ZE trajectory. In the Constant Emissions definition, both CO_2 emissions and aerosol emissions are held constant.

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[43] The precise trajectory of a constant concentration scenario would depend on the trajectory of the airborne CO_2 fraction under a situation of dramatically declining CO_2 emissions. The long-term airborne fraction is well constrained by ocean chemistry, but the transient response is less well understood and has no observational precedent. Therefore, different modeling teams make different assumptions about the shape of the emission curve that would correspond to constant concentrations over the next 50-100 years. The NRC 2011 report estimates that an 80% reduction in CO_2 emissions would be required within 40-50 years in order to maintain a constant concentration, with additional reductions to follow. In this figure, I assume the absolute value of the carbon sink would (on average) remain roughly steady for the first few years, requiring an immediate 54% reduction in CO_2 emissions (1 minus the 46% airborne fraction; see Appendix J) followed by a linear path to the 80% emission reduction. This 54% assumption is fairly consistent with, though slightly less aggressive than estimates by the Real Climate team that constant concentration would require an immediate 60-70% emission reduction followed by continued reductions. Solomon et al. estimate that a reduction above 90% would eventually be required to sustain constant concentration over centuries, so I have assumed 95% in this figure.

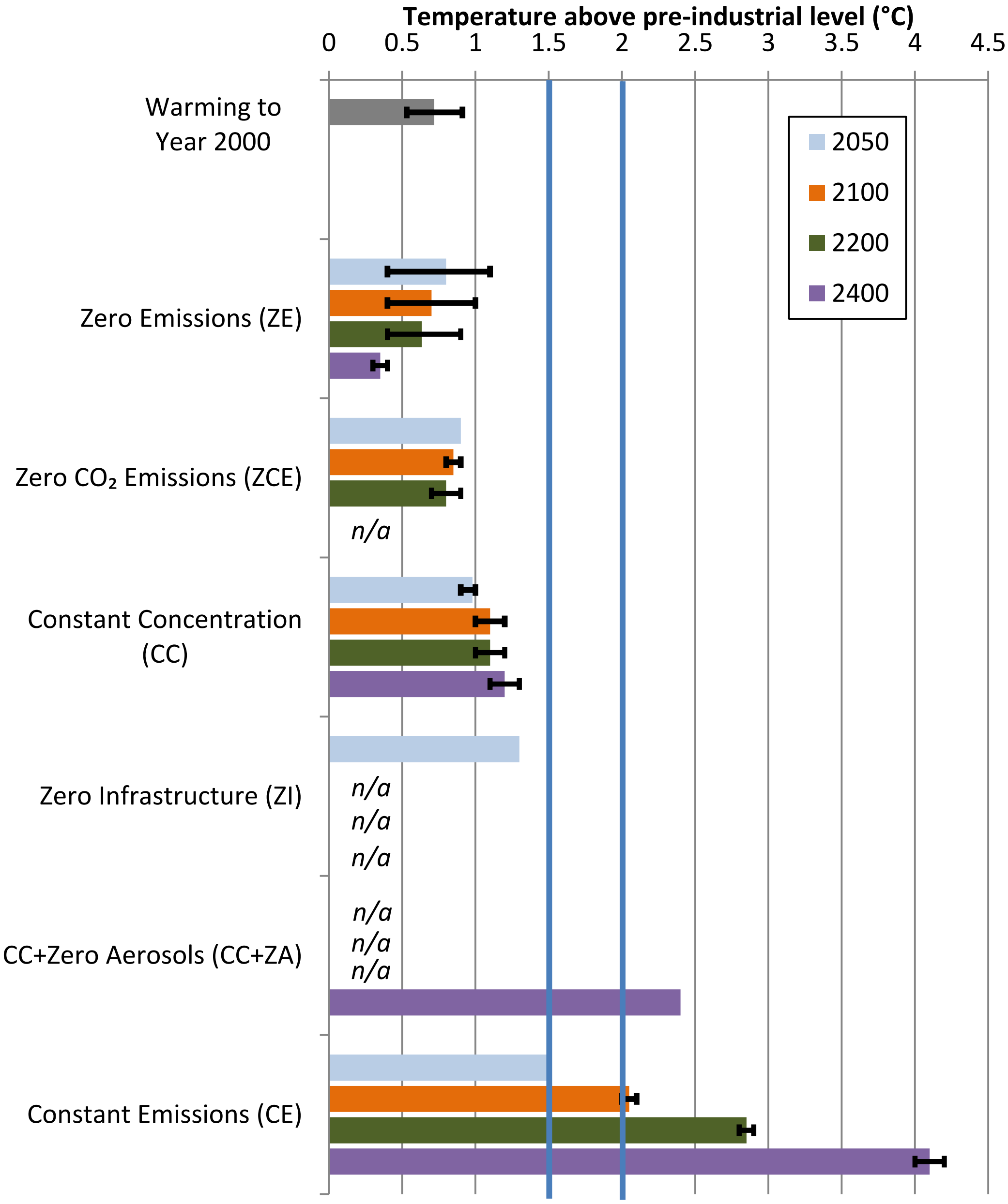

Figure 2-13: Temperature Change Associated with Different Definitions of Committed Warming
The temperature shown for each definition is the average projection for each definition made by the authors cited in Table 2-8. The error bars reflect the high and low ends of the central estimates made by these authors. ZI and CC+ZA have no error bars because those data points reflect single authors; ZI is provided for 2050 only and CC+ZA is provided for equilibrium only and presented here in year 2400. The estimate from each author and the full range of uncertainty for each estimate is shown in Appendix B. Six authors calculated temperature results starting the scenarios from year 2000, two started in year 2005, and two started in 2010. Warming to-date and its error bars are from IPCC AR4. [4] Blue vertical lines represent temperature thresholds of 1.5°C and 2°C above pre-industrial levels, as referenced in the Copenhagen Accord [3].

2.5 Summary of Climate Outcomes for Box Choice

The chapters ahead focus on the mitigation required to achieve each of the action boxes outlined in Chapter 1: “delay / slow down” (Box 1), “avoid 1.5-2°C” (Box 2), or “avoid 3-4°C” (Box 3). As shown in this chapter, all of these goals remain physically possible, though the time horizon to achieve them is short. Without mitigation on the scale of RCP3-PD, the 2°C temperature ceiling will be exceeded by mid-century.[44] Similarly, short of mitigation on the scale of RCP4.5 or SRES B1, the 3°C mark will be passed by the end of the century. The median temperature at year 2100 in the reference scenarios is projected to be 3.3-4.8°C above pre-industrial levels (section 2.2.b). Current emission trends and government pledges for the future are consistent with temperatures of 3-4°C above pre-industrial levels, if emissions beyond the pledge period continue on a trajectory between RCP 4.5 and RCP 6.0. “Committed” warming in 2100 ranges from 0.7-2.0°C, depending on whether the definition of “committed” includes elements of societal inertia.

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[44] Exception: SRES B1 would postpone 2°C beyond mid-century to 2080 according to Joshi et al., but only to 2045 or 2060 according to Prinn et al. and IPCC AR4, respectively. Note that the actual emission trajectory assigned to B1 differs by modeling group (see section 2.1), so this disparity of dates may not be as inconsistent as it appears.

Section II <u>Mitigation of Near-Term Climate Change</u>

Section II focuses on mitigation of near-term climate change, corresponding to Box 1 (delay) and Box 2 (avoid 1.5-2°C) of the Climate Boxes Framework that was introduced in Chapter 1 (Table 1-1). Near-term climate is defined in this dissertation as the climate of the next 20-40 years, a time period chosen to correspond to the lifetimes of most people currently in senior leadership roles.

Mitigation of near-term climate change has received scant academic attention to-date. As of June 2012, only 233 articles on “near-term climate” could be found in Web of Science, versus 16,557 articles on “long-term climate”. Of these 233 articles, roughly half (132) address mitigation of near-term climate change, the topic covered by this section of the dissertation. The other half focus instead on climate modeling and measurements, climate change impacts, or climate change adaptation.

Chapter 3 introduces the concept of the parallel pursuit of near-term and long-term climate mitigation. It identifies the disproportionate influence that short- and medium-lived radiatively active gases and aerosols[45] have on the near-term climate and makes the case for separate policies to manage these pollutants. This separation is particularly relevant in the context of incomplete and evolving knowledge of near-term climate change, as will be discussed in Chapter 6. Throughout the dissertation, these pollutants will be referenced with the shorthand term “short- and medium-lived pollutants”.

As with near-term climate, mitigation of climate change via reduction of short-lived pollutants has also received limited academic attention. As of June 2012, only 53 articles turned up on Web of Science for “short-lived air pollutants”, 99 for “short-lived climate emissions”, 108 for “short-lived trace gases”, 27 for “short-lived climate pollutants,” and 7 for “short-lived greenhouse gases”.

In Chapter 4, I examine the reductions of short- and medium-lived pollutants that have been accomplished to-date and review the handful of studies of maximum technical feasible reductions. Then in Chapter 5, I examine the magnitude of delay of climate change that is possible via these maximum reductions of short- and medium-lived pollutants. I close the

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[45] See footnote 9 for atmospheric lifetimes.

chapter and the section with a brief discussion of the impact that geo-engineering[46] might have on near-term climate.

The findings of Section II allow us to start to fill in the mitigation requirements of the Climate Boxes Framework (Table 2-9). Chapter 3 shows that the radiative forcing that drives near-term climate change is produced by a mix of short-, medium-, and long-lived pollutants. In other words, reducing all warming pollutants (CO_2 and non-CO_2) is important for reducing climate outcomes in the next 20-40 years (top row of Table 2-9). Delaying requires reducing emissions of all warming pollutants in proportion to the desired delay (with relative pollutant contributions influenced by constraints on technical feasibility noted in section 4.4 and speed of implementation) or might be accomplished via geo-engineering (Box 1 in Table 2-9).

Section III then explores the pros and cons of attention to the near-term climate, mitigation via short-lived pollutants, and geo-engineering.

	Most concerned about climate outcomes in the next 20-40 years	**Most concerned about long-term climate outcomes**	**Not concerned**
In general	Reduce all warming pollutants (CO_2 and non-CO_2)		n/a
Delay or slow down climate change	Box 1: Reduce emissions of all warming pollutants in proportion to the desired delay, and /or Geoengineering (SRM)[a]	n/a	n/a
Avoid 1.5°C or 2°C	Box 2		n/a
Avoid 3°C or 4°C	n/a	Box 3	n/a
Don't delay or avoid climate change	n/a	n/a	Box 4

Table 2-9: The Climate Boxes Framework, with Box 1 Mitigation Identified

[a] See footnote 10.

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[46] Geo-engineering is an anthropogenic change in the earth system to alter climate – e.g., by increasing reflectivity of sunlight or increasing carbon capture by plants.

Chapter 3 Parallel Pursuit of Near-Term and Long-Term Climate Mitigation

I published the following article in October 2009 [67] and have copied an excerpt here verbatim. A critical finding is that maximizing mitigation of near-term climate and maximizing mitigation of long-term climate requires emphasis on different pollutants and different sources. This means that the mitigation options are different for Box 1 (delay), Box 2 (Avoid 1.5-2°C), and Box 3 (Avoid 3-4°C).

3.1 Excerpt from Parallel Pursuit of Near-Term and Long-Term Climate Mitigation (Jackson, *Science* 2009)[47]

It is well accepted that reduction of carbon dioxide (CO_2) emissions is the lynchpin of any long-term climate stabilization strategy, due to the long lifetime of CO_2 in the atmosphere. [68] However, a focus on CO_2 may prove ineffective in the near term without comparable attention to pollutants with shorter lifetimes....[48]

Mitigation of near-term climate change involves different pollutants and source activities than mitigation of long-term climate change. Figure 3-1 shows that positive RF resulting from the next 20 years of human activity (columns 3 and 4) will exceed positive RF remaining, after decay, from historical human activity (column 2). Short-lived pollutants (black carbon, tropospheric ozone) and medium-lived pollutants (methane) account for more than half (57-60%) of the positive RF generated in years 1-20. These findings complement prior studies that highlight the importance of short- and medium-lived pollutants [5, 69-71].

Figure 3-2 shows the top 10 pollutant-generating activities contributing to net RF (positive RF minus negative RF) in year 20, taking into account the emission of multiple pollutants from each source activity [72]. The seven sources that appear only on the left side (purple bars) would be overlooked by mitigation strategies focusing exclusively on long-lived pollutants.

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[47] Excerpted text is from the accepted version of the article, per the License to Publish in *Science*. Minor word changes were made for the final article. The full final article can be found at: http://www.sciencemag.org/content/326/5952/526.full.pdf.

[48] The e-folding time (required to decrease to 37% of original airborne amount) is on the order of days to weeks for short-lived pollutants (e.g., black and organic carbon, tropospheric ozone, and sulfur dioxide), a decade for medium-lived (e.g., methane and some halocarbons), and a century for long-lived (e.g., nitrous oxide, some halocarbons). CO_2 takes roughly a century to reach 37%, then decays more slowly over millennia.

The distinctly different sources of near-term and long-term RF lend themselves to … [a] two-pronged mitigation approach. This decoupling is convenient for policy development and implementation; while the importance of long-term climate stabilization is clear, the perceived urgency of near-term mitigation will evolve with our knowledge of the climate system. Additionally, optimal near-term mitigation strategies will reflect decadal oscillations [4], seasonal and regional variations [73, 74], and evolving knowledge of aerosol-climate effects [75, 76] and methane-atmosphere interactions [75] – considerations unique to the near term.

Thus, short- and medium-lived sources (black carbon, tropospheric ozone, methane) must be regulated separately and dynamically. The long-term mitigation treaty should focus exclusively on steady reduction of long-lived pollutants. A separate treaty for short- and medium-lived sources should include standards that evolve based on periodic recommendations of an independent international scientific panel. The framework of "best available control technology" (strict) and "lowest achievable emissions rate" (stricter) from the U.S. Clean Air Act [77] can be used as a model.

Such a two-pronged institutional framework would reflect the evolving scientific understanding of near-term climate change, the scientific certainty around long-term climate change, and the opportunity to separately adjust the pace of near-term and long-term mitigation efforts.

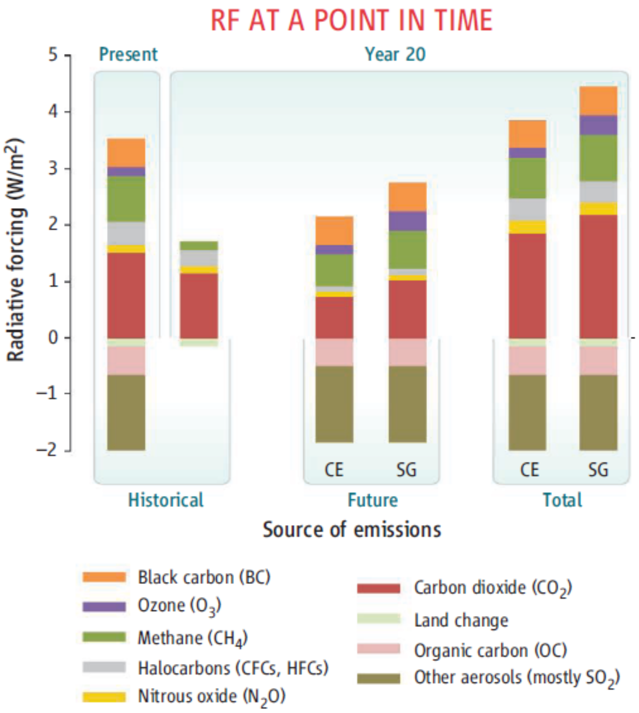

Figure 3-1: Global radiative forcing.

Reproduced with permission from Jackson 2009 [67], per the License to Publish in *Science.*

The leftmost bar shows RF attributable to historical human emissions (1750-2000). The next bar represents historical RF that would remain after 20 years of atmospheric decay, if one assumes zero additional human emissions in years 1 to 20. The next two bars represent RF in year 20 resulting from human emissions (beginning at 0 RF and incorporating atmospheric decay). Two scenarios are depicted: Emissions remain constant at year 2000 levels (CE), or emissions grow steadily at current rates (SG). [49] [30] The rightmost columns show total RF experienced in year 20 (historical + future emissions) for the CE and SG scenarios.

(Data for year 2000 RF are based on [78], emissions are from [79], decay rates are based on the lifetimes on p.212 in [75] and historical CO_2 decay is calculated according to p.824 in [62]. Growth rates are from [79] and [80]. Zero growth of emissions assumed for BC, OC, SO_2, and halocarbons. Each year's RF for short-lived pollutants (BC, OC, O_3, SO_2) is due only to emissions in that year; thus, the RF does not accumulate from one year to the next. The contributions of black carbon and ozone are conservative, as they do not reflect recent near-double estimates of black carbon's RF [76] nor recent estimates of ozone's indirect land sink effect [81].)[50]

Ozone generated from atmospheric methane is included under methane. Land change includes physical changes in planetary reflectivity (albedo) and evapotranspiration caused by changes in surface vegetation cover. Emissions from land change are included under each pollutant (e.g., CO_2 includes deforestation).

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[49] The same analysis applied to the IPCC's SRES marker scenarios (A1, A2, B1, B2) produces results that fall largely within the bounds of these two scenarios (see Figure 3-3).

[50] The text in parentheses appeared as a footnote in the original article, and is presented in the text here for technical reasons to accommodate references to source documents.

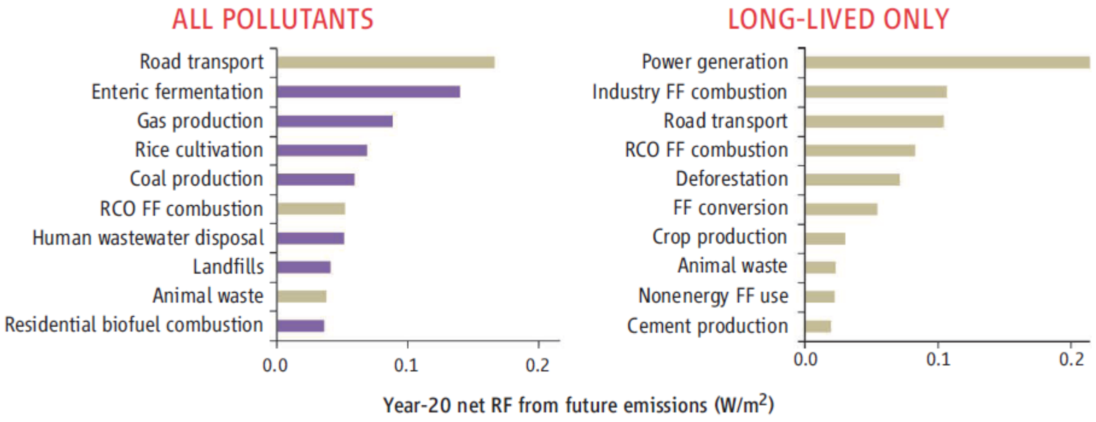

Figure 3-2: Top 10 global sources of year 20 net RF

Reproduced with permission from Jackson 2009 [67], per the License to Publish in *Science.*
Excludes historical emissions. Analysis combines results from Figure 3-1 (third bar, CE scenario) with source activity data from [79] and [82]. SG scenario is omitted (insufficient data on activity-level growth rates). Long-lived pollutants (CO_2, N_2O) have only positive RF; pollutants that are not long-lived have both positive (BC, O_3) and negative RF (OC, SO_2). Hence a source may show higher or lower RF on the left versus right (e.g., power generation emits both warming (long-lived CO_2) and cooling (short-lived SO_2) pollutants, which offset at this time scale). Halocarbons are excluded because activity data are not available for gases addressed by the Montreal Protocol. FF, fossil fuel; RCO, residential, commercial, and other. Data reflect uncertainty because of incomplete measurement and reporting infrastructure for non-CO_2 pollutants.

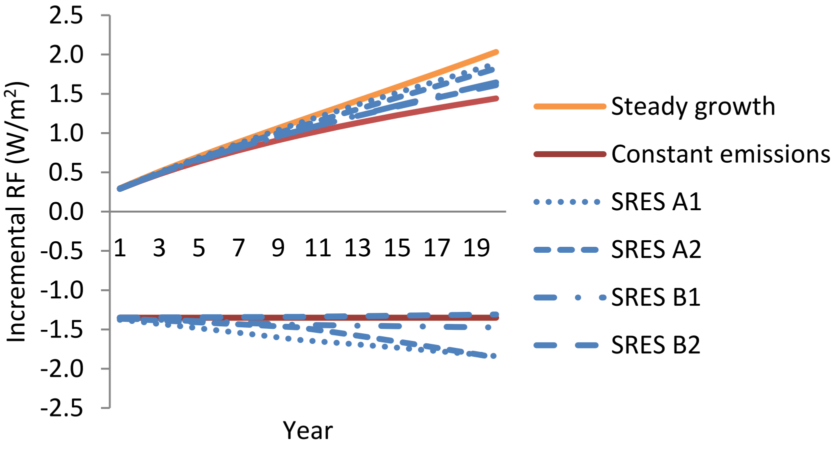

Figure 3-3: Near-term RF for constant emissions (CE), steady growth (SG), and SRES scenarios (S1)[51]

Reproduced with permission from Jackson 2009 [67], per the License to Publish in *Science.*
Methods and sources are the same as Figure 1. The set of lines above zero includes emissions from CO_2, N_2O, CH_4, and O_3. The set of lines below zero includes emissions from SO_2 and NO_x. Emissions from BC and OC are excluded from the comparison due to their exclusion from the marker scenarios. Halocarbon contributions are negligible in this time horizon. Note that the CE and SG scenarios bound the SRES scenarios for the warming pollutants. The modeled scenarios for cooling pollutants (flat-line) are more conservative (warmer) than most of the SRES scenarios.

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[51] This figure and caption appeared as supporting on-line material for the original article.

Chapter 4 Mitigation Potential and Progress on Short- and Medium-Lived Pollutants

In Chapter 3, I demonstrated that short- and medium-lived pollutants are responsible for the majority of positive RF over a 20-year time horizon in the early 21st century. These pollutants are thus important for near-term climate and potentially important for the mitigation strategy to delay climate change (Box 1) or avoid a temperature change of 1.5-2°C above pre-industrial levels (Box 2).

The importance of short- and medium-lived pollutants to mitigation strategy depends on how easy or difficult it is to change their emission rate. In this chapter, I will present the past emission trends for these pollutants, identify the sources and regions responsible for driving those trends, and explore the potential for reductions of their future emissions.

4.1 Short- and Medium-Lived Pollutants

Short- and medium-lived pollutants are significant because they are removed from the atmosphere in relatively short periods of time after being emitted. For short-lived pollutants with atmospheric lifetimes of days to weeks, constant emissions are required to maintain the same level of atmospheric concentration. Emission reductions of these pollutants can have a significant near-term effect in reducing radiative forcing – e.g., a 10% reduction of emissions of a short-lived pollutant results in a near-immediate 10% year-over-year *reduction* in the atmospheric concentration and radiative forcing from that pollutant. In contrast, long-lived pollutants remain in the atmosphere for many decades to centuries after emission. Each year's emissions add to the atmospheric concentration. This means that a 10% reduction in emissions of a long-lived pollutant results in a 10% smaller *increase* each year in the atmospheric concentration and radiative forcing than would have otherwise occurred.

The atmospheric removal times are thus important for the near-term radiative forcing outcome of reducing a pollutant. Figure 4-1 shows those lifetimes, along with the relative radiative forcing contributions, of different pollutants. The lifetime is described by the e-folding time, the amount of time required for the airborne amount to decrease to 37% of original airborne amount. This lifetime is on the order of days to weeks for short-lived pollutants (e.g., black and organic carbon, tropospheric ozone, and sulfur dioxide), a decade for medium-lived (e.g., methane and some halocarbons), and a century for long-lived (e.g., nitrous oxide, some halocarbons). CO_2 takes roughly a century to reach 37%, then decays more slowly over millennia.

As shown in Figure 4-1, pollutants with short, medium, and long lifetimes are all significant contributors to radiative forcing: carbon dioxide (CO_2) (long); methane (CH_4) (medium); and black carbon (BC), organic carbon (OC), and sulfate aerosols from sulfur dioxide (SO_2) (short). These pollutants will be discussed throughout the rest of the dissertation.

Pollutants making minor contributions (1-10% of RF) also span the lifetimes: nitrous oxide (N_2O) and chlorofluorocarbons (CFCs) (long); hydrochlorofluorocarbons (HCFCs) (medium); and tropospheric ozone (O_3)[52] and nitrate aerosols from nitrogen oxides (NO_x) (short). These pollutants receive limited treatment in the dissertation. CFCs and HCFCs are being reduced via the Montreal Protocol and require no further discussion here. N_2O is difficult and expensive to reduce, with a maximum feasible reduction potential of less than 10% at $60/ton CO_2eq [83, 84].[53] [54] Tropospheric O_3 and nitrates are covered in this chapter, alongside the other short-lived pollutants.

Pollutants making immaterial contributions (<1% of RF) include the medium-lived and long-lived hydrofluorocarbons (HFCs), many of which are being used to replace CFCs and HCFCs. The current radiative forcing from these pollutants in 2005 was 0.01 W/m^2, less than 1% of total positive forcing of over 3 W/m^2. HFC emissions are growing rapidly, and without intervention, UNEP [85] estimates that their RF could be 0.1-0.4 W/m^2 in 2050. If such growth occurred, HFCs could move into the category of minor contributors. Aside from mention here, HFCs do not receive specific attention in this dissertation.

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[52] Note that ozone (O_3) is not emitted directly and is formed in the atmosphere from precursors: methane (CH_4), non-methane volatile organic compounds (NMVOCs), carbon monoxide (CO), and nitrogen oxides (NO_x includes NO and NO_2)

[53] Maximum possible reductions in 2050 of N_2O's two primary sources (fertilizer use and animal waste) are 35% of the 2050 baseline, at a marginal cost of $1000 and $500 per tCeq, per Lucas et al. 2007.

[54] Note, N_2O also has a very small (0.01 W/m^2) cooling effect from its role in destroying stratospheric ozone.

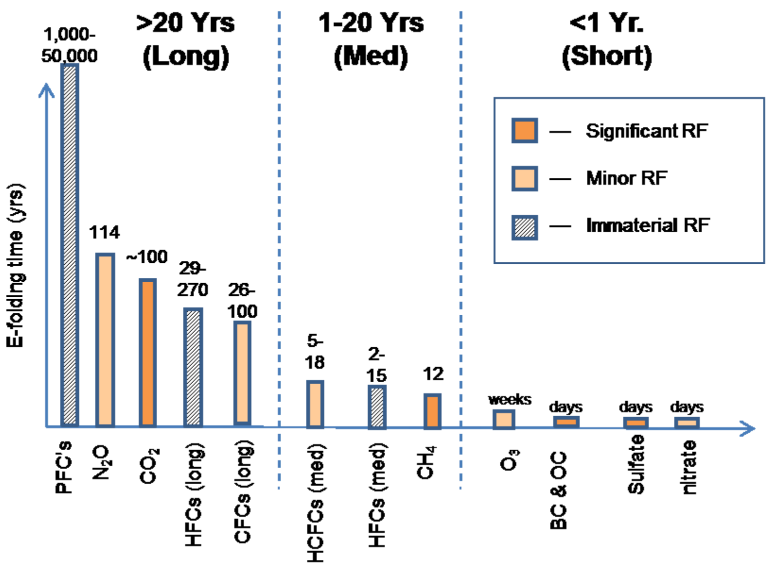

Figure 4-1: Comparison of Atmospheric Lifetimes of Radiatively Active Pollutants
Lifetime data are from IPCC AR4 WGI. Note, the atmospheric removal of CO_2 involves multiple sinks that operate over timescales from decades to millennia, and as such CO_2 does not have an e-folding time per se. The ~100 years shown should be interpreted as the time to remove 63% from the atmosphere if there were no additional emissions. The ranking of significance is assessed based on the contribution to radiative forcing of each atmospheric constituent. I have defined a “significant” contribution as >10% of RF, a “minor” contribution as 1-10%, and an “immaterial” contribution as less than 1%t. The ranking was done both by the forcing from emissions to-date (first bar in Figure 3-1) and by the forcing that would result from 20 years of constant emissions (third bar in Figure 3-1); results from both methods are the same.

4.2 Methods

In section 4.3, I review the historical emission trends of short-lived pollutants and methane, plotting data from EDGAR 4.2 to understand the regional and source-level drivers of key trends.[55] In section 4.4, I turn to the potential for future emission reductions, drawing upon a series of studies (2006-2011) by Unger et al. 2006 [86], Cofala et al. 2007 [87], and Shindell et al. 2011 [36, 88][56] and a 2006 report by the U.S. Environmental Protection Agency (EPA) [83]. Examining the series of studies allows the opportunity to examine how estimates of mitigation potential have evolved over time. Additionally, this series of studies is the foundation for UNEP's 2011 estimate [36] of temperature change that could be avoided via mitigation of short-and medium-lived pollutants (see section 4.4.b and Appendix F). The EPA study provides a point of contrast, though only for methane, from another expert team with a different approach. While Unger et al., Cofala et al., and Shindell et al. estimate the maximum *technically* feasible reductions, the EPA team estimates the maximum feasible reductions within a cost limit of $60/ton CO_2eq. Both teams do bottom-up assessments of potential reductions by sector.

All of the maximum feasible reduction studies present data in the form of reductions versus a future reference scenario or against a given historical year (from different emission inventories). To enable an apples-to-apples comparison, I compiled data from the sources and re-computed in absolute terms with a standard reporting convention (e.g., Gt CH_4 vs. Gt CO_2eq, or Gt NO_2 vs. Gt N), then compared versus EDGAR baseline historical data [46]. I also obtained sector-level data from the UNEP team to compare versus the sector-level EPA data. [89] I translated the emission reductions into radiative forcing reductions as described in the captions for Figure 4-11 and Figure 4-13.

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[55] See more detail on EDGAR in Appendix C.

[56] Seven people were authors on at least two of these three papers: D. Shindell, M. Amann, J. Cofala, D. Streets, Z. Klimont, K. Kupiainen, and L. Hoglund-Isaksson.

4.3 Emissions Trends To-Date for Short- and Medium-Lived Pollutants

While there have been localized emission reductions in some regions for some pollutants, at a global scale, emissions of all short- and medium-lived pollutants have seen flat to increasing trends over the past decade and most have grown for the past four decades. This section reviews the trends for each pollutant.

Black carbon (BC) has large uncertainty in its emission history, as shown in Figure 4-2 and Figure 4-3. Figure 4-2 shows the 150-year emission history from three authors and Figure 4-3 shows the 30-year history from a dozen authors. Over the longer 150-year timescale, global BC emissions have steadily increased. Over the past thirty years, there is conflicting judgment on whether emissions have increased or decreased. Over the past decade, the limited analyses suggest that emissions have been fairly flat.

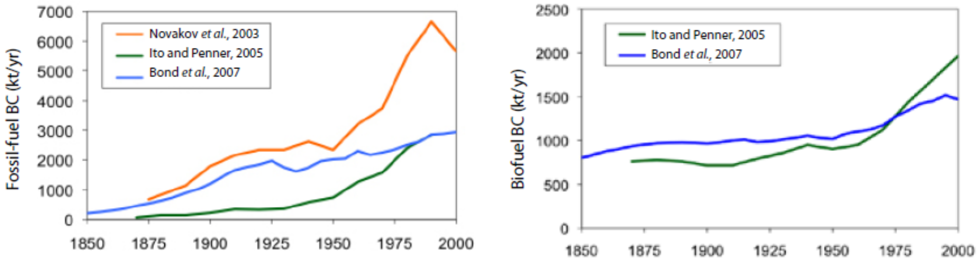

Figure 4-2: 150 Years of Global Black Carbon Emissions, from Fossil Fuel (left) and Biofuel (right)
Reprinted with permission from UNEP Integrated Assessment 2011, p.25. [36]

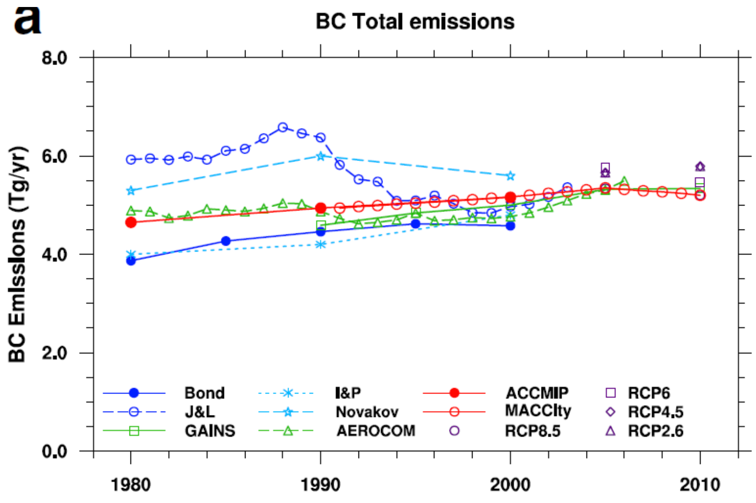

Figure 4-3: 30 Years of Global Black Carbon Emissions, 1980-2010
Reprinted with kind permission from Springer Science and Business Media, from Granier et al., Climatic Change 2011 [90]. Results are shown from eight different inventories and the RCP scenarios. All inventories are calculated based on estimates of activities data (e.g., fuel consumption, commodity production) and emission factors (emissions per unit of activity). Tg = Mt.

Global methane emissions have increased over 40% since 1970, and have been rising steadily over the past decade after a plateau in the 1990s (Figure 4-4). Emissions of the other ozone precursors have also been either growing (NO_x) or showing high volatility and no clear trend (NMVOCs and CO). (Figure 4-4)

The steady growth of methane emissions has been a consistent trend across most sources for several decades, as shown in Figure 4-5. Exceptions are a three-decade decline in emissions from rice cultivation (though rising slightly recently) and an abrupt increase in fugitive emissions from solid fuels,[57] which corresponds to the increase in coal use. [33][58] At a regional level, only the USA and OECD Europe[59] have shrinking methane emissions (dotted lines in Figure 4-6). These declines are due to large reductions in methane from solid waste disposal on land (i.e., landfill gas) (both Europe and USA) and fugitive emissions from solid fuel (i.e., coal) (OECD only). For details on USA and OECD Europe, see Appendix D.

Globally, the cooling aerosols (OC, SO_2, and NO_x) are also trending either flat or up.[60] Organic carbon (OC) is co-emitted with black carbon (BC) from biofuel and coal, so it has a similar emissions pattern. [82] NO_x has been rising steadily for forty years, with a slight recent decline (Figure 4-7). SO_2 has been rising globally since the early 2000s, after a two-decade decline shown in Figure 4-7. This pattern holds across all of the top sources, shown in Figure 4-8. Figure 4-9 demonstrates that this pattern is attributable to dramatic SO_2 emissions growth in China, offsetting steady reductions in the US and OECD Europe.[61] More recent data by Lu et al. 2011 suggest that Chinese SO_2 emissions in 2010 have declined from their peak. [91] This has been attributed in part to a 2007 Chinese government requirement that all state-controlled key polluting facilities[62] install continuous emission monitoring equipment by the end of 2008 and do more frequent inspections. [91-93]

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[57] Fugitive emissions are those that leak from mines, wells, pipelines, etc. during the extraction and distribution of coal, oil, and natural gas.

[58] Total primary energy demand for coal increased by 48% globally between 1990-2009, with a plateau in the 1990s followed by a steep upward trend in demand starting in the early 2000s.

[59] OECD = Organization for Economic Cooperation and Development; includes 34 countries.

[60] Upward global trend includes increases in some regions and decreases in others (see Figure 4-9).

[61] Note, reduced SO_2 emissions in one region do not physically offset the impact of increased SO_2 emissions in another region because their climate effects are regional in nature. The offset is arithmetic in the global total emissions.

[62] Includes both power plants and industry. Note, power plants accounted for only 21% of China's SO_2 emissions in 2010. Industrial sources accounted for 66%.

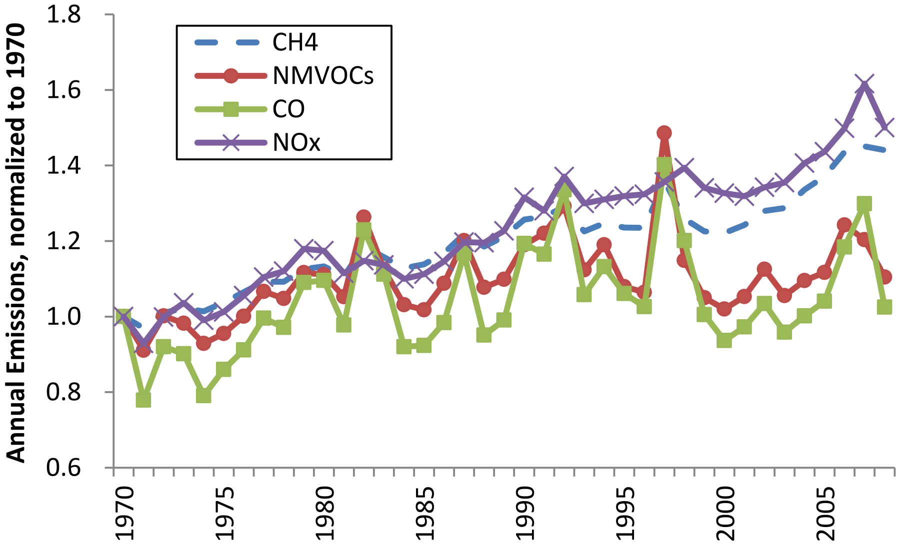

Figure 4-4: CH_4 and the Other Tropospheric Ozone Precursors, 1970-2008
Data source: EDGAR 4.2 database [46]

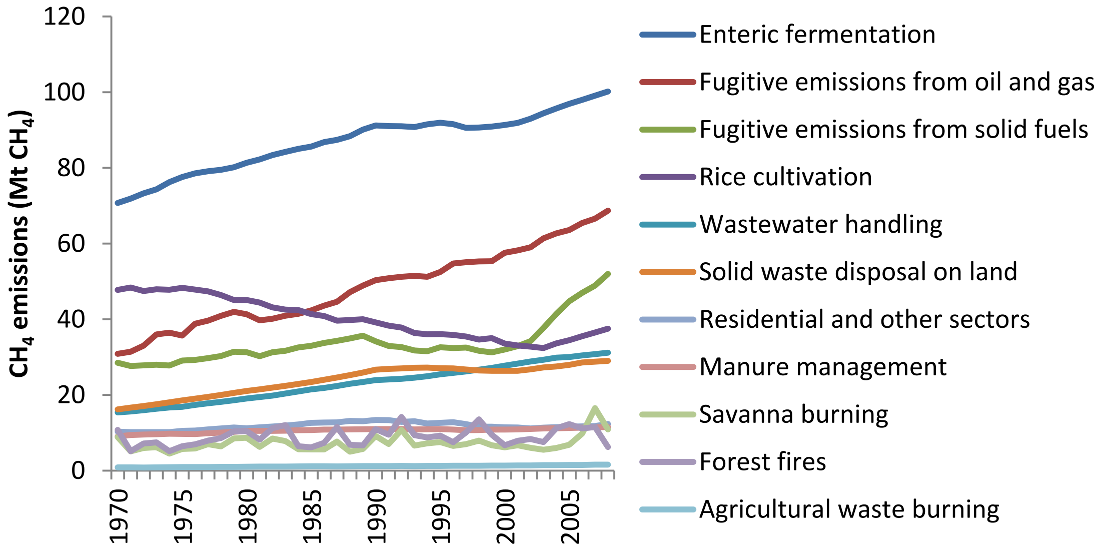

Figure 4-5: Global Methane (CH_4) Emissions by Source, 1970-2008
Data source: EDGAR 4.2 database [46]

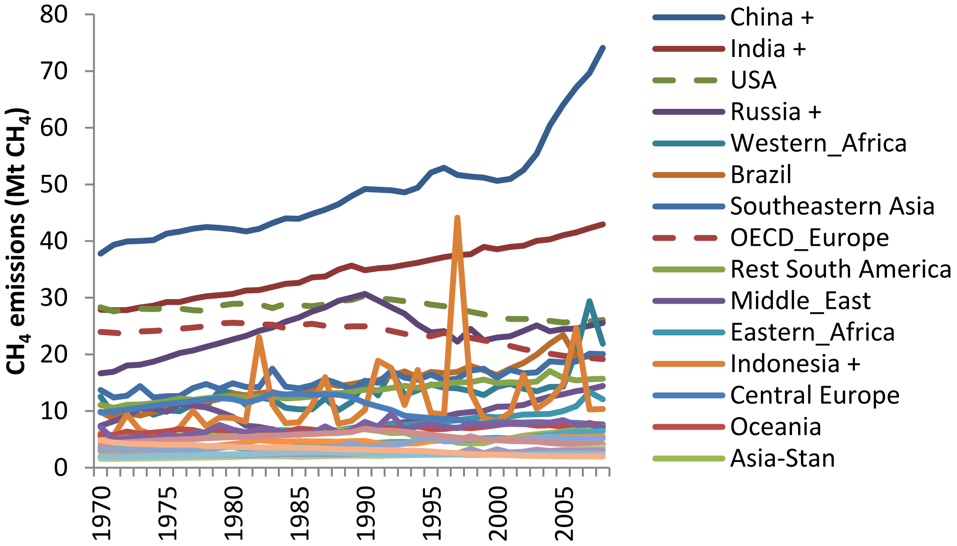

Figure 4-6: Methane (CH_4) Emissions by Region, 1970-2008[63]

Data source: EDGAR 4.2 database [46]

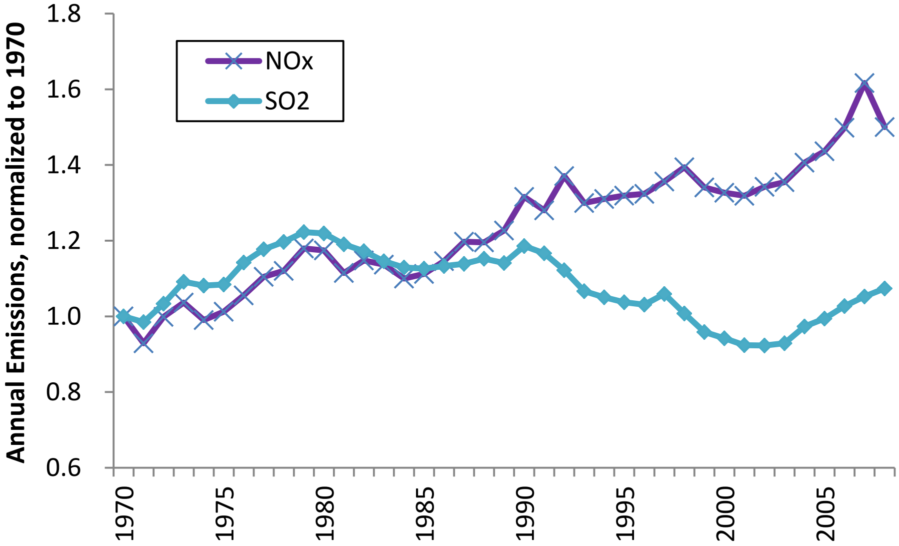

Figure 4-7: Cooling Pollutant Emissions (SO_2 and NO_x), 1970-2008[64]

Data source: EDGAR 4.2 database [46]

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[63] Note, EDGAR has defined the "China+" region to include China, Hong Kong, Macao, Mongolia, and Taiwan. The "India+" region includes India, Afghanistan, Bangladesh, Bhutan, Sri Lanka, Maldives, Nepal, and Pakistan. The "Russia+" region includes the Russian Federation, Georgia, Azerbaijan, and Armenia. "Ukraine+" includes Ukraine, Belarus, and Moldova. "Asia-Stan" also consists of former republics of the USSR: Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. "Central Europe" includes Poland, Czech Republic, Slovakia, Hungary, Romania, Bulgaria, Bosnia and Herzegovina, Croatia, Serbia and Montenegro, Slovenia, Republic of Macedonia, Lithuania, Latvia, Estonia, Albania, Cyprus, and Malta. "Southeast Asia" includes Brunei, Cambodia, Lao, Myanmar, Malaysia, Philippines, Singapore, Thailand, Timor-Leste, and Vietnam.

[64] Note, NO_x is both a cooling pollutant and a warming pollutant. See section 7.1 for explanation of its dual role.

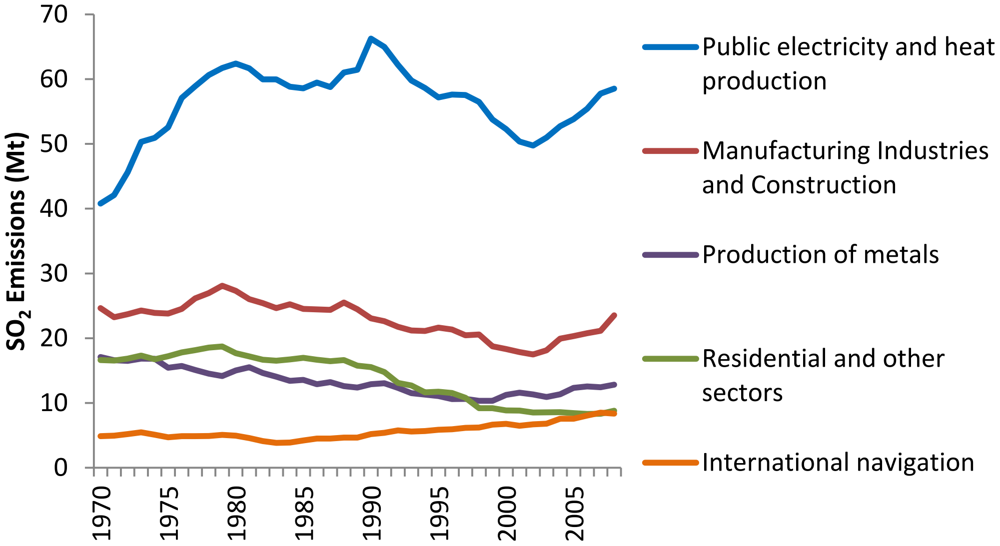

Figure 4-8: Global SO_2 Emissions by Source, 1970-2008 (top 5 sources)
Data source: EDGAR 4.2 database [46]

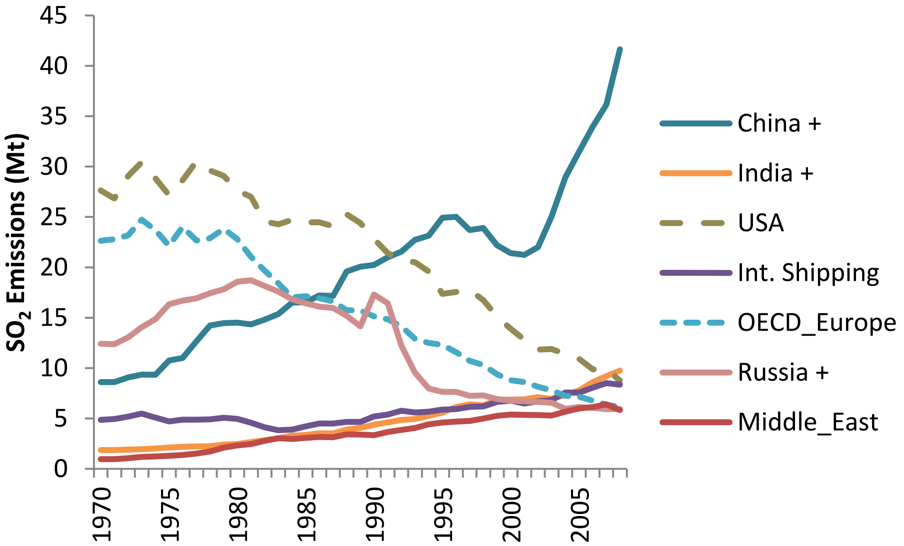

Figure 4-9: SO_2 Emissions by Region, 1970-2008 (top 7 regions)
Data source: EDGAR 4.2 database [46]

4.4 Maximum Feasible Reduction Potential for Short- and Medium-Lived Pollutants

While short- and medium-lived pollutant emissions have been steadily trending upwards, significant potential exists for reducing these emissions. Estimates of maximum technically feasible reductions (MTFR) encompass all reductions that would be possible with technologies available today, without regard to cost or implementation constraints. These reductions provide an upper boundary on what is possible today without major changes in behavior or development patterns, a limit that might rise in the future as technologies advance. The MTFR approach was taken by three of the four studies shown in this section (Unger et al., Cofala et al., and Shindell et al. / UNEP). An alternate approach of maximum economically feasible reductions estimates the emission reductions that would be feasible given a cost restriction. The EPA report provides an estimate of maximum economically feasible reductions only for methane[65] and only up to a cost of \$60/ton CO_2eq.[66] As we will see below, methane reductions have the largest potential for reducing radiative forcing among short- and medium-lived pollutants, so the EPA report provides data for the most important cross-study comparisons.

In the sections below, I compare the magnitude and variance of reduction estimates across studies and across pollutants and the evolution of these estimates over time. Then I explore the radiative forcing implications of these reductions, the uncertainties in those calculations and the implications for mitigation, and the maximum potential temperature reduction from reducing short- and medium-lived pollutants.

4.4.a Comparing Estimates of Maximum Feasible Reductions

All four studies examined show substantial feasible emission reduction potential, across all short- and medium-lived pollutants (see Figure 4-10). Methane (CH_4) has the lowest maximum technically feasible reductions (MTFR), with estimates ranging from 16-43% reductions below 2005 emissions, at any cost. When the cost constraint is added by the EPA study, the maximum feasible reduction falls at the lower end of the range, at 18%. Most of the feasible reductions come from the fossil fuel production and distribution and the waste and landfill source categories, each of which has technology options to reduce emissions by about half. In the

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[65] The EPA report does provide MFR estimates for other greenhouse gases, but not for the short-lived pollutants.

[66] EPA defines CO_2eq. using the GWP100 metric.

livestock source category (about ⅓ of CH_4 emissions), limited technology options exist for reducing the methane produced by ruminant animals.[67]

All of the other pollutants have MTFR close to 50% of 2005 levels or greater: NO_x, BC, and OC have wide-ranging MFR estimates: NO_x, 61-81%; BC, 47-83%; and OC, 60-88%. The MTFRs for the rest of the pollutants are above 60% and in tighter ranges: NMVOCs, 62%[68]; CO, 71-85%; and SO_2, 69-82%.

Estimates of maximum technically feasible reductions (MTFR) have increased over time for each pollutant. For every pollutant, the most recent study (UNEP 2011) has the highest MTFR of all four studies. For five of six pollutants that have estimates from multiple studies, the lowest estimated reductions were made by the earliest study. This finding is significant because the three MTFR studies (Unger et al. 2006, Cofala et al. 2007, Shindell et al. 2011 / UNEP 2011) had significant overlapping authorship, suggesting that what is technically feasible has expanded over time. A useful project for future research would be to identify which sources and technologies have been responsible for the increases in reduction potential estimates and to explore the implications for further reductions.

Note, data have been presented versus 2005 emissions for comparability with the 2005 RF data used in the next section. A replica of Figure 4-10 is shown in Appendix E with reductions compared to the most recently available (2008) data. Methane emissions grew between 2005 and 2008, so its reduction to 2030 is 2-4 percentage points steeper when compared to 2008 rather than to 2005. Other pollutants have not grown materially, so their reduction percentages are similar relative to 2008 and to 2005.

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[67] Ruminants (including cattle, sheep, goats, and others) are mammals with multiple stomach chambers, with the first one called the rumen. They soften food in the rumen and then re-chew it. Methane is produced by enteric fermentation in the rumen and emitted when the animals burp.

[68] Single estimate from Unger et al. 2006.

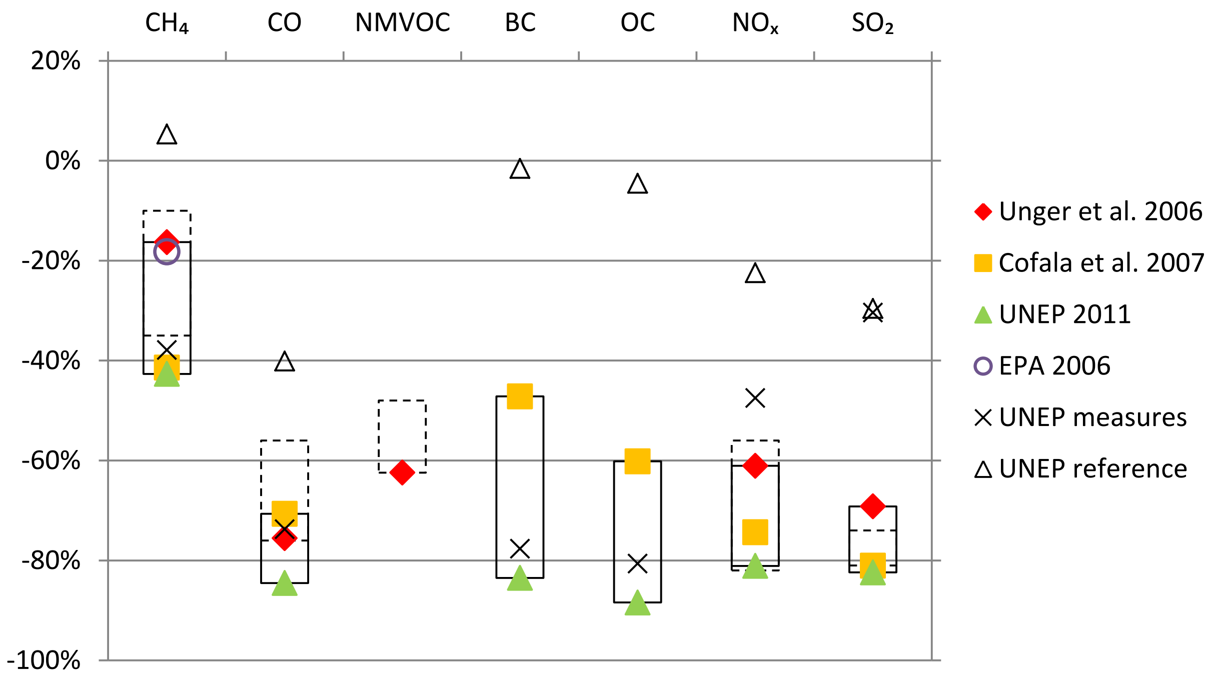

Figure 4-10: Maximum Feasible Reductions by Pollutant, as a % of 2005 Emissions
Maximum technically feasible reductions for each pollutant are shown, as assessed in 2006 by Unger et al. [86], 2007 by Cofala et al. [87], and 2011 by Shindell et al. in Science [88] and in a 2011 UNEP report [36] (labeled UNEP 2011 in the chart). Note that estimates of maximum technically feasible reductions for most pollutants increased over time. Maximum economically feasible reductions at $60/ton CO_2eq are shown for methane (CH_4), as assessed by the EPA in 2006 [83]. Reductions are calculated by taking the 2030 emissions provided by each study (2020 emissions from the EPA report), converting them to standard units, and comparing them against 2005 actuals from the EDGAR 4.2 database [46]. For black carbon (BC) and organic carbon (OC), EDGAR data were unavailable and 2030 emissions of those pollutants are compared to the historical levels reported within the studies (year 2000 for Cofala et al. and year 2005 for UNEP). UNEP measures are those assumed in the UNEP 2011 report for aggressive mitigation of short- and medium-lived pollutants [36]. The UNEP reference case projects emissions in absence of any change to current policies. The temperature results of the UNEP measures relative to the UNEP reference case are discussed in section 4.4.b and in Appendix F. A solid box brackets the maximum and minimum feasible reduction estimates for each pollutant, as calculated against the standard EDGAR 2005 baseline. The EDGAR 4.2 data are more recent than the historical datasets used in all of the studies and the reduction percentages using the EDGAR 4.2 data are somewhat greater than the percentages calculated in the original studies for some pollutants. A dashed box brackets the maximum and minimum percentage reduction relative to 2005 based on the dataset used in each study (baselines of 1995 or 2000 are proportionally projected to 2005 relative to EDGAR data). Detailed source data for CH_4 and BC and a version of this chart relative to 2008 emissions are shown in Appendix E.

4.4.b Radiative Forcing Changes from Maximum Feasible Emission Reductions

In this section, we will look at the radiative forcing implications of reducing short- and medium-lived pollutants at the low and high ends of what was presented as the maximum technically or economically feasible for each pollutant in Figure 4-10 (“Min MFR” and “Max MFR”). The UNEP 2011 study [36] presented an estimate of the potential near-term temperature benefit of mitigating short- and medium-lived pollutants, so I have also included the UNEP mitigation scenario (“UNEP measures”) and the UNEP measures relative to the UNEP reference scenario (“UNEP meas. beyond ref.”) alongside the MFR results in this section. The UNEP measures scenario is noteworthy because the UNEP team evaluated 400 technically feasible measures[69] and selected the 16 with the largest climate benefit.[70] [71]

I have calculated the radiative forcing (RF) changes that would result from the emission reductions in each of the four scenarios (Min MFR, Max MFR, UNEP measures, UNEP reference) and results are presented in Figure 4-11 and Figure 4-12. Methods are described in the captions.

From Figure 4-11, we see in all four scenarios, reducing black carbon (BC) has the greatest projected benefit for reducing radiative forcing (0.3-0.5 W/m^2). However, the uncertainty around the benefit is very large and crosses zero (uncertainty is discussed further in section 4.4.b.i). Methane (CH_4) reductions provide the second largest radiative forcing benefit in three of the four scenarios (0.1-0.3 W/m^2). The radiative forcing benefit for methane has a narrow range of uncertainty. Sulfur dioxide (SO_2) reductions provide the largest radiative forcing *increase* (0.2-0.6 W/m^2), with a wide range of uncertainty on magnitude. Because SO_2 causes respiratory illness, some of these reductions are included in the reference case. (see section 7.1)

The non-SO_2 short-lived pollutants (SLPs) (CO, NMVOC, NO_x, BC, OC) are all products of incomplete combustion and are emitted in varying proportions from different combustion sources. In Figure 4-12, the non-SO_2 SLPs are shown in total. Their radiative forcing reduction potential in aggregate (0.2-0.4 W/m^2) is on the same order of magnitude as methane (CH_4) (0.1-0.3 W/m^2), but the uncertainty around the benefit is much wider and crosses zero. Sulfur reductions are of the same order of magnitude as well (0.2-0.6 W/m^2), in the opposite direction

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[69] These 400 measures were all included in Figure 4-10 for UNEP 2011’s MTFR.

[70] Note, the temperature results shown in Chapter 5 include 14 of the 16 measures; UNEP and Shindell et al. excluded coal briquettes and pellet stoves from the global temperature results (the main benefit of those two measures is reduced black carbon in the Arctic).

[71] Note, some technical options improve air quality but increase radiative forcing, due to co-emission of cooling pollutants alongside the warming pollutants. These options were not included among the 16 selected measures.

and also highly uncertain. Among short- and medium-lived pollutants, methane reductions provide the most certain radiative forcing benefits. UNEP estimates that the temperature reduction potential from short- and medium-lived pollutants that corresponds to these RF estimates (based on the UNEP meas. minus ref. bar in Figure 4-11) is 0.5°C (0.2-0.8°C), though this estimate may be somewhat high for reasons discussed in Appendix F.

Figure 4-13 shows the same radiative forcing, grouped by atmospheric constituents instead of by emissions. Many of the emitted pollutants have effects on multiple gases and aerosols in the atmosphere. Atmospheric methane (CH_4) concentrations change based not only on CH_4 emissions, but also on carbon monoxide (CO) and non-methane volatile organic compound (NMVOC) emissions (which drive up atmospheric CH_4) and NO_x (which drives down atmospheric CH_4). Tropospheric ozone (O_3) increases as the result of increases in emissions of the ozone precursors (CH_4, CO, NMVOCs, NO_x). Stratospheric water vapor (H_2O) increases with CH_4 emissions. Atmospheric CO_2 increases with CO, NMVOC, and CH_4 emissions. Nitrate aerosols (N-aerosols) are produced by NO_x emissions. Sulfate aerosols (S-aerosols) are produced by SO_2 emissions.

From Figure 4-13, we see that black carbon (BC) is the atmospheric constituent showing the highest radiative forcing reduction for all scenarios, but with wide uncertainty. Tropospheric ozone shows the next highest radiative forcing benefit, with medium uncertainty. Methane (CH_4) shows the third highest benefit, with narrow uncertainty.

4.4.b.i Key Assumptions and Uncertainty

Two types of uncertainty are predominantly responsible for the length of the error bars in Figure 4-11, Figure 4-12, and Figure 4-13. First is the wide uncertainty in the direct forcing from black carbon (note the long solid error bar on black carbon). Second is the uncertainty regarding the magnitude of the aerosol indirect effect (AIE) and the attribution of that effect among the different aerosols (note the long dotted error bar on all of the aerosols). There are other notable uncertainties regarding tropospheric ozone, organic carbon, and the direct effect of sulfate aerosols[72], but they are smaller than the BC forcing and AIE uncertainties.

The direct effect of an aerosol is the forcing attributable to absorption or reflection by the particle itself. The indirect effect of an aerosol is the forcing attributable to the changes that its

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[72] The RF calculation for the sulfate column and its solid error bar assumes a 50/50 split between sulfate's direct and indirect effect, so the uncertainty on sulfate RF in the solid error bar should be perceived as half attributable to uncertainty in the direct effect and half attributable to uncertainty in the indirect effect. The additional length of the dotted error bar is attributable entirely to uncertainty in the indirect effect.

presence causes in cloud albedo (by providing nuclei for condensation or by increasing the lifetime of clouds via drizzle suppression, increased cloud height, or increased cloud lifetime). Uncertainty in calculating the global forcing of aerosols is the product of both incomplete knowledge of cloud physics and the complexity of summing up local and regional effects into a globally relevant number. [75]

I have calculated the error bars using a combination of assumptions from IPCC AR4 and the UNEP 2011 report. The columns in Figure 4-11, Figure 4-12, and Figure 4-13 reflect results that were calculated in a way intended to be closely comparable with the UNEP report. This method differs somewhat from the assumptions used in Chapter 3 [67]; results using the Chapter 3 method are shown here as triangles. Error bars include the full range of uncertainty provided by UNEP for direct forcing of BC, OC, and sulfate (similar or wider range than IPCC AR4) and by IPCC AR4 for tropospheric ozone, nitrate, and the aerosol indirect effect (AIE) from cloud albedo (wider than UNEP). The solid error bars are calculated to be consistent with the UNEP report's approach of attributing all variation in the AIE to sulfates. The dashed error bars include attribution of the AIE to all aerosols, either by attributing half to soot (BC and OC) and half to non-soot (sulfate aerosols, nitrate aerosols, mineral dust) per Hansen 2007 [78]or by spreading the AIE forcing in proportion to the absolute value of each aerosol's direct forcing.[73]

The solid error bars never cross the zero line, but the dashed lines cross zero for black carbon and for the total of the non-SO_2 short-lived pollutants (driven primarily by the uncertainties in black carbon and organic carbon). The difference between the solid and dashed error bars is whether there is a negative indirect effect of soot (BC and OC) on clouds. In order for net forcing to cross zero, the indirect effect must exceed the direct effect. Recent estimates of aerosol's negative forcing have increased since AR4 [43, 75][74] and are significantly larger than the negative aerosol forcing estimates used in the UNEP report. [36][75]

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[73] Note, the dashed error bars for BC and OC extend beyond the ranges found in the UNEP report due to the AIE assumptions made here.

[74] Total forcing from all aerosols was estimated by Hansen et al. 2011 to be -1.6 W/m^2 (-1.9 to -1.3 W/m^2), which is a larger and more narrow estimate of negative aerosol forcing than reported in 2007 in AR4 (-1.25 W/m^2; -2.7 to 0.4 W/m^2).

[75] The central estimate of present-day aerosol forcing in the UNEP report is ~-0.5 W/m^2. This estimate was derived from the report as follows: BC: 0.5 W/m^2 (0.0 to 1.0 W/m^2); OC: -0.19 W/m^2 (-0.08 to -0.30 W/m^2); Nitrate aerosol: -0.10 W/m^2 ± 66% (-0.03 to -0.17 W/m^2); Sulfate aerosol direct: -0.34 W/m^2 ± 66% (-0.12 to -0.56 W/m^2); Sulfate aerosol indirect: same as sulfate aerosol direct. Sulfate aerosol direct was estimated by taking the 2030 RF from Figure 5.1 of the UNEP report (-0.29 W/m^2) and scaling it by the ratio of the 2005 emissions to 2030 emissions to get -0.34 W/m^2 in 2005.

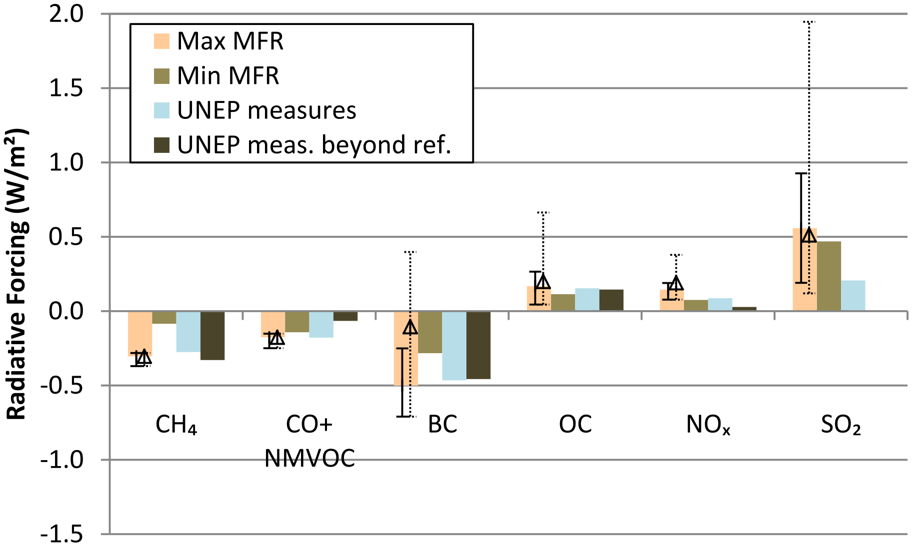

Figure 4-11: Radiative Forcing Change Attributable to Emission Reduction of Each Short- and Medium-Lived Pollutant at Maximum Feasible Reductions and with UNEP Measures

Max and Min MFR assume the maximum and minimum estimates of MFR made by different authors for each pollutant as shown in Figure 4-10. UNEP measures are those assumed in the UNEP 2011 report for aggressive mitigation of short- and medium-lived pollutants (shown in Figure 4-10). RF from UNEP measures relative to the reference case are shown in black. The reduction in radiative forcing (RF) attributable to each pollutant is calculated based on the emission reductions shown in Figure 4-10. The RF change attributable to each pollutant is summed across the RF change in each atmospheric constituent attributable to that pollutant. The methods for calculating the RF change in each atmospheric constituent are described in the caption for Figure 4-13. Error bars for all four scenarios are of similar magnitude and are shown on a single scenario for visual clarity. The triangles show results using a different method (see section 4.4.b.i).

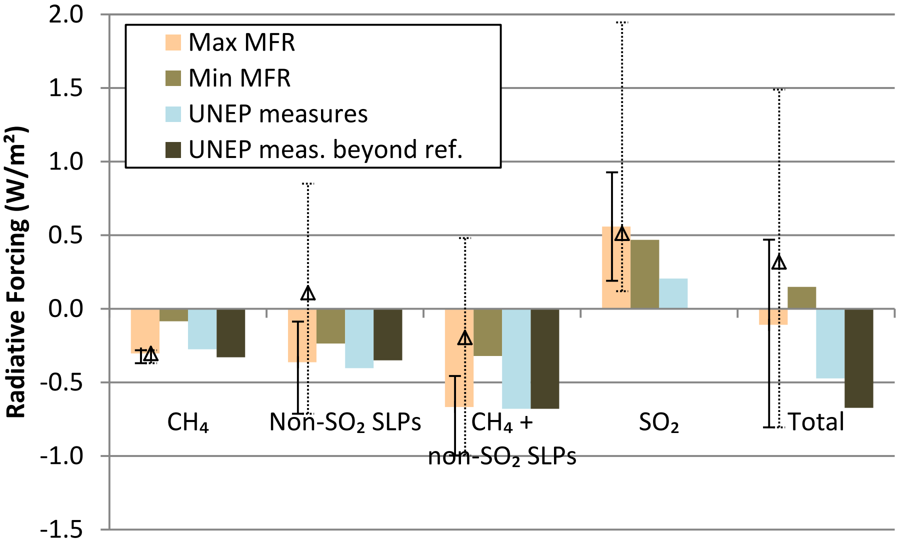

Figure 4-12: Replica of Figure 4-11, with Totals Across Pollutants

Methods are the same as Figure 4-11. Non-SO_2 short-lived pollutants (SLPs) include CO, NMVOCs, BC, OC, and NO_x. Note that nearly the same SO_2 reductions are assumed by UNEP in the measures and reference cases, thus the total bar comparing the cases excludes the warming effect of reducing SO_2.

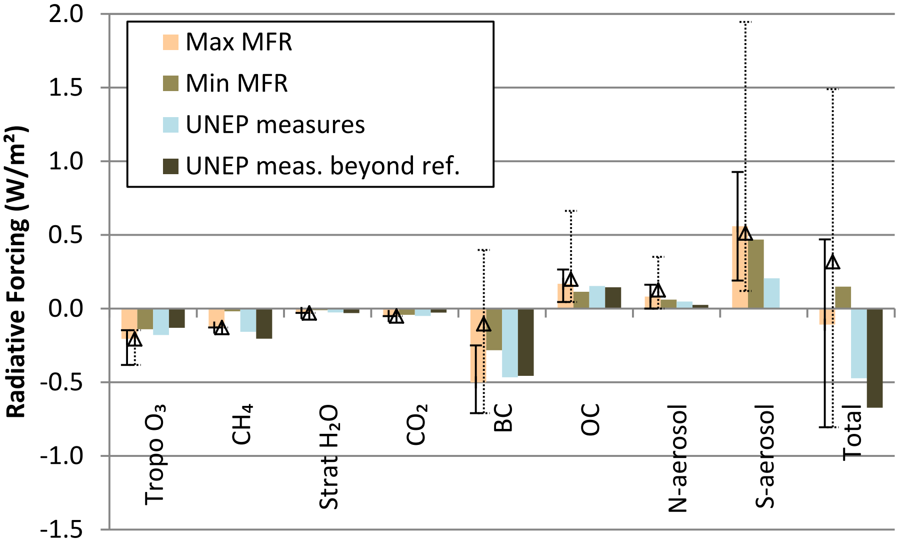

Figure 4-13: Radiative Forcing Change Attributable to Changes in Atmospheric Constituents, as a Result of Emission Reductions of Short- and Medium-Lived Pollutant at Maximum Feasible Reductions and with UNEP Measures

Four scenarios (Max MFR, Min MFR, UNEP measures, and UNEP meas. beyond ref.) are defined the same way as in Figure 4-11 and the Totals are the same values. Emission reductions are based on Figure 4-10. Relative contributions of each emitted pollutant (CH_4, CO, NMVOC, BC, OC, NO_x, SO_2) to the atmospheric concentration of each airborne constituent (tropospheric O_3, CH_4, stratospheric H_2O vapor, CO_2, BC, OC, nitrogen aerosol, sulfate aerosol) were proportionally derived from their RF contributions in Table 2.13 of IPCC AR4 WGI [75] (exceptions described below for BC, OC, and S-aerosols). For all atmospheric constituents except methane, the change in RF for the atmospheric constituent was calculated by multiplying the reduction in emissions of each pollutant by the contribution of that pollutant to the RF of the atmospheric constituent and summing across emitted pollutants. This is an imperfect calculation for the change in tropospheric ozone, due to ozone's dependence on relative local concentrations of its precursors as well as local meteorology (more on this in section 7.1), and the reductions shown here for ozone should be considered ballpark estimates. For the change in atmospheric RF of methane, the calculation assumes the atmospheric concentration reaches a new steady state based on a constant emission level of contributing pollutants at the reduced level. Because methane's e-folding time is so short (~ a decade) (see section 4.1), the new steady state concentration is approached within about two decades, making this a reasonable approximation. Methane's RF at the new concentration is calculated based on its radiative efficiency (RF per ppb) at the new concentration, based on the formula from IPCC TAR [94]. The change in methane RF is the new RF minus the 2005 RF (which is at approximately steady state if emissions were to hold constant at current levels). Black carbon (BC), organic carbon (OC), and sulfate aerosols (S-aerosols) are short-lived and their global RF is assumed to change in proportion with emissions (local variations noted in section 7.1). 100% of the aerosol indirect effect (AIE) is assigned to the S-aerosols, at 1x the S-aerosol direct effect, consistent with the assumptions made by the UNEP report [36]. The magnitude of the AIE and its attribution to the different aerosols is highly uncertain. This chart assumes the 2005 RF for BC and OC used in the UNEP 2011 report [36] (0.6 W/m^2 for BC, ~-0.19 W/m^2 for OC), including the effective forcing from deposition on snow. The method for computing error bars and triangles and the implications of uncertainty are discussed in the text. Error bars for all four scenarios are of similar magnitude and are shown on a single scenario for visual clarity.

4.5 Radiative Forcing and Temperature Benefit Potential from 100% Emission Reduction of Short- and Medium-Lived Pollutants

As estimates of maximum technically feasible reductions continue to increase (Figure 4-10), it is worth exploring the boundary represented by a 100% reduction of short- and medium-lived pollutants. I have computed the radiative forcing and equilibrium temperature outcomes of this bounding scenario and the results are shown in Figure 4-14 and Figure 4-15.

Radiative forcing (RF) and its uncertainty are computed in the same way as described in the previous section. The bar for "Uncertainty I" is equivalent to the solid error bar in the MTFR figures and the "Uncertainty II" bar is equivalent to the dotted error bar in the MTFR figures.

The best estimate for temperature is calculated using an approximation of 0.45°C per 1 W/m^2, corresponding to the transient climate response of 1.65°C for a doubling of CO_2 (3.7 W/m^2) [42]. Thus, the temperature diagram is directly proportional to the radiative forcing diagram. Additional bars are shown that are calculated with the low and high ends of the 90% confidence interval for transient climate response (1.1°C-2.5°C). [42] Additional uncertainty (not shown) exists around the efficacy of the forcing from short-lived pollutants in generating the temperature response; studies estimate that the temperature response may vary from the central estimate by up to ± 40% for different pollutants. [75]

The largest radiative forcing and temperature benefit potential lies in methane (CH_4), with 0.8 W/m^2 and 0.4°C and a small range of uncertainty. Since methane currently has the smallest MTFR (as a percentage of emissions) among the short- and medium-lived pollutants (Figure 4-10), there is significant room for technical advances in methane reductions to significantly reduce radiative forcing. The total potential from non-SO_2 SLPs (with direct effects only) is about half as large as methane: 0.45 W/m^2 and 0.2°C, with a wide range of uncertainty that extends below zero with indirect effects. The current cooling effect of sulfates (including direct and indirect effects) is approximately 0.7-1.1 W/m^2 and 0.3-0.5°C, [95][76] with a wide range of uncertainty.

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[76] The lower end of the range corresponds to the UNEP assumptions used throughout this section (the green triangle in Figure 4-14 and Figure 4-15) and the higher end of the range corresponds to the best estimate from IPCC AR4 (black triangles), with all aerosol indirect effect assigned to sulfate. Personal communication with Shindell in November 2012 confirmed that the sulfate forcing may be too small under the UNEP assumptions. The IPCC best estimate is therefore carried forward for use in further analyses in Chapter 13 and conclusions in Chapter 16.

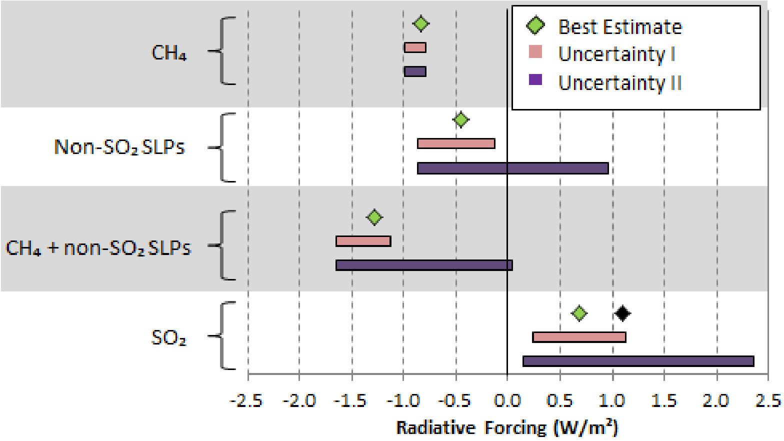

Figure 4-14: Radiative Forcing Change Resulting from 100% Reduction of Short- and Medium-Lived Pollutants

Methods are the same as Figure 4-11. Baseline level is year 2005. Non-SO_2 short-lived pollutants (SLPs) include CO, NMVOCs, BC, OC, and NO_x. Bars represent uncertainty ranges around the best estimate (diamond). The "Uncertainty I" bar limits the aerosol indirect effect (AIE) to be equal to the direct effect of SO_2. The "Uncertainty II" bar allows AIE to span its full range of uncertainty and attributes it across all aerosols (see section 4.4.b.i). Black diamond for SO_2 equals the sulfate direct effect plus total AIE given as best estimates in IPCC AR4. [75]

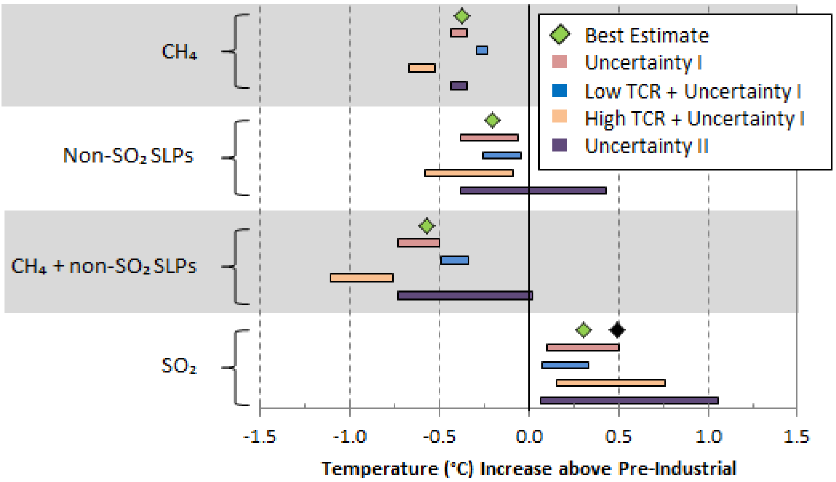

Figure 4-15: Change in Transient Temperature Resulting from 100% Emission Reduction of Short- and Medium-Lived Pollutants, relative to Constant Emissions

Temperature is calculated by multiplying the radiative forcing in Figure 4-14 by 1.65°C per 3.7 W/m^2 (best estimate for transient climate response (TCR) from NRCS 2011). [42] "Uncertainty I" and "Uncertainty II" bars do not include variations in TCR. "Low TCR" and "High TCR" bars reflect TCR of 1.1°C and 2.5°C, the 90% confidence interval from NRC 2011. [42] Non-SO_2 short-lived pollutants (SLPs) include CO, NMVOCs, BC, OC, and NO_x.

4.6 Summary

Sustained emission reductions of short- and medium-lived warming pollutants have thus far not been seen at the global level, although there have been sustained regional reductions of CH_4 and SO_2 in the United States and OECD Europe. Technologically, it is feasible to make major reductions in emissions of all short- and medium-lived pollutants with today's technologies, with reductions ranging from 15-45% for CH_4 to 45-90% for the short-lived pollutants. The estimates of what is feasible have increased in the studies published over the past five years. Current estimates of maximum feasible reductions equate in radiative forcing to 0.1-0.3 W/m^2 for methane with narrow uncertainty, 0.2-0.4 W/m^2 for non-SO_2 short-lived pollutants with wide uncertainty that includes crossing zero, and 0.2-0.6 W/m^2 in the cooling direction for SO_2. Total mitigation potential if 100% emission reductions were possible would be 0.8 W/m^2 (0.4°C) for methane, 0.45 W/m^2 (0.2°C) for non-SO_2 short-lived pollutants, and cooling of 0.7-1.1 W/m^2 (0.3-0.5°C) from SO_2, with the caveat re wide uncertainty as provide in sections 4.4.b.i and 4.5.

Despite the high MTFRs, reduction of these pollutants is not necessarily easy, as it requires an investment of time, money, and effort by many people. [36][77] Emissions are highly fragmented among source types [46] and emitters (e.g., many millions of people, stoves, vehicles), complicating the process of technology adoption. [36] The socially feasible timeline for MTFR reductions of short- and medium-lived pollutants is an open research question.

The next chapter explores the length of time for which climate change in the near-term could be slowed down or delayed by different approaches, and section 5.2 explores the magnitude of influence on near-term temperature that is possible via reductions of short- and medium-lived pollutants like those discussed in this chapter. The amount of climate change that can be delayed or avoided via short- and medium-lived pollutants must be handicapped by the fraction of MTFR that a decision-maker considers socially feasible to achieve in the near-term time horizon and by the uncertainties of radiative forcing and climate sensitivity discussed in this chapter.

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[77] Per UNEP 2011: "Many of the structural changes examined here present formidable hurdles to implementation…. These include costs for measures such as the diesel particle filters (DPFs) or CH_4 capture technologies, enforcement for measures such as the ban of the open burning of agricultural
waste or the elimination of high-emitting vehicles, and the challenge of providing modern fuels to hundreds of millions of people using traditional cookstoves."

Chapter 5 Potential for Delaying Climate Change

Logic and physics tell us that most mitigation efforts[78] will delay (i.e., slow down or reduce) near-term climate change to some extent, and the findings of Chapter 3 suggest that emission reductions of short- and medium-lived pollutants will be particularly effective at delaying near-term climate change.

This chapter explores two key questions regarding the feasibility of Box 1 (delay): 1) How much potential exists for delaying near-term climate change?, and 2) What mitigation would be required to achieve a given length of delay? While many authors publish scenarios that implicitly include delay, the delay implications of these results have rarely been drawn out. The unconventionality of this approach was noted by Joshi et al. 2011, who argued for the importance of "changing the emphasis from 'what might happen' to 'when it might happen.'" [50]

The chapter is divided into three sections, one for each of three mitigation approaches to delaying near-term climate outcomes: 1) maximum technically feasible emission reduction of short- and medium-lived pollutants, 1) reduced levels of CO_2 emissions, or 3) geo-engineering. For the first two approaches, I calculate the delay potential and then compare the results with standard scenarios. For the third approach, I summarize the scientific literature.

5.1 Methods

In this chapter, I calculate two types of delay. The first type of delay results from a step change in radiative forcing (e.g., reducing emissions of short-lived pollutants) and the second type results from a change in the growth rate of radiative forcing (e.g., reducing emissions of CO_2). A step change in RF shifts the RF curve down, whereas a change in growth rate changes the slope of the RF curve. The difference is illustrated in Figure 5-1, in which the solid lines illustrate different rates of RF growth and the dotted lines illustrate step changes relative to the solid lines.

Calculating delay requires calculating the year at which a given temperature change is reached. To calculate temperature, I apply the following equation:

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[78] Exception: Reduction of emissions from sources with high levels of both long-lived warming pollutants (e.g., CO_2) and short-lived cooling pollutants (e.g., SO_2) results in higher near-term temperatures and lower long-term temperatures than would occur in absence of the emission reduction. (see section 7.1 for more information)

$$Temp(Y) = TCR * (RF_{2005} + r * Y) \qquad \text{Eq. 5.1}$$

Temp = temperature change above pre-industrial (°C),
Y = year,
TCR = transient climate response (°C per W/m^2),
RF_{2005} = the radiative forcing in year 2005 = 1.6 W/m^2 [75],
r = RF growth rate (W/m^2/yr)

With algebraic manipulation, the year of arrival at a given temperature is:

$$Y = \left(\frac{Temp}{r*TCR}\right) - \left(\frac{RF_{2005}}{r}\right), \text{ or} \qquad \text{Eq. 5.2}$$
$$Y = \left(\frac{1}{r}\right) * \left(\frac{Temp - RF_{2005}*TCR}{TCR}\right) \qquad \text{Eq. 5.3}$$

Transient climate response (TCR) is the temperature response to a change in RF that follows within years to decades after the associated emissions (see the discussion of the warming process in section 6.2.b.ii.i). It is specifically defined as the temperature response in year 70 to a modeling experiment in which the CO_2 concentration is increased by 1% per year for 70 years, then stabilized. [62] Values used for the TCR are shown in Table 13-1.[79] I make the simplifying conservative assumption that TCR is coincident with RF. Because I am assuming a linear growth rate of RF (discussed below) and because the time horizon is relatively short to the temperatures discussed in this chapter (1.5-2°C), the assumption of TCR and RF coincidence does not materially change my delay calculation ($Y_1 – Y_0$). I.e., Y_1 and Y_0 may be shifted forward or backward in time by roughly the same amount, so that Y_1-Y_0 should be little affected.

For the step change in RF, manipulating Eq. 5.1 and Eq. 5.2 produces Eq. 5.4 for delay:

$$Temp(Y_0) = TCR * (RF_{2005} + r * Y_0)$$
$$Temp(Y_1) = TCR * (RF_{2005} + r * Y_1 - S), \text{ where S = step change in RF}$$

$$Setting\ T = Temp(Y_0) = Temp(Y_1)$$
$$Y_1 = \left(\frac{T}{r*TCR}\right) - \left(\frac{RF_{2005} - S}{r}\right)$$
$$Y_0 = \left(\frac{T}{r*TCR}\right) - \left(\frac{RF_{2005}}{r}\right)$$
$$Delay(step\_change) = Y_1 - Y_0 = \frac{S}{r} \qquad \text{Eq. 5.4}$$

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[79] Table 13-1 shows TCR in the standard units of °C per 3.7 W/m^2 (corresponding to a doubling of CO_2). I have converted TCR for use in the formula to °C per 1 W/m^2.

For the change in RF growth rate, manipulating Eq. 5.3 produces the following equation for delay:

$$Delay(rate\_change) = \left(\frac{1}{r_2} - \frac{1}{r_1}\right) * \left(\frac{Temp - RF_{2005} * TCR}{TCR}\right) \qquad \text{Eq. 5.5}$$

Two simplifications are made in my calculations of RF. First, I assume that the step change in RF for short-lived pollutants occurs instantaneously; relaxing this assumption to account for non-instantaneous implementation of mitigation measures would reduce the delay achievable for very near-term temperatures.

Second, I assume a linear growth rate of RF (see Figure 5-2). Note that if all emissions were CO_2, this would be approximately equivalent to setting a constant emission rate.[80] The linear RF growth assumption allows stylized bounding scenarios and separates the effects of delaying versus avoiding. The constant linear growth line does not avoid any temperature increase, illustrating the potential for delay of a temperature increase by either shifting the line down or changing the slope. Linear trajectories with annual RF growth ranging from 0.01 W/m^2 per year to 0.07 W/m^2 per year are examined in section 5.3 and are shown in Figure 5-2.

The linear growth assumption should have little effect on the bounding analysis done for a shift of the line (step change of short-lived pollutants). However, the analysis of changing line slopes (e.g., via changes in CO_2 emissions) requires words of caution in interpretation, because they lend themselves to comparison with the RCP scenarios. While each of the RCP scenarios has long stretches of near-linearity, the overall shape of RCP 8.5 is concave, RCP 6.0 is near-linear, and RCP 4.5 and RCP 3-PD are convex (Figure 5-3). This means that delays produced by shifting between different RCP scenarios, particularly those with different shapes, will be different than the delays calculated for stylized linear bounding scenarios (see section 5.3.b).

At several points, I refer to the current growth rate of RF. I calculate this value from the atmospheric concentrations of each pollutant provided in the RCP database for 1996-2005 [26, 29]. The RF for CO_2 is calculated using Eq. 15.1. The RF for CH_4 and N_2O is calculated using the equations in Table 6.2 of the IPCC Third Assessment Report [94]. The RF for all other pollutants is calculated by multiplying the atmospheric concentration by the radiative efficiency provided in Table 2.14 of IPCC AR4 [75]. The annual growth is calculated by simple subtraction and the linear growth rate over time is the average annual growth. The growth rate for 1996-2005 (10 years), as well as for 2001-2005 (5 years), was 0.033 W/m^2 / year (between L3 and L4 in Figure 5-2).

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[80] Constant emissions of CO_2 (assuming a constant airborne fraction) would produce slightly less than linear growth of RF due to the gradually decline of radiative efficiency of CO_2 with increasing atmospheric concentrations.

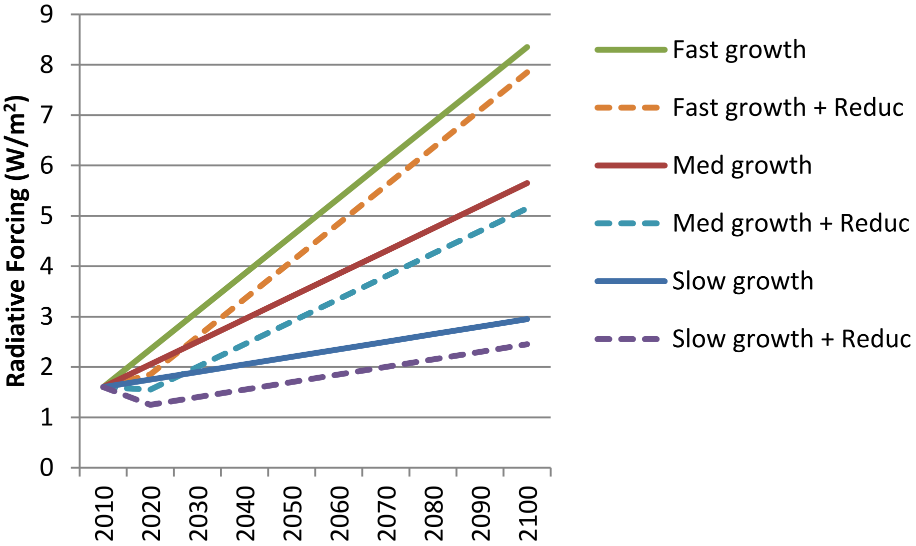

Figure 5-1: Step Changes and Rate Changes in Radiative Forcing
This chart illustrates different rates of growth in RF (solid lines) and the effect of an RF step change (dotted lines). Each dotted line is shifted down 0.5 W/m^2 from the corresponding solid line, the amount found for maximum technically feasible reductions of short- and medium-lived pollutants in section 4.4.b.

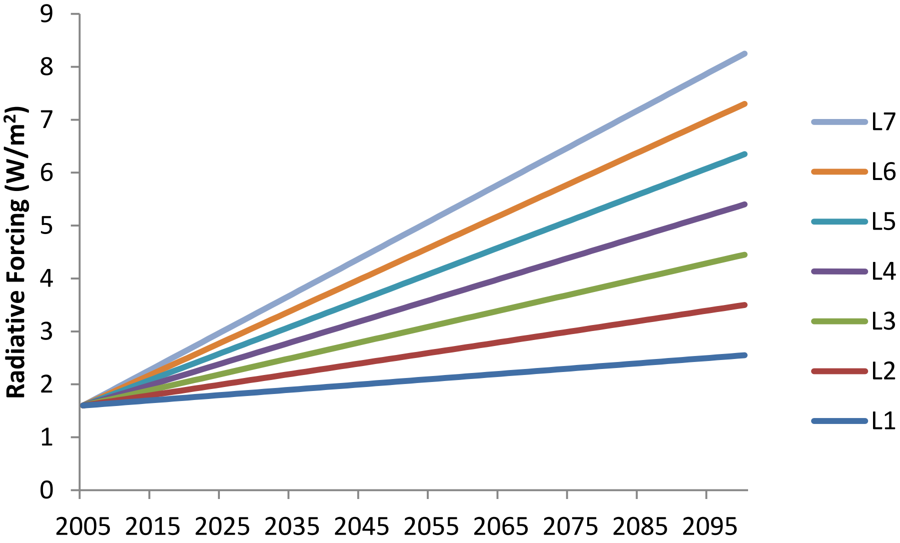

Figure 5-2: Stylized Linear Trajectories separated by 0.01 W/m^2 per year
These trajectories start at the year 2005 RF (1.6 W/m^2) and increase steadily at rates ranging from 0.01 W/m^2 per year (L1) to 0.07 W/m^2 per year (L7). “L” stands for linear.

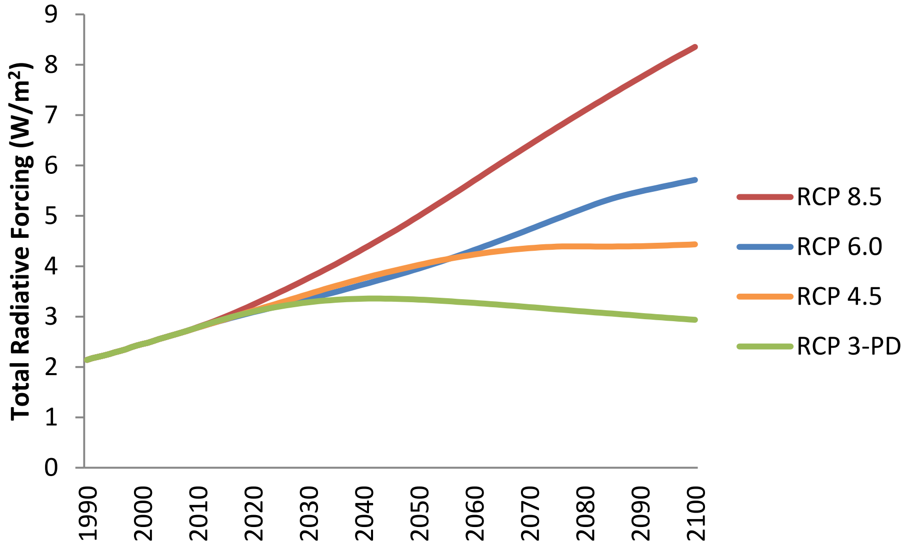

Figure 5-3: Radiative Forcing from Medium- and Long-Lived Pollutants in the RCP Scenarios
The RF corresponding to the atmospheric concentrations of each pollutant provided in the RCP database [26, 29] are calculated as described in section 5.1. Note that RF from short-lived pollutants (both warming and cooling) is not available in the dataset and is thus not included in the graph, and that this RF makes up the difference between the year 2100 RF in the graph and the year 2100 targets of the RCP scenarios: 2.6 W/m^2, 4.5 W/m^2, 6.0 W/m^2, 8.5 W/m^2.

5.2 Delay via Short- and Medium-Lived Pollutants

The delay that is possible via short- and medium-lived pollutants depends on their maximum technically feasible reductions (MTFR) (section 4.4.b) and on the underlying growth rate of RF from other sources, primarily CO_2. This relationship, as derived in section 5.1, is defined by the following equation[81]:

$$Delay(step\_change) = Y_1 - Y_0 = \frac{S}{r} \quad \text{Eq. 5.6}$$

Y = year
S = step change (W/m^2)
r = underlying growth rate of RF (W/m^2 per year)

Based on the MTFR of 0.5 W/m^2 found in section 4.4.b and the current RF growth rate of 0.033 W/m^2 per year calculated in section 5.1, Eq. 5.6 shows that MTFR of short- and medium-lived

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[81] Note, in addition to a step-change, the reduction of short- and medium-lived pollutants could also create a change in the slope of the line if the growth rate of the short- and medium-lived pollutants that remained was different than the growth rate of those pollutants before the reduction, but this effect would be small relative to the step change and is not discussed further here.

pollutants would produce a delay of approximately 15 years.[82] This delay applies to avoiding any temperature change (note that temperature is not part of Eq. 5.6). I.e., the date for reaching 1.5°C would move out 15 years from where it otherwise would have been, as would the date for 2°C, 3°C, etc. This consistent 15 year delay is illustrated in Figure 5-4.

If the underlying growth rate of total RF (r in Eq. 5.6) continues to grow, the delay that can be achieved by MTFR of short- and medium-lived pollutants will decrease (r is in the denominator). Figure 5-5 shows the years of delay that correspond to a range of underlying growth rates reflecting the full range of RCP scenarios.[83] Depending on the underlying RF growth rate, MTFR from short- and medium-lived pollutants may result in delay between 7-33 years, which I will approximate to 5-35 years for the rest of the dissertation.

These results are consistent with the UNEP results discussed in section 4.4 and shown in Appendix F (Figure F-1). Those results showed that near-maximum mitigation of short- and medium-lived pollutants, even without aggressive CO_2 mitigation, would delay arrival at both 1.5°C and 2°C by ~15 years (from ~2030 to ~2045 and from ~2045 to ~2060, respectively) (in Figure F-1, compare "Reference" line with "CH_4 + all BC measures" line).

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[82] Note, the 0.5 W/m^2 includes both short-lived pollutants and methane, which is medium-lived. While reductions of the short-lived pollutants would cause a true step change in RF within a single year, the methane emission reductions would produce more of a sloped RF reduction and plateau over a period of several decades.

[83] The rates of RF growth associated with the highest three RCP scenarios (RCP 4.5, RCP 6.0 and RCP 8.5) are .0.03 to 0.07 W/m^2 per year (calculated as (RF_{2100} – RF_{2005}) / 95 years). The lowest scenario (RCP 3-PD) peaks and declines; its growth rate through the peak is approximately 0.015 W/m^2 per year (calculated through 2050).

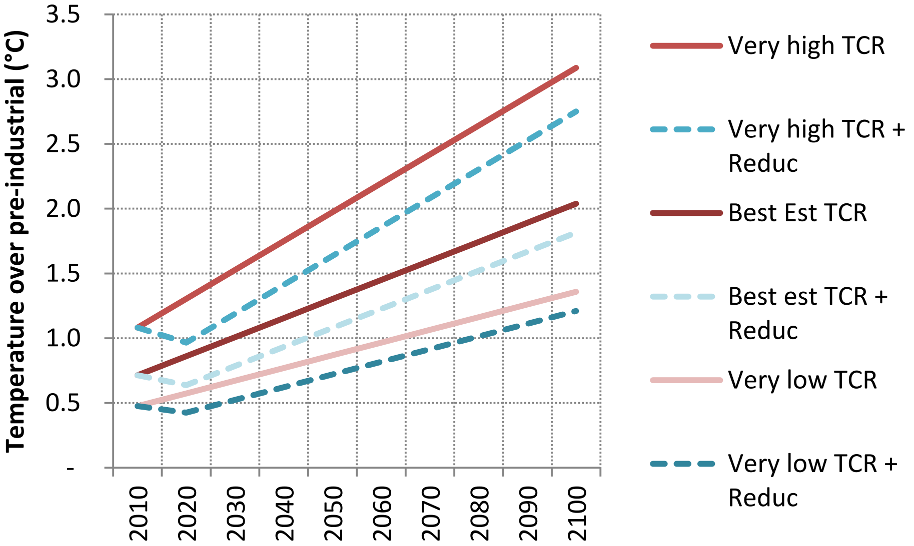

Figure 5-4: Delay from MTFR of Short- and Medium-Lived Pollutants at Current RF Growth Rate
Solid lines show the temperature before the step change of 0.5 W/m^2; dotted lines show the temperature after the step change. Temperature is calculated based on Eq. 5.1. Note that the delay is 15 years between any pair of solid and dotted lines for any temperature. This result is specific to the assumption made about the underlying RF growth rate (see section 5.1) and is constant across all lines in the graph. Three different values of the transient climate response (TCR) are shown to demonstrate that the years of delay are identical regardless of TCR value. Note, this chart looks similar to, but is different from, Figure 5-1, which shows RF (instead of temperature) for a range of scenarios.

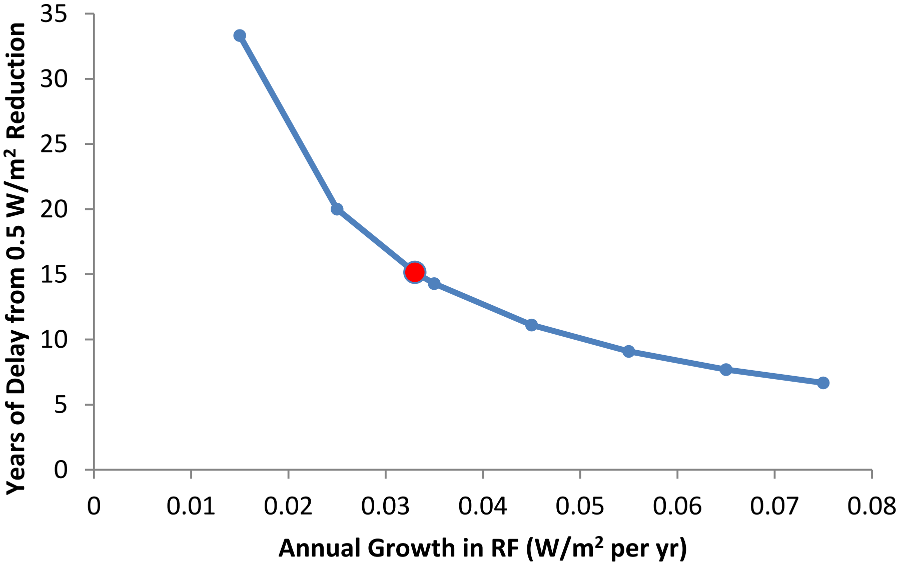

Figure 5-5: Relationship between Years of Delay from an RF Step Change and the Underlying RF Growth Rate
Years of delay are calculated based on Eq. 5.6 and a step change RF reduction of 0.5 W/m^2. The red dot corresponds to the current RF growth rate of all medium- and long-lived pollutants, calculated as described in section 5.1.

5.3 Delay via CO_2 Emission Reductions

The delay that is possible via CO_2 emission reductions differs from the delay possible via emission reductions of short- and medium-lived pollutants because, even with modest reductions of CO_2 emissions, the concentration of CO_2 continues to increase in the atmosphere. This means that CO_2 emission reductions result in a change in the rate of RF growth (the solid line in Figure 5-1) instead of a step change in RF.

In this section, I consider the delay that can be created by reducing the rate of RF growth in increments equal to 0.01 W/m^2 per year (equivalent to reducing annual CO_2 emissions by 10-19 Gt CO_2).[84] The average rates of RF growth for 2005-2100 associated with the highest three RCP scenarios are 0.03 to 0.07 W/m^2 per year (calculated as ($RF_{2100} - RF_{2005}$) / 95 years), so 0.01 W/m^2 per year is a meaningful reduction relative to those rates and relative to today's rate (~0.03 W/m^2; see section 5.1). Note that this discussion does not assume that any temperature change is avoided. CO_2 emissions continue at a lower level and temperature changes are only delayed.

The delay achievable via reducing the annual RF growth (e.g., via a lower level of CO_2 emissions) depends on three parameters: the annual RF growth before the reduction, the transient climate response (TCR), and the temperature being delayed. The relationship is defined by Eq. 5.5, reproduced below.

$$Delay(rate\_change) = \left(\frac{1}{r_2} - \frac{1}{r_1}\right) * \left(\frac{Temp - RF_{2005} * TCR}{TCR}\right) \qquad \text{Eq. 5.7}$$

r_2 = rate of RF growth after the reduction (W/m^2 per year),
r_1 = rate of RF growth before the reduction (W/m^2 per year),
RF_{2005} = the radiative forcing in year 2005 = 1.6 W/m^2, and
TCR = transient climate response (°C per W/m^2)

This equation shows that longer delays are associated with lower starting RF growth rates, lower levels of transient climate response, and higher temperatures being delayed.

The delays of 2°C and 1.5°C that are achievable with each 0.01 W/m^2 per year reduction in the RF growth rate are shown in Table 5-1 and Table 5-2, respectively. Stylized linear growth rates

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[84] Radiative efficiency (W/m^2 per ppm) falls as the CO_2 concentration rises (see Eq. 15.1). RF growth of 0.01 W/m^2 would be attributable to a higher level of emissions at higher baseline RF levels. At today's concentration, 10.3 Gt CO_2 produces 0.01 W/m^2.

that would reach 4.5 W/m^2, 6.0 W/m^2, and 8.5 W/m^2 in 2100, along with the current RF growth rate, are noted on the sides for reference. There are several points to note from the tables.

Among the three parameters (the annual RF growth before the reduction, the transient climate response (TCR), and the temperature being delayed), the starting RF growth rate and the TCR value have the largest influence on the level of delay. The delay possible from an increment of 0.01 W/m^2 per year reduction is 1-12 years at a starting RF rate of 0.07 W/m^2 per year, versus 10-85 years from a starting RF rate of 0.03 W/m^2 per year (approximately today's rate, as shown in section 5.1) – a multiple of approximately 7x. Similarly, a multiple of 4-8x separates the delay at very low TCR values (8-256 years) from the delay at very high TCR values (1-68 years). The difference in delay between temperatures of 1.5°C or 2°C is small in comparison – on the order of 2x, with longer delays for 2°C than 1.5°C.

Considering the best estimate column and baseline RF growth in the range of Stylized 4.5 to Stylized 8.5, a reduction increment of 0.01 W/m^2 per year can delay the arrival of 1.5°C for 4-29 years and can delay the arrival of 2°C for 7- 48 years. For the rest of the dissertation, I will round these to 5-30 years delay of 1.5°C and 5-50 years delay of 2°C per increment of 0.01 W/m^2 per year of lower RF growth. At today's RF growth rate and best estimate TCR, this quantity of reduction (0.01 W/m^2/year) from today's levels would delay 2°C for ~50 years (see green box in Table 5-1).

5.3.a Special Case: Emissions from Forest Fires and Post-Burn Decay

Anthropogenic forest fires and post-burn decay (primarily from deforestation) accounted for 11% of CO_2 emissions in 2008 (a low fire year) and 14% of CO_2 emissions on average from 2004-2008. [46] Annual emissions from forest fires were approximately 5 Gt CO_2 per year from 2004-2008, and these emissions contributed approximately 0.004 W/m^2 each year to RF.[85] This means that eliminating deforestation and its associated anthropogenic forest fires and post-burn decay (or planting the equivalent number of trees) would delay 2°C by ~20 years (40% of the 0.01 W/m^2 / year increment discussed above).

Emissions from forest fires are a special case because they leave behind land that can become re-vegetated (though not necessarily with forest) over many decades and centuries, partially re-capturing the CO_2 to an extent that will vary with different climate conditions. The net cumulative CO_2 emissions from forest fires and post-burn decay, once the land has re-

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[85] Calculation: (5 Gt CO_2/year * 0.46 (airborne fraction) / 7.92 Gt airborne CO_2 / ppm) * 0.014 W/m^2 / ppm (current radiative efficiency) = .004 W/m^2

vegetated, will be smaller at equilibrium (many hundreds to a few thousands of years hence) than during the transient period (the next century or two). This means that reductions of CO_2 emissions from forest fires and post-burn decay could be very important in the near-term for Box 1 (can produce a delay of 20 years to 2°C) and may be important for avoiding transient temperature peaks in Box 2 (avoid 1.5-2°C) and Box 3 (avoid 3-4°C) (see section 15.1.c). However, they may be less important to avoiding temperature changes at equilibrium (Box 2 and Box 3) than CO_2 emissions from fossil fuels (see Chapter 9 and Chapter 15).

5.3.b Special Case: Delay Embedded in the RCP Scenarios

Avoiding a given temperature increase involves delaying lesser temperature increases, even while the opposite does not hold true (delay does not necessarily involve avoiding a temperature increase). This sub-section blurs the line between avoiding and delaying by discussing the delay of 1.5°C and 2°C that is implicit in the shift from an RCP 8.5 trajectory to an RCP 4.5 trajectory (avoid plus delay) and the delay that is explicit in the shift from a Stylized linear 8.5 trajectory to a Stylized linear 4.5 trajectory (delay only).

The summation rows of Table 5-1 and Table 5-2 show that 1.5°C would be reached 34 years later in Stylized 4.5 versus Stylized 8.5, using the best estimate for TCR. 2°C would be reached 55 years later. For the remainder of the dissertation, I will summarize the delay potential between Stylized 8.5 and Stylized 4.5 as 35 years for 1.5°C and 55 years for 2°C. If TCR were very high, these delay numbers would be 11 and 26 years for 1.5°C and 2°C between Stylized 8.5 and Stylized 4.5.

Comparing these figures to the delay values compiled from other papers in Chapter 2 (Table 2-5), I find that the models referenced in Chapter 2 have lower delay estimates. Among those presented, Joshi et al. [50]show the highest 2°C delay, with 35 years between B1 and A2. IPCC AR4 [28] shows 15 years and Prinn et al. [38] show 5 years between these same scenarios. Recall from Table 2-4 that B1 is similar to RCP 4.5 and A2 is a bit below RCP 8.5. Similar to IPCC AR4, Rogelj et al. [37] show a 15 year delay of 2°C between RCP 8.5 and RCP 4.5.

About half of the difference between the 55 years found for the stylized scenarios and the 5-35 years found for the RCPs can be explained by the high TCR applied by Rogelj et al.[86] and the

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[86] TCR for Rogelj et al. is calculated from the year 2100 median temperature change versus pre-industrial as shown in Figure 2-3, divided by the target RF for year 2100 for each scenario. RCP 4.5 = 2.6°C / 4.5 W/m^2 = 0.57 °C per W/m^2. RCP 6.0 = 3.1°C / 6.0 W/m^2 = 0.52 °C per W/m^2. RCP 8.5 = 4.9°C / 8.5 W/m^2 = 0.58 °C per W/m^2. Multiplying by 3.7 W/m^2 to put into standard units produces a TCR range of 1.9-2.1°C, near the high end of the

very high TCR applied by Prinn et al..[87] This can be quantified using the values from the bottom row of Table 5-1. A high TCR (Rogelj et al.) corresponds to a delay between Stylized 8.5 and Stylized 4.5 of 34 years. This means that 21 years of the 40 years difference between 55 years and 15 years is explained by TCR. A very high TCR (Prinn et al.) corresponds to a delay between Stylized 8.5 and Stylized 4.5 of 26 years. This means that 29 years of the 50 years difference between 55 years and 5 years is explained by TCR.

The other half is explained by curve shape. The stylized scenarios are defined to be linear, with emissions continuing indefinitely at the same level, and are designed specifically for the purpose of doing bounding analysis on delay. The RCP scenarios have non-linear trajectories, and RCP 8.5 and RCP 4.5 have trajectories with opposite curvatures (see Figure 5-3). RCP 4.5 is designed to stabilize in 2100, so it has a convex shape. RCP 8.5 is designed to continue growing beyond 2100 and has a concave shape. The linear line for RCP 8.5 would be left of the concave line and the linear line for RCP 4.5 would be right of the convex line, so comparison of the stylized linear scenarios shows a larger delay than comparison of the RCP scenarios. It illustrates the stylized scenarios truly are bounding scenarios, since the actual scenarios will sit between them.

We can conclude that the delay in reaching 2°C between a scenario reaching 8.5 W/m^2 in 2100 and a scenario reaching 4.5 W/m^2 in 2100 is likely to be greater than 5-35 years (given the use of high TCR in the modeled scenarios in Table 2-5) and less than the maximum of 55 years found in this section.

66% confidence interval for TCR shown in Table 13-1. Use of a higher-than-best-estimate TCR may reflect an expectation of carbon cycle feedbacks.

[87] TCR for Prinn et al. is calculated from the year 2100 temperature change shown in Figure 2-4, adjusted to be comparable to pre-industrial, and from the year 2100 net RF from all pollutants shown in Figure A-3. Two sample scenarios (REF and B1) were calculated and found to have approximately the same TCR: 0.65-0.67 C per W/m^2. Multiplying by 3.7 W/m^2 to put into standard units produces a TCR range of 2.4-2.5°C, at the high end of the 90% confidence interval for TCR shown in Table 13-1.

	Transient Climate Response					
Annual RF growth (W/m^2), before rate reduction	Very Low (90% confid.)	Low (66% confid)	Best Est (50/50)	High (66% Confid)	Very High (90% confid)	Avg. RF growth, 2005-2100
0.02	256	205	144	88	68	
0.03	85	68	48	29	23	Stylized 4.5; current
0.04	43	34	24	15	11	
0.05	26	20	14	9	7	Stylized 6.0
0.06	17	14	10	6	5	
0.07	12	10	7	4	3	Stylized 8.5
Stylized 8.5 to 4.5	98	78	55	34	26	

Table 5-1: Number of Years Delay in Reaching 2°C above Pre-Industrial, from 0.01 W/m^2 RF Growth Rate Decrease

Chart shows the years of delay that are attributable to each 0.01 W/m^2 per year decrease in RF growth (e.g., the 0.07 row shows the years of delay from reducing RF growth from 0.07 W/m^2/year to 0.06 W/m^2/year). Years of delay are calculated based on Eq. 5.7. TCR values are from NRC 2011 [42] as shown in Table 13-1. Stylized linear growth rates (constant emission trajectories) that would reach 4.5 W/m^2, 6.0 W/m^2, and 8.5 W/m^2 in 2100, along with the current growth rate, are noted. The stylized RF growth rate is calculated as: ($RF_{2100} - RF_{2005}$) / 95 years. Current RF growth rate is the CO_2 RF growth rate calculated in section 5.1 (CO_2 RF and total RF are currently approximately the same) [75]. Grey boxes highlight the reduction from Stylized 8.5 to Stylized 4.5 discussed in the text. The green box highlights the delay possible with reductions below current emission levels.

	Transient Climate Response					
Annual RF growth (W/m^2), before rate reduction	Very Low (90% confid.)	Low (66% confid)	Best Est (50/50)	High (66% Confid)	Very High (90% confid)	Avg. RF growth, 2005-2100
0.02	172	133	88	46	31	
0.03	57	44	29	15	10	Stylized 4.5; current
0.04	29	22	15	8	5	
0.05	17	13	9	5	3	Stylized 6.0
0.06	11	9	6	3	2	
0.07	8	6	4	2	1	Stylized 8.5
Stylized 8.5 to 4.5	66	51	34	18	12	

Table 5-2: Replica of Table 5-1, for 1.5°C above pre-Industrial

Methods and description are the same as Table 5-1.

5.4 Delay via Geo-engineering

Geo-engineering via solar radiation management (SRM) has also been proposed as an approach to temporarily halt climate change. SRM is an intentional alteration of the planet's reflective properties so that less sunlight is absorbed. Large-scale SRM technologies have the potential to fully offset average global anthropogenic warming, while altering regional climate patterns. These technologies are in the research phase and include regular sulfur particle injection into the stratosphere, cloud seeding, and mirrors in space. [96] Such technologies could potentially delay many climate impacts indefinitely, with the caveats that temperature would change quickly if the technologies went out of use. SRM would not address ocean acidification, which is driven by atmospheric CO_2 concentration, and would change the spatial distribution of temperature and precipitation patterns in ways that would have "potential to drive regional climates outside the envelope of greenhouse-gas induced warming, creating 'novel' conditions". [97] Other considerations are discussed in section 7.3. [96]

Small-scale, surface-level SRM technologies such as white roofs and reflective pavement differ from large-scale SRM in both their deployment and their effects. Deployment for small-scale SRM could be distributed and modular, rather than centralized, and the technology is available today. Research results are currently conflicting as to whether these technologies could slow down climate change if deployed at scale [98], or whether they would have actually have a net warming effect due to an increase in surface air stability and a consequent decrease in cloudiness [99].

Carbon capture approaches such as afforestation, reforestation, or ocean fertilization are also often categorized under geo-engineering, but differ from SRM in two dimensions. First, they directly address pollution rather than masking its effects and two, they involve lag times inherent in the implementation of carbon capture. The potential for delay of climate change via carbon capture is similar to the potential for delay via CO_2 emission reduction and depends on the magnitude of carbon capture. The magnitude of carbon capture in the near-term would likely have a fraction of the climate impact relative to SRM due carbon capture's gradual change in radiative forcing versus SRM's abrupt change in radiative forcing. [100] Additional pros and cons of SRM will be discussed in section 7.3.

5.5 Summary of Potential for Delay

Global warming of 1.5°C or 2°C above pre-industrial levels could be delayed by 5-35 years via maximum technically feasible reductions of short- and medium-lived pollutants based on technological and physical feasibility, with the range depending on the RF growth rate from all pollutants. At the current RF growth rate, a delay of 15 years would be possible from short- and medium-lived pollutants. The same delay applies to both 1.5°C and 2°C.

Lower CO_2 emissions can also delay temperatures, even if the trajectory is not a path to stabilization. I found that for constant emission paths separated by 0.01 W/m^2/year (10-19 Gt CO_2/year), moving to a lower emission path could delay reaching a 2°C temperature increase by 5-50 years, with longer delays from lower original trajectories (closer to RCP 4.5) and shorter delays from higher original trajectories (closer to RCP 8.5). This quantity of reduction (0.01 W/m^2/year) from today's levels would delay 2°C for ~50 years; the challenge of implementing this magnitude of reduction is discussed in Chapter 10. To put this into context, eliminating all anthropogenic forest fires (0.004 W/m^2/year) would delay 2°C for ~20 years.

All but the most stringent all-pollutant emission scenarios presented in section 2.3 *delay* arrival at a temperature increase of 1.5°C or 2°C (above pre-industrial levels) rather than *avoid* it completely (see Table 2-5). There are 5-35 years[88] between arrival at a 2°C increase (above pre-industrial levels) from the lowest to the highest all-pollutant emission scenarios[89] (e.g., SRES B1 vs. A1FI, RCP 4.5 vs. RCP 8.5, or Shell "blueprints" vs. "scramble") (see Table 2-5). The physical maximum spread between RCP 8.5 and RCP 4.5 was found in this chapter to be 55 years for 2°C if both curves were linear and the best estimate of transient climate response (TCR) was used. Higher TCR values reduce the delay potential by 2-3x.

In summary, there are multiple mitigation approaches to create delays of 5-55 years if delay (Box 1) is the goal. Delay is also possible via geo-engineering. SRM cannot delay ocean acidification, but can delay planetary warming, with geographic variations and side effects, for a length of time determined by the durability of international institutions and political will

All delay options have upsides and downsides that will be discussed in sections 7.1-7.3. First, however, the next chapter will consider the larger question of what benefits delay itself (Box 1) can provide.

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[88] IPCC AR4 2007, Prinn et al. 2011, and Rogelj et al. 2011 show a delay of at most 15-20 years; Joshi et al. 2011 find a delay of up to 35 years.

[89] Lowest to highest within a given set of scenarios (e.g., within SRES or within Shell)

Section III Context for Decisions Regarding Near-Term Climate Change

Section II established that mitigation of near-term climate change involves a greater focus on short- and medium-lived pollutants and a focus on mitigation in different sources relative to mitigation of long-term climate change. It also showed that significant mitigation of short- and medium-lived pollutants is technologically possible, though not yet globally demonstrated, and can be effective in delaying climate change and thus reducing near-term climate change.

Chapter 6 and Chapter 7 build on Chapter 5, which introduced the point that there are multiple options to achieve the Box 1 goal of delaying near-term climate outcomes. In other words, there is not just a choice to make among boxes, but also a choice to be made for the mitigation approach within a given box, particularly for Box 1. Chapter 6 explores the pros and cons of choosing Box 1 (delay) and Chapter 7 explores the pros and cons of the non-CO_2 mitigation approaches within Box 1 (short-lived pollutants and geo-engineering).

Chapter 8 explores the gaps in scientific research about mitigation of near-term climate change and the importance of this research to inform mitigation decisions and adaptation planning.

Combined, these chapters address the mitigation options that apply specifically to the near-term column of the Climate Boxes Framework. In Section IV, I will turn to Box 2, the avoidance of 1.5°C or 2°C, which straddles near-term and long-term climate outcomes.

Chapter 6 The Possible Benefits of Delaying Climate Change

In Chapter 5, I showed that it is technically possible to delay a given climate change (global 2°C temperature increase) by 5-50 years. In this chapter, I turn to the climate change impacts that would be delayed. To re-emphasize here, delay may be the goal (Box 1) or it may be a side benefit of permanently avoiding a longer-term temperature increase (Box 2 or Box 3). In all of these cases, the impacts of climate change are delayed by mitigation to some extent. In Box 2 (avoid 1.5-2°C) and Box 3 (avoid 3-4°C), some impacts are permanently avoided by mitigation.

In this chapter, I explore the possible benefits of a delay of the Box 1 type, in which climate change is slowed down but not avoided. First, we look at the tipping points that sit on the near-term horizon to get a better sense of the large-scale climate outcomes to be delayed. Next, I ask whether the length of delays described in Chapter 5 materially affect those impacts that are related to rate of climate change. Next, I ask whether delay leads to improvement in the long-term climate outcome. Finally, I outline pragmatic reasons why delay may be desirable.

I conclude that preference for minimizing near-term climate change is best-supported on grounds of minimizing impacts during one's lifetime or increasing the time available for human adaptation. The jury is still out on whether minimization of near-term climate change (with the same long-term emissions trajectory) has positive longer-term effects. While such benefits are considered possible, there is so far little evidence as to whether changes in the rate of near-term climate change within the ranges possible via mitigation can significantly alter ecological impacts, and little evidence that reducing the rate of near-term climate change has the benefit of reducing long-term climate change.

6.1 What Impacts Would be Delayed?

Changes to the physical climate drive impacts on water supplies, ecosystems, food, coastal conditions, and health. These impacts are summarized in Figure 6-1. Without aggressive mitigation, the average global temperature will surpass 2°C above pre-industrial levels by mid-century. As shown in the figure, some of the impacts associated with 2°C of global warming are expected to include: increased water stress (shortages of freshwater) for a billion people; increased incidences of floods, storms, and wildfires; increases in climate-related illnesses and deaths (e.g., diarrheal disease, infectious disease, heat-related illness), and coral bleaching and some species extinctions. [101] Mitigation aimed at near-term climate change aims to delay (Box 1) or avoid (Box 2) these impacts.

Additionally, mitigation aimed at the near-term would address several large-scale dimensions of the climate system, most prominently the melting of ice. Figure 6-2 shows a number of large-scale climate outcomes, most of which are also considered tipping elements in the climate system. Tipping elements are dimensions of the climate system that can experience a qualitative state change (e.g., switch in ecosystem, switch in dominant weather pattern) in response to a relatively small trigger.

Lenton describes the climate tipping point for a given tipping element as follows: "A small change in forcing triggers a strongly nonlinear response in the internal dynamics of part of the climate system, qualitatively changing its future state." [102] His team convened a working group of experts in 2005 to assess the likely range of global warming corresponding to critical threshold values of relevant control parameters for each tipping element. Their conclusions are illustrated in Figure 6-2.

To understand the tipping points that are likely to be crossed in the near-term horizon (and hence what can be delayed or avoided), the climate changes in the top graph of Figure 6-2 are juxtaposed with the range of likely temperatures in 2030 and 2050 that would accompany the SRES and RCP scenarios in the bottom graph. Here we see that Arctic summer sea ice is the only tipping element that is both triggered at the 1-2°C temperature increase projected for the near-term horizon and has a sufficiently short transition time (~ 10 years) to be experienced in this horizon. Melt of the Greenland ice sheet is triggered by the near-term temperature increase, but has a long enough transition time (> 300 years) that a small fraction of the corresponding sea level rise will be observed in the near-term horizon.[90] [103-105]

Transition may have already begun for both of these tipping elements. Arctic summer sea ice extent set a new record low in 2012, and the six years with the smallest summer sea ice extent have been the six most recent years (2007-2012). [106] Over the past decade, Greenland has been experiencing declining albedo in summer months and an accelerating (though proportionally small) loss of ice mass balance. [107] The extent that these transitions could be slowed (or reversed) by aggressive mitigation is not well quantified, a topic that is revisited in Chapter 8. The remaining tipping points and transitions are considered unlikely to occur during the near-term horizon.

Two additional large-scale climate elements with rapid transition times belong in a discussion of the near-term horizon (see bottom right of Figure 6-2). A shift in the Indian summer monsoon

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[90] Full melt of the Greenland ice sheet would result in sea level rise of 7.3 meters (IPCC AR4). Maximum sea level rise physically possible from all melt sources in the 21st century is 2 meters (Pfeffer et al. 2008), with estimates ranging from 0.75-1.9 meters depending on the emission scenario (Vermeer and Rahmstorf 2009).

(ISM) and development of an Arctic ozone hole could happen on the order of 1 year, but the dynamics are not yet well enough understood to predict when they will occur. Prediction for the ISM is also complicated by the important influences of regional aerosol loading and variations in the El Niño Southern Oscillation. The other large-scale changes (non-tipping-elements) shown in Figure 6-2 have transition timescales on the order of a century or more, making them less central to a discussion of the near-term.

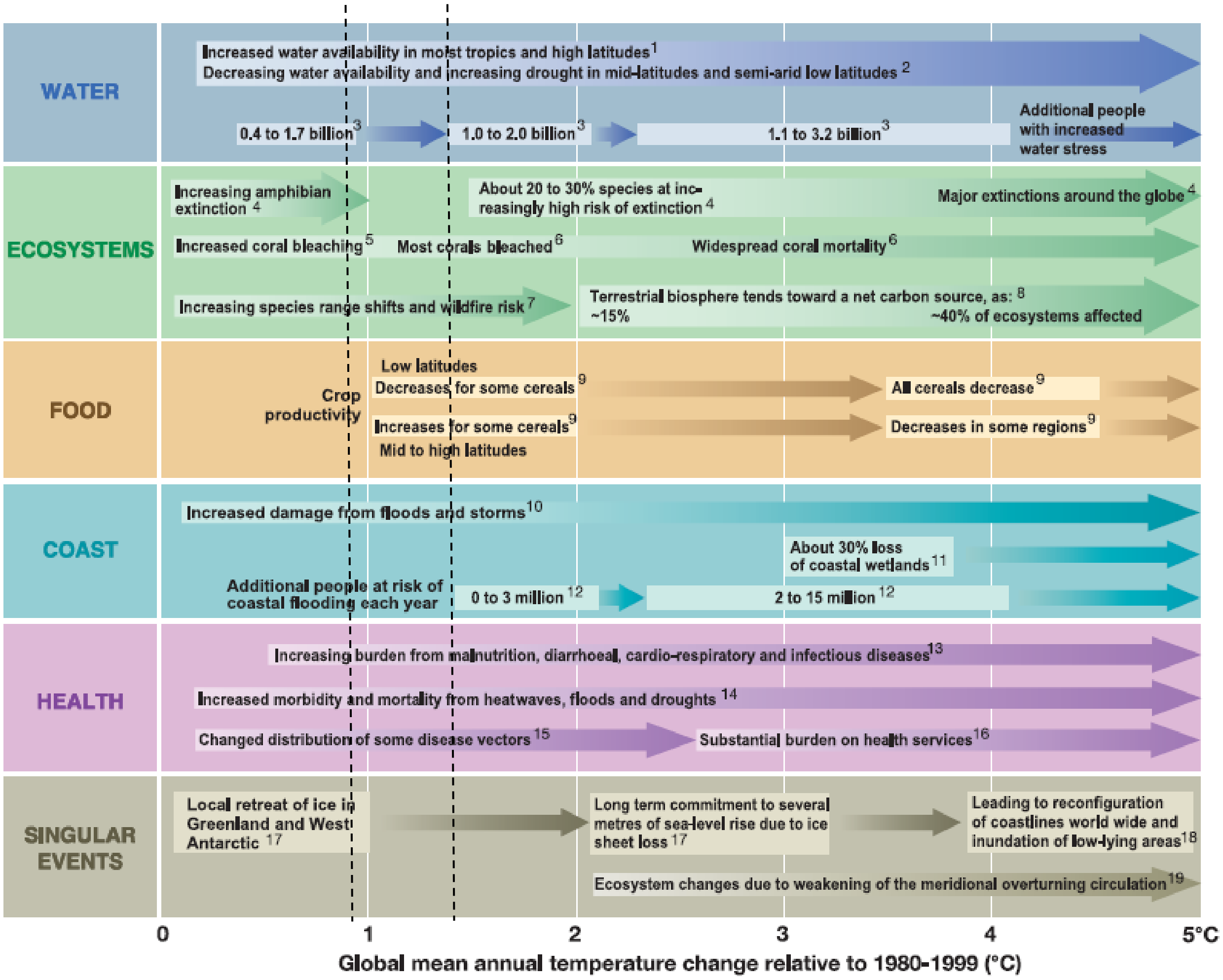

Figure 6-1: Summary of Global Impacts of Climate Change, by Temperature

Figure copied with permission from IPCC AR4 Working Group II Technical Summary [101]

Dotted lines are added and indicate 1.5°C and 2°C of warming above pre-industrial levels.

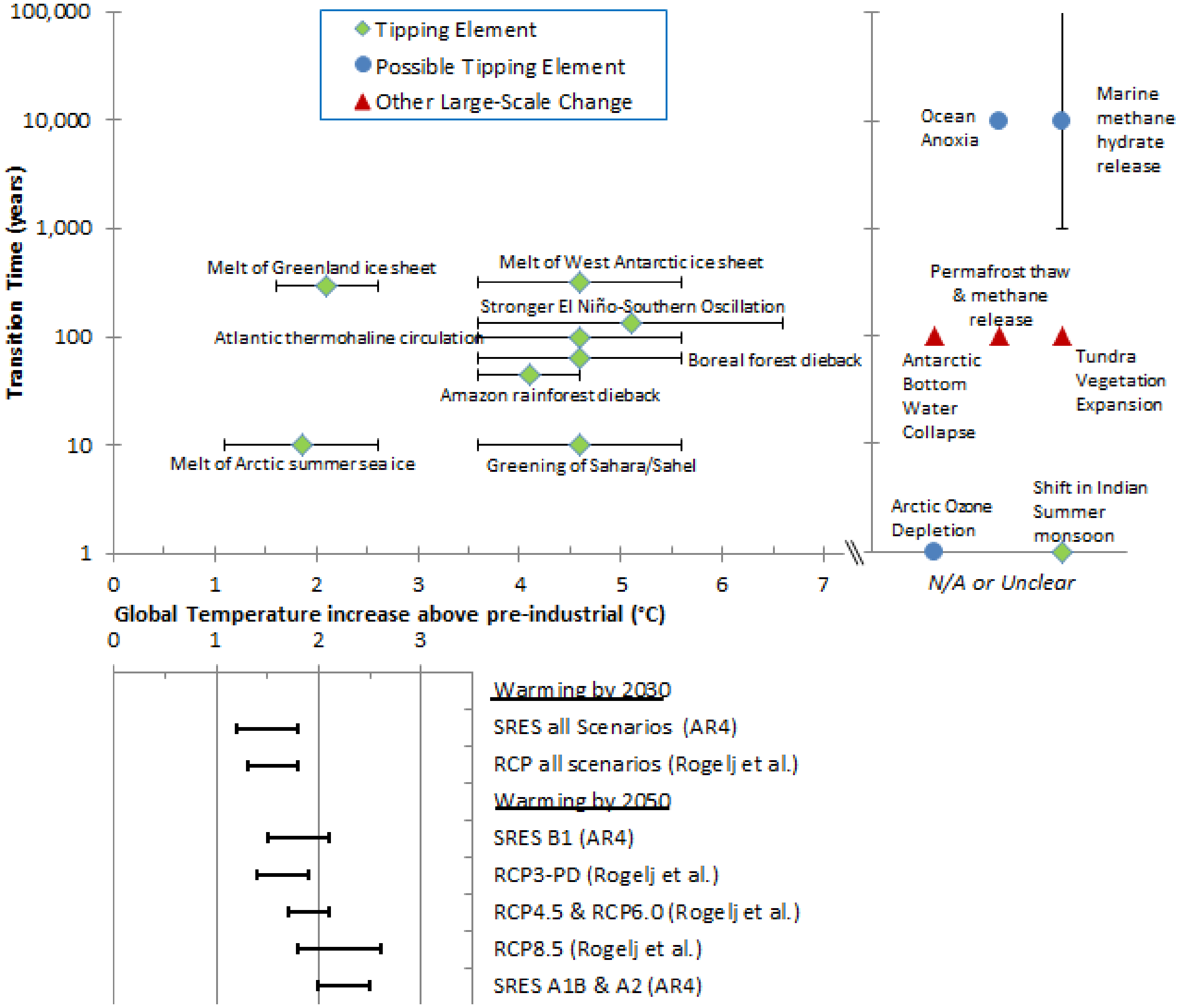

Figure 6-2: Global Tipping Elements and Large-Scale Changes, by Temperature and Transition Timescale The top chart shows the level of global temperature change at which tipping elements are expected to be triggered, based on judgments of the expert group convened by Lenton et al. [102]. The bottom chart shows the temperature changes expected by 2030 and 2050, visually interpolated from Figure 2-2 and Figure 2-5. [28, 37] Transition time is the number of years required for a change to occur (e.g., ice to melt, methane to be released) after the temperature threshold has passed (note the logarithmic scale). Large-scale climate changes for which there is no specific known temperature trigger are shown on the right side of the chart ("N/A or Unclear"). Those that are expected to be continuous processes with no strong threshold behavior (tundra vegetation expansion, permafrost methane release) are shown as "other large-scale changes". Antarctic Bottom Water collapse is also included in this category because the collapse is expected to be transient and followed by a recovery. Arctic ozone depletion (from cooling of the stratosphere), marine methane hydrate release (from warming), and ocean anoxia (from accelerated phosphorus input) are possible tipping elements with very different transition timescales; a trigger temperature for these changes has not been identified.

6.2 Climate and Ecology Perspective on Delaying versus Avoiding

A "delay" approach has the clear benefit of delaying negative outcomes. What is less clear is whether it might actually improve long-term ecological and climate outcomes. This section explores whether there is evidence for improvement on either of the following paths:

1) Some impacts might be driven by rate of climate change, and a slower rate of change may avoid or reduce those impacts
2) Long-term climate change might be reduced by avoiding feedbacks[91] mediated by the rate of climate change

While there are reasons to expect that both might be true, little evidence to support either point has been published to-date, and I conclude that more research is needed.

6.2.a Are Some Ecological Impacts Avoided by Delaying?

Chapter 5 showed that mitigation actions can delay climate changes by 5-50 years. To what extent would a delay of this length help ecological adaptation? Would the slightly slower rate of change materially change the ecological impacts? This question is largely unexplored in the literature, and deserves more research.

Rate of climate change is known, in general, to affect the fate of organisms. At a very slow rate of climate change, organisms evolve; at a very high rate of climate change, species cannot evolve or adapt quickly enough and go extinct. At rates in between, individuals migrate and disperse and within-species variations lead to some populations of a species surviving and others dying off. In the case of migration and dispersal, the rate of latitudinal and elevational shifts in species climate envelopes, relative to the rate that populations of species are able to shift their habitat ranges, influences species survival and species composition. Species survival in a new location also depends on factors such as availability of food and water sources and appropriate habitat. [108]

The difference in the rate of climate change between the different mitigation options discussed in Chapter 5 is small relative to the difference between current and paleoclimatic rates of change. E.g., Figure F-1 shows 2020-2070 warming of 0.33°C per decade under the reference scenario and 0.13°C per decade with aggressive mitigation of CO_2 and near-maximum technically feasible mitigation of short- and medium-lived pollutants. In comparison, the rate of change during the geologically rapid glacial-interglacial transitions is estimated on the order

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[91] Feedbacks are changes to elements of the climate system that result in an amplification or de-amplification of the original climate response. E.g., melting of ice in response to higher temperatures reduces planetary albedo (reflectivity), increasing the energy reaching earth's surface and increasing temperature.

of 0.01°C per decade[92] [109]; even with aggressive mitigation, 21st century warming would be on the order of 10 times faster.

The question at-hand is whether the lower rate of change provided by the delay approaches (mitigation via short- and medium-lived pollutants or via low versus high SRES and RCP scenarios) is material to species survival and composition, at a scale of impacts that decision-makers would consider relevant to mitigation policy. In other words, does a rate of change of ~0.1°C/decade result in significantly different ecological impacts than a change of ~0.3°C/decade, if both paths are heading to the same equilibrium temperature (i.e., delaying, not avoiding, the temperature increase)?

There have been no studies published to-date testing whether a difference in ecological impacts resulting from slowing the rate of climate change (*delay*) via one mitigation path versus another, en route to a given equilibrium temperature. Many studies have demonstrated reduced ecological impacts from *avoiding* higher levels of climate change, since there is a magnitude of climate change for each species and for some ecological systems, above which they cannot survive. The prominent impact assessment reports (e.g., IPCC AR4 2007 [25], US GCRP 2009 [40]) have focused on the magnitude of climate change that is expected to produce different impacts. The GCRP report also provided comparisons for the impacts in a given future year that would be experienced under one scenario versus another, but without discussion of whether impacts are being delayed or avoided completely.

Species composition within regions will also change as the climate changes, and in some cases, these composition changes are expected to be pronounced at an ecosystem level, on a scale that would be relevant to mitigation policy. Examples include die-off of the Amazon rainforest, die-off of the existing boreal forest, northward advance of shrubs into tundra and forests into shrubland, and greening of the Sahel desert. These large-scale species composition changes are expected to be tied to the *magnitude* of climate change (see Figure 6-2); no discussion has been published of how reducing the rate of climate change within the range possible via mitigation (e.g., to ~0.1°C/decade versus ~0.3°C/decade) might or might not affect these large-scale changes.

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[92] Per IPCC AR4: "The largest temperature changes of the past million years are the glacial cycles, during which the global mean temperature changed by 4°C to 7°C between ice ages and warm interglacial periods (local changes were much larger, for example near the continental ice sheets). However, the data indicate that the global warming at the end of an ice age was a gradual process taking about 5,000 years." This equates to 0.008-0.014°C per decade.

In summary, it is known that rate of climate change affects organisms in general and ecologists consider it plausible that global warming of ~0.3°C/decade versus global warming of ~0.1°C/decade could make a material difference for ecological impacts, at a scale that is relevant to mitigation policy. [110] However, no hard evidence has yet been published to support this statement. More research is needed (see Chapter 8 and section 16.3).

6.2.b Does Delaying Improve the Long-Term Climate Outcome?

There are at least two possible mechanisms by which delaying (i.e., slowing down) climate change in the near-term could reduce the long-term temperature change: 1) via processes that are determined by the rate of climate change (versus only the magnitude) and are relevant at near-term temperatures, and 2) via a delay that reduces transient feedbacks and shaves the peak warming.

6.2.b.i Rate of Change and Long-Term Climate Outcomes

Rate of climate change is suspected to be a driver of climate system changes [111, 112] and reducing the risk of irreversible change is commonly cited as a reason to slow down near-term climate change (e.g., [15]). However, limited evidence exists to support the hypothesis that rate of change drives large-scale climate outcomes and none exists to support it for the near-term horizon; more research is needed. Two examples that do have supporting evidence for the long-term are the Atlantic currents (thermohaline circulation (THC) and Atlantic subpolar gyre (ASG)) and peatland carbon release. The rate of freshwater influx to the North Atlantic Ocean and Nordic Sea from melting ice is correlated with the strength of the THC and the ASG. [113, 114] However, a climate-driven shift in the THC is not expected in the near-term, rather to occur at a temperature increase of 3.5-5.5°C above pre-industrial levels and over a 100 year timescale (see Figure 6-2). [102] The timeline for the ASG is not yet known. A rate-induced release of carbon from peatlands is considered mathematically possible at levels of global warming above 0.8-0.9°C per decade [115], but this is well above the rate of warming projected over the next 200 years, even for the high RCP 8.5 scenario (0.4-0.5°C/decade) (see Figure 2-5).

6.2.b.ii Can a Delay Reduce Transient Feedbacks and Shave Peak Warming?

The next question is whether a delay can reduce transient feedbacks and shave peak warming. Answering this question requires a brief detour into the relationship between emissions, radiative forcing, planetary energy imbalance, feedbacks, and temperature.

6.2.b.ii.i Summary of the Warming Process

Emissions that increase atmospheric concentrations of warming pollutants increase radiative forcing (RF) and the planetary energy imbalance (EIB). Planetary EIB is the extra energy (W/m^2) that is radiated toward the earth from the top of the atmosphere in excess of the energy that is re-radiated out into space. A planetary EIB, with more incoming solar radiation than outgoing infrared radiation, creates warming at a rate (°C/yr) that is based on the total net energy input per year (J/yr) and the heat capacity of the earth (J/°C). As the planet warms, the outgoing infrared radiation increases in an amount proportional to the increase in temperature and, if the incoming energy remains constant, the planetary EIB slowly falls, reducing the rate of warming. When the energy in and energy out at the earth's surface equilibrate, climate change is fully realized.

There are two reasons, however, why energy radiated toward earth from the top of the atmosphere may not remain constant and is steadily increasing today. First, a warming planet triggers feedbacks such as sea ice melt that reduces albedo (reflectivity) and increases the absorption of incoming solar radiation, or such as methane release from warming soils that increases the atmospheric concentration of warming pollutants and re-radiates infrared radiation back toward the earth's surface. Second, continued anthropogenic emissions may increase the atmospheric concentration of warming pollutants. Absent continued emissions, pollutant concentrations decline in the atmosphere (see lifetime chart in Figure 4-1). CO_2 and other long-lived pollutants have long atmospheric lifetimes and a small fraction remains in the atmosphere for hundreds to thousands of years.

Radiative forcing (RF) is the planetary energy imbalance associated with a given atmospheric concentration of pollutants, before taking into account any temperature response of the earth or any feedbacks. Thus, the RF for a constant atmospheric concentration remains a constant, while the planetary energy imbalance (EIB) and the planet's temperature change over time and eventually equilibrate in response to the presence of the atmospheric pollutants. Warming is rapid in the early years when EIB is high and warming is much slower in subsequent years, as higher temperatures increase outgoing infrared radiation and reduce the EIB (see Figure 6-3). The process is lengthened by the many centuries required for deep ocean heat mixing. Approximately half to two-thirds of temperature change occurs within decades of initiation of the forcing, while the full equilibration process to a constant concentration and constant RF takes many centuries (see Figure 6-4). The percentage and pace of change that occurs within the first couple hundred years is a subject of on-going scientific research that rests on the efficiency of ocean heat mixing, with a range of possibilities illustrated in Figure 6-5.

In a case where anthropogenic radiative forcing peaks and declines, the temperature response depends in part on the magnitude of feedbacks that have already been triggered and the persistence of those feedbacks - i.e., how long it would take for a feedback to reverse upon a reduction of the radiative forcing. Figure 6-6 provides examples of climate system elements that respond more or less quickly as the climate warms and cools. Some processes are fully reversible (e.g., amount of water vapor in the air) while others, particularly those with spatial or temporal patterns, are qualitatively irreversible. A similar pattern may or may not emerge after cooling, but the pattern will not be identical (e.g., for landscape changes, even if the same type of ecosystem returns to an area, it will be qualitatively different from the original).

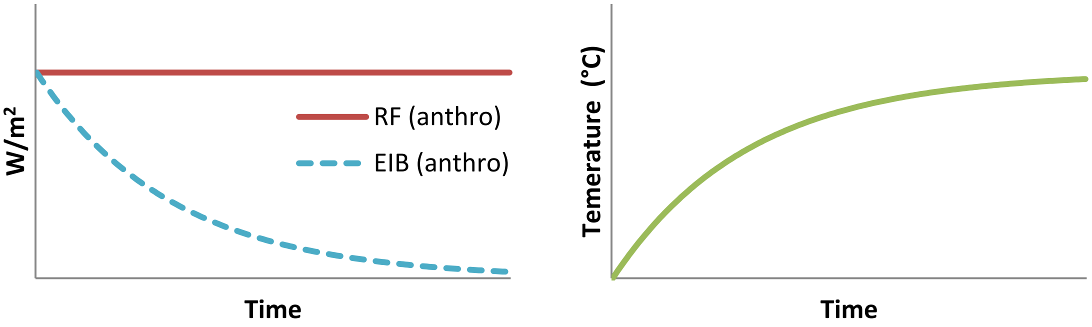


Figure 6-3: Stylized Diagram of Constant Concentration Scenario
Radiative forcing is constant in a constant concentration scenario. Energy imbalance falls as temperature rises. Feedbacks are excluded from this diagram. Corresponding emissions are illustrated in Figure 2-12a. A slice of the temperature graph after the initial steep slope is shown in Figure 6-4.

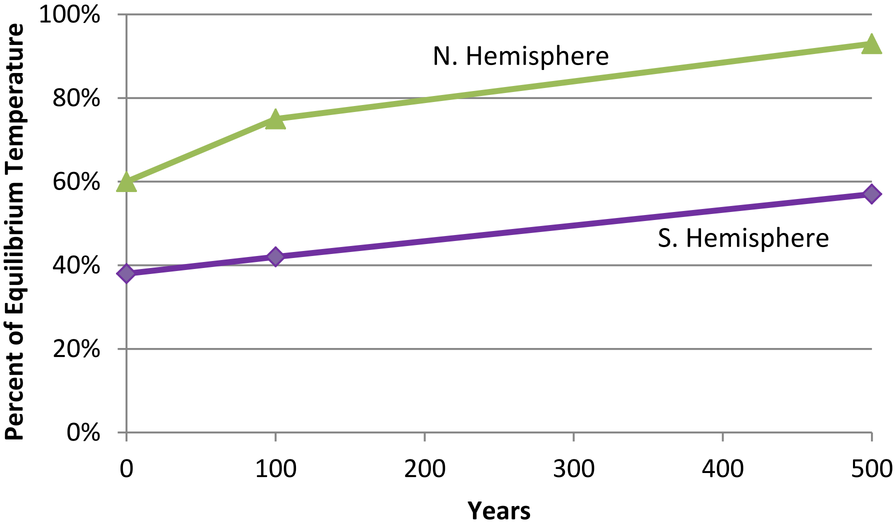


Figure 6-4: Fraction of Equilibrium Warming in the First 500 Years
Data are from Stouffer 2004 [116]. This graph shows the temperature response to a modeling experiment in which the CO_2 concentration is increased by 1% per year for 70 years, then stabilized. Year 0 on the chart corresponds to year 70 of the experiment, the first year of stabilized RF. Roughly half of equilibrium temperature response (40% in the Southern Hemisphere, 60% in the Northern Hemisphere) is already apparent at this starting point. The Northern Hemisphere warms to 75% of equilibrium warming by 100 years, but the Southern Hemisphere warms more slowly due to a higher fraction of its surface covered by ocean. The global warming at 100 years is approximately 60% of equilibrium warming. Warming continues more slowly over the subsequent centuries and extends beyond this chart, with 100% of equilibrium warming for the Northern Hemisphere at about 1000 years and 100% for the Southern Hemisphere at about 4000 years.

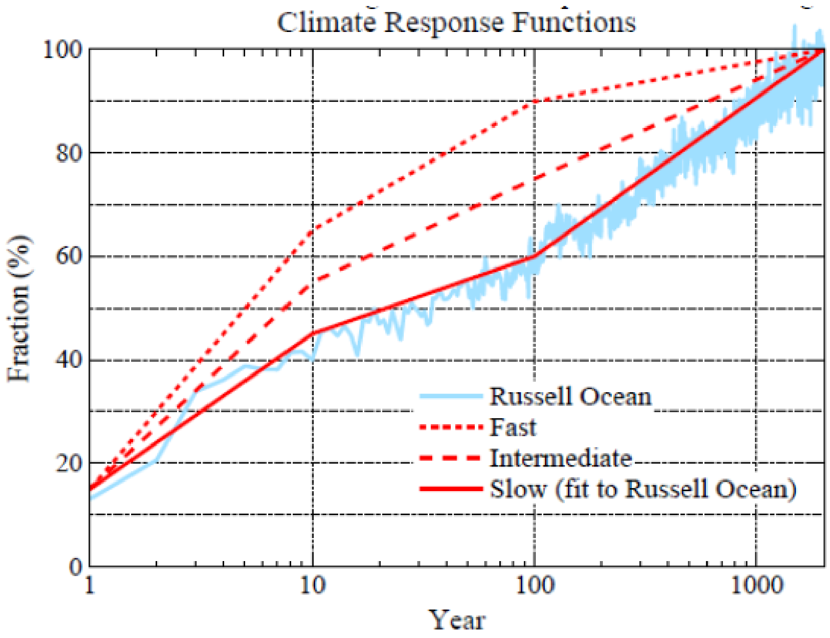
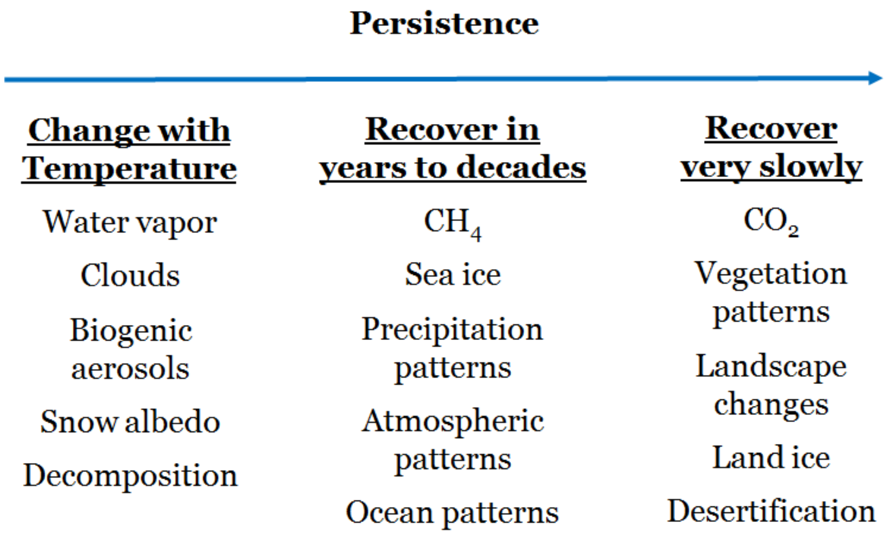


Figure 6-5: Alternative Climate Response Functions, from Hansen et al. 2011
Reproduced with permission from Hansen et al. 2011 [43], under the Creative Commons Attribution 3.0 License. The climate response function is the fraction of equilibrium temperature (excluding slow feedbacks) that is realized after a given number of years following an instantaneous doubling of CO_2 concentration (note that this is a related but different scenario than the 1% per year growth to doubling that was used in Figure 6-4). The fast and slow lines bound the range that Hansen et al. find could match the real-world response, the slow line matches most climate models, and the intermediate line represents their best estimate.



Persistence

Change with Temperature	Recover in years to decades	Recover very slowly
Water vapor	CH_4	CO_2
Clouds	Sea ice	Vegetation patterns
Biogenic aerosols	Precipitation patterns	Landscape changes
Snow albedo	Atmospheric patterns	Land ice
Decomposition	Ocean patterns	Desertification

Figure 6-6: Changes in Climate System and Feedbacks, categorized by persistence
I define persistence in this chart as how long it would take for a feedback or other earth system change to reverse upon a reduction of radiative forcing. Placement on this chart is based on general mechanics of earth system processes. Surface temperature changes in response to the RF reduction would begin immediately and increase over time, as described in Figure 6-4 and Figure 6-5, with cooling occurring faster than warming [116]. The climate changes in the "change with temperature" column respond directly and almost immediately to surface temperature changes on a local basis.[93] [94] The processes in the "recover in years to decades" column involve heating or cooling of the ocean, sea ice, and deep soils over multiple years due to high heat capacity. The processes in the "recover very slowly" column involve physical changes that are cumulative over many decades (e.g., land ice) and ecological processes that involve multiple generations of plants and other organisms.

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[93] In addition to ambient temperature, snow albedo's persistence varies based on what is underneath (e.g., ice, vegetation) and surrounding (e.g., ice field versus forest), and hence snow albedo persistence has some dependence on long-term changes in vegetation patterns and landscape changes.

[94] Decomposition in this chart refers to the decomposition rate of a given vegetation type. Note that different vegetation types have varying decomposition rates, such that total decomposition has dependence on long-term changes in vegetation patterns.

6.2.b.ii.ii Can a Delay Reduce Transient Feedbacks and Shave Peak Warming?

To the best of current knowledge, the initiation and magnitude of climate feedbacks is most closely correlated with the magnitude and duration of climate change, not the rate of climate change (see sections 6.2.a and 6.2.b.i). Thus, the mechanism for reducing the total feedbacks experienced between today and equilibrium is to reduce the magnitude and duration of peak warming.

Most mitigation scenarios fit the profile of Figure 6-7 (top), with RF rising and eventually stabilizing at a given level, corresponding to a constant atmospheric concentration of pollutants. Maintaining a steady atmospheric concentration of CO_2 over a millennium is estimated to require over 90% reduction in emissions versus today's levels, so it is difficult to do better than RF stabilization. [66]

In a standard scenario of this type, if the path to RF stabilization takes longer (Figure 6-7), feedbacks are simply delayed, not reduced, because the same climate change that triggers the feedbacks occurs, just at a slower rate, and the higher temperature persists for centuries. Peak warming occurs at equilibrium and its magnitude is unaffected by the delay.

For a delay to reduce transient feedbacks and shave peak warming, then, a situation must first exist in which peak warming occurs at a point aside from equilibrium (a transient temperature peak). A significant reduction in RF must occur, such that the new RF has an equilibrium temperature that is lower than the temperature at the time of the RF peak (see Figure 6-8). Said another way, RF would fall after the point when much of the temperature increase associated with the peak RF had been realized, for example with a multi-decade plateau at the high RF level followed by a significant RF reduction.

The constraint on the possible occurrence of a transient temperature peak and decline scenario ties back to the fraction of equilibrium warming that occurs within decades of an RF change, shown in Figure 6-4 and Figure 6-5 to be 50-60%, with an upper bound of ~75% of equilibrium warming. If that fraction is 55%, then RF must drop more than 45% from the peak in order for the transient temperature to exceed the equilibrium temperature (assuming a linear relationship between RF and temperature). If the fraction is instead 75%, then RF must still drop 25% from its peak in order for transient temperature to exceed equilibrium temperature. This situation could arise, for example, if net negative CO_2 emissions were implemented at some future date, reducing the CO_2 concentration and RF. A handful of RF peak and decline (also known as "overshoot") scenarios envisioned in the literature fit this description and involve a temperature peak and decline during this century. [117] It could also arise in a circumstance with a high transient airborne CO_2 fraction, followed by very low future emissions and a low equilibrium airborne fraction. Additional circumstances that could involve transient temperature peaks are discussed in sections 13.2.a and 15.1.c.

On the small fraction of trajectories that involve transient temperature peaks, whether *delaying* climate change reduces feedbacks and reduces peak warming depends on the nature of the delay. Some feedbacks have lag times, such that they require years at a given temperature to fully realize the feedback (e.g., melting an ice sheet or warming the ocean floor to depth). A slower approach toward the same transient temperature peak may actually increase feedbacks if it means that more years are spent at temperatures above equilibrium (compare scenario B with scenario A in Figure 6-9). In contrast, if the years to the RF drop are equal, the delay would imply a lower transient temperature peak irrespective of feedbacks and would lower feedbacks as well (compare scenario C with scenario A in Figure 6-9). However, given the lower peak RF, this is really more an “avoid” scenario than a “delay” scenario.

In summary, peak warming is likely to occur at equilibrium in the majority of emission scenarios and delay of climate change does not avoid feedbacks or reduce peak warming. There are a handful of special cases in which peak warming could occur at a point prior to equilibrium; even within those, it is difficult to find a pure “delay” scenario in which delaying climate change could reduce feedbacks and peak warming.

6.3 Summary Discussion: A Pragmatic Perspective on Delay

In short, magnitude of climate change (not rate of change) is the primary driver of large-scale ecological impacts and long-term climate outcomes. Today’s state-of-the-art climate models assume no significant long-term climate benefit of near-term climate change delays (see section 9.1), and there has been little research on the topic of whether rate of climate change has lasting effects that are distinct from magnitude of change. A long-term climatic or ecological benefit of delay, if it did exist, would be an important consideration for mitigation policy and for climate modeling. This topic deserves further research.

Regardless of whether delay produces long-term benefits, delay has intrinsic near-term benefits, via reducing impacts experienced in the near-term and delaying some impacts beyond the near-term. There are numerous pragmatic reasons for delaying climate outcomes: a) to delay a negative experience (perhaps even beyond one’s lifetime), b) to delay an uncertain experience, c) to “buy time” for adaptation [15, 50], d) to allow time to learn how to better adapt, e) to reduce the costs and increase the feasibility of societal and ecosystem adaptation

[118], f) to “buy time” for more mitigation action to happen [71], and g) to provide modest mitigation successes that build confidence and capacity for more aggressive mitigation.

Arguments for and against the various methods of achieving delay are discussed in Chapter 7.

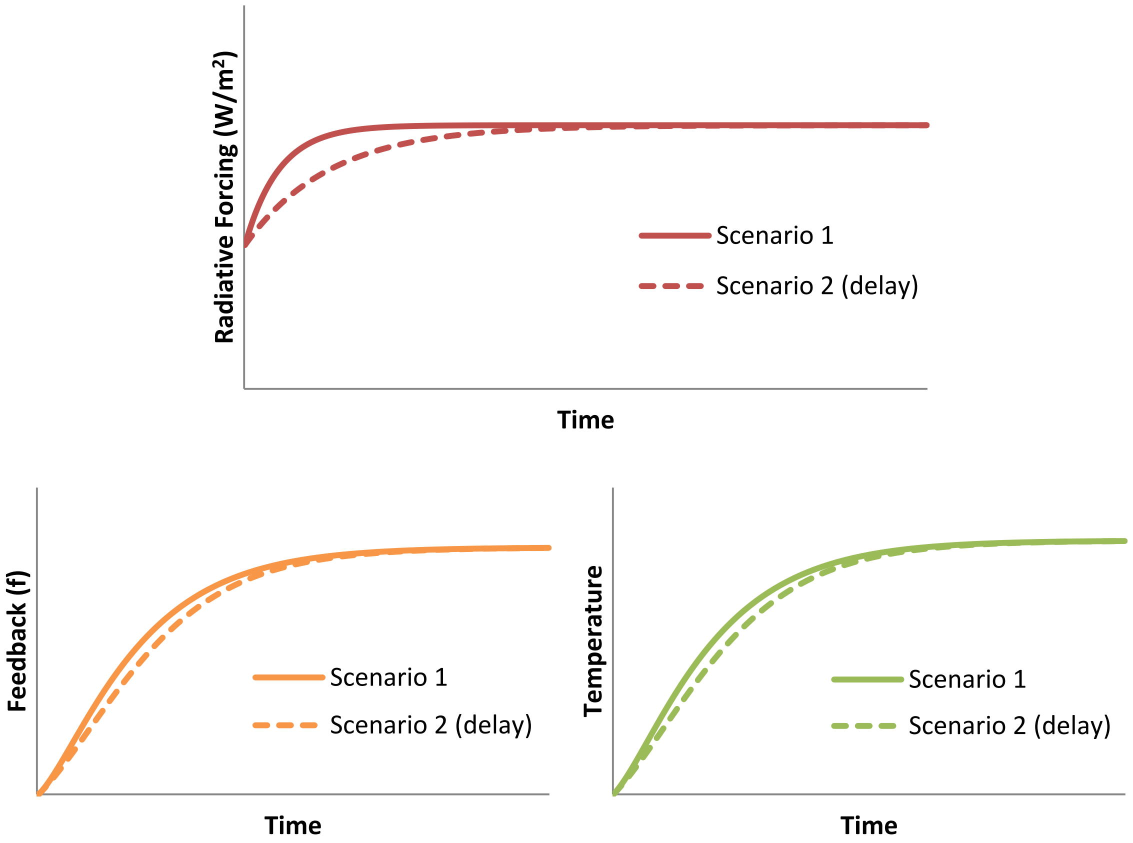

Figure 6-7: Stylized Diagram of a Rise and Plateau of Radiative Forcing, with and without Delay
Top figure shows radiative forcing trajectory, with and without delay. Bottom figures show corresponding feedbacks (left) and temperature increase (right). The diagram assumes that energy imbalance (EIB) (not shown) accounts for feedback and declines exponentially, temperature growth is proportional to EIB, and feedback is proportional to temperature. The transient feedback parameter (f) is the amplification multiplier for the climate response.

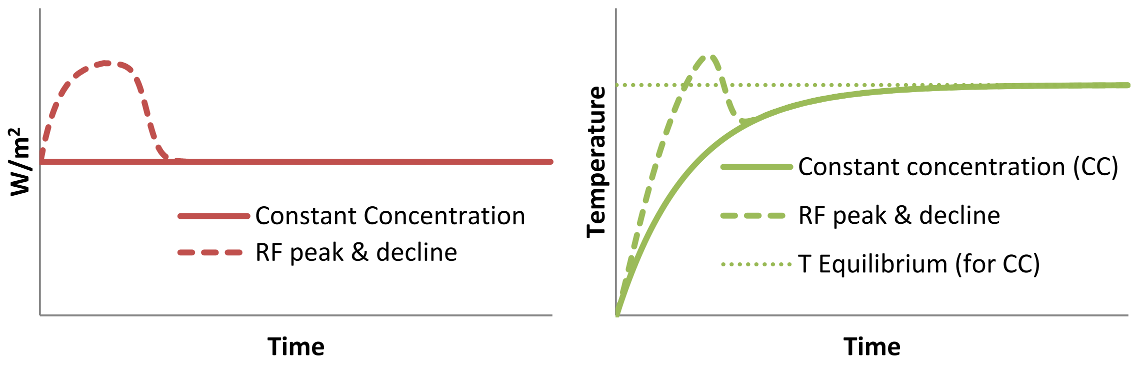

Figure 6-8: Stylized Diagram of a Rise, Decline, and Plateau of Radiative Forcing (dotted) and Constant RF (solid)

The temperature peak is proportionally smaller and of shorter duration than the RF peak due to the lags discussed in section 6.2.b.ii.i. Temperature shown does not include feedbacks, so both scenarios follow the same temperature trajectory after the radiative forcing plateaus. If feedbacks were shown in this diagram, the temperature in the peak and decline scenario would remain above the temperature in the constant concentration scenario for some length of time after the RF plateaued, with the duration of elevated temperature dependent on the strength and persistence of the feedbacks (see Figure 6-6) that were triggered during the temperature peak. (Notice that the temperature peak exceeds the equilibrium temperature for the CC scenario, so different feedbacks would be triggered during the peak.)

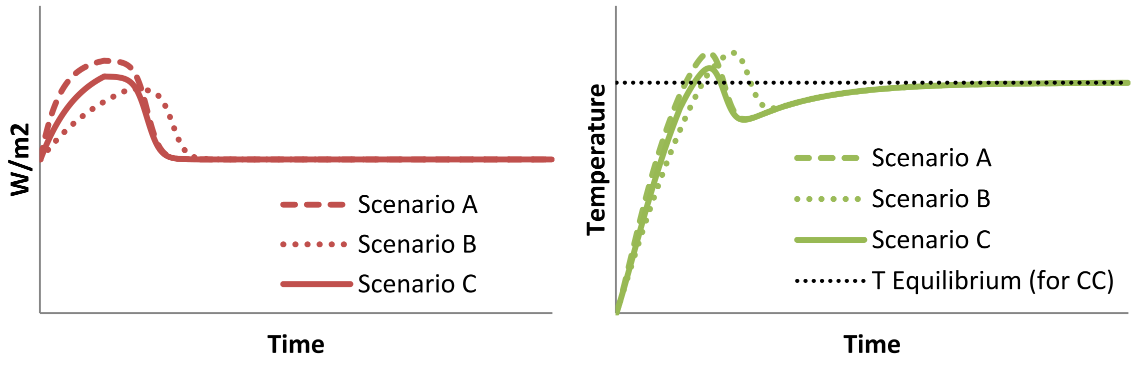

Figure 6-9: Stylized Diagram of Different Temperature Overshoot Trajectories

Scenario A is as shown in Figure 6-8. Scenario B delays climate change then hits the same warming peak as Scenario A; more time is spent at temperatures above the equilibrium temperature in Scenario B than in Scenario A. Scenario C delays climate change slightly relative to Scenario A, then peaks RF in the same year as Scenario A, resulting in a lower transient warming peak. Implications for feedbacks are discussed in the text. Temperatures shown do not include feedbacks.

Chapter 7 Issues to Consider Regarding Mitigation of Near-Term Climate Change

In Chapter 5, I presented three mitigation approaches for Box 1 that would delay near-term climate outcomes: 1) aggressive emission reduction of short- and medium-lived pollutants, 2) reducing the annual emission level of CO_2, or 3) geo-engineering via solar radiation management (SRM). In this chapter, I explore the issues that complicate decisions about reducing short-lived pollutants or pursuing geo-engineering.

7.1 Challenges to Mitigating Climate via Short- and Medium-Lived Pollutants

Short-lived pollutants have a mix of positive and negative effects on climate, human health, and ecosystem health. For some short-lived pollutants, it is non-trivial to determine whether an increase or decrease in emissions in a given location would have a net beneficial or detrimental effect and the magnitude of the effect. This difficulty arises because of the multiple warming and cooling roles that some pollutants play, their effects on human health, the complexity of aerosol-cloud interactions, the importance of local factors such as meteorology and concentrations of other reactive pollutants in determining atmospheric concentrations, the co-emission of multiple pollutants in different ratios from different sources, and varying perspectives on the relative societal importance of different climate, health, and ecosystem effects.

The nitrogen oxides (NO_x) are a good example of a group of pollutants whose reduction-benefit is difficult to quantify. [119, 120] NO_x has both warming effects via its contributions to tropospheric ozone (O_3) and cooling effects via its form as a nitrate aerosol[95] and its role in reducing methane (via increased concentration of hydroxyl radicals). [75] [96] [97] (Note that NO_x was shown in both Figure 4-4 and Figure 4-7.) On a global mean level, the sign of the net RF caused by surface emission of NO_x is negative (cooling) if the effect of ozone increases and if the effect of nitrogen deposition on CO_2 uptake by vegetation (the CO_2 land sink) is ignored.[98] [99]

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[95] Note, the confidence interval for the RF of nitrate aerosol includes zero (AR4: 0 to -0.20 W/m^2), so the papers cited in this paragraph focus primarily on O_3 and CH_4 effects.

[96] Note, the effect on methane (a medium-lived pollutant) influences RF for a longer duration than the effect on ozone or aerosol loads (short-lived).

[97] NO_x also has a small effect on sulfate ion (SO_4^{-2}) concentrations through its effect on O_3, OH, and H_2O_2 concentrations, but models disagree on the direction and magnitude of the effect (Fry et al. 2012). No effect of NO_x on N_2O is reported in IPCC AR4.

[98] IPCC AR4 did not attribute any change in CO_2 to NO_x emissions.

If the CO_2 sink change is included, NO_x may have a net positive RF (warming), though this result is pending further research. [121] The ratio and magnitude of warming and cooling effects of NO_x emissions vary with location and season, but the net result is directionally the same in all regions. [119, 121, 122] The ratio and magnitude of warming and cooling also varies with elevation of emissions, because the relative efficiency of photochemical O_3 production versus CH_4 destruction is greater in the upper troposphere than at the surface – which means that higher-elevation emissions of NO_x (e.g., from aircraft) produce a net warming effect (regardless of the CO_2 sink inclusion). [122] In addition to its complex effects on climate, NO_x also has negative human health effects as an inhaled particulate, negative health and agricultural effects as a contributor to tropospheric ozone, and negative ecosystem effects as a precursor to acid rain.

Tropospheric ozone is a warming agent, and is also detrimental to both human health and to plants. [123] Calculating the effect of changes in ozone precursor emissions on ozone concentration is non-trivial, however. Tropospheric ozone concentration is a function of net chemical production (production from precursors minus chemical loss), stratosphere-troposphere exchange, and dry deposition. The first and last depend on the concentration of precursors and existing ozone, as well as on local and regional-scale meteorological conditions. This means that the location of emission reductions matters for how much the precursor reductions affect ozone concentrations. Additionally, chemical production slows and loss increases in a warmer, wetter climate, with lower net chemical production in most regions in a changing climate. [86] Radiative forcing of ozone is also dependent on relative humidity, which varies by location and with changing climate, and on vertical distribution, with higher radiative efficiency per molecule in the upper troposphere. [86, 119] This means that a certain percentage reduction of ozone precursors does not produce the same percentage reduction in ozone RF, and the relationship between reductions of emissions and RF varies by location and with climate. [86, 119, 121]

Black carbon (a warming aerosol in most cases) is complicated in other ways. It has a direct absorptive effect (warming), a deposition effect on snow (warming), and semi-direct and indirect effects on clouds (likely cooling, but sign unclear). [36] Effects of black carbon deposition on snow depend on proximity to snow and hence vary with emission location. Indirect effects of all aerosols have particularly wide uncertainty, as discussed in section 4.4.b.i, as well as wide variation by location depending on local meteorology. Black carbon is also co-emitted with organic carbon (a cooling aerosol) in proportions that differ by source. [82, 124] Fossil fuel sources have higher proportions of BC to OC than do biomass sources [124], and

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[99] Ozone reduces the carbon sink and nitrogen deposition increases the carbon sink.

there is fairly good confidence that the combined result of BC and OC emissions from fossil fuel sources produces warming [75]. It is much less certain what the net effect is for the BC and OC from biomass sources in most locations, with the exception of known warming near sensitive snow and ice areas (e.g., Himalayas). In addition to their climate effect, the BC and OC from both biomass and fossil fuel burning contribute to indoor and outdoor air pollution and respiratory illness. Reduction of these pollutants at maximum technically feasible levels (see section 4.4) could avoid over two million premature health-related deaths per year. [88]

Finally, emissions of SO_2 produce sulfate aerosols, which scatter light and have indirect effects on clouds, producing cooling in most locations that are not already highly reflective. The magnitude of cooling attributable to sulfates is estimated to be large but widely uncertain (see Figure 4-13 and section 4.4.b.i). While beneficial from a climate perspective, SO_2 emissions cause human respiratory ailments from the sulfate aerosols and environmental side effects from sulfuric acid deposition. [125]

In summary, reductions of short- and medium-lived pollutants have effects on climate, health, and ecosystems, and these effects are not always in the same positive or negative direction. Additionally, because these pollutants are short-lived, they have limited time to travel and their effects are spatially variable, not uniform across the globe. Their effects depend on location-specific factors such as meteorology, background pollutant concentrations, population density, ecosystem types, etc. Any quantification of the potential benefits of climate mitigation via short-lived pollutants thus requires spatial analysis of the outcomes.

7.2 Arguments For and Against Mitigation of Short-Lived Pollutants

Methane and short-lived forcing agents (aerosols and tropospheric ozone) are increasingly recognized by international policymakers as having potential to play an important role in the mitigation of climate change. The Global Methane Initiative (formerly the Methane to Markets Partnership)[100] was launched in 2004 with the goal to “advance cost-effective, near-term methane recovery and use as a clean energy source.” [126] The Tromso Declaration by the Arctic Council in April 2009 “urge[d] implementation of early actions where possible on methane and other short-lived climate forcers” and established a task force on short-lived climate forcers. [127] In September 2010, the Global Alliance for Clean Cookstoves launched[101] with the goal for “100 million homes to adopt clean and efficient stoves and fuels by 2020.”

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[100] The Global Methane Initiative currently has 40 participating nations, including the United States, representing 60% of global CH_4 emissions. Four sectors are targeted: agriculture, coal mines, landfills, and oil and gas systems.

[101] Partners include: United States, Germany, Norway, Netherlands, Peru, UN Foundation, Morgan Stanley, and Shell. Note that the nations with most of the cookstoves are not part of the partnership.

[128] In February 2012, the Climate and Clean Air Coalition of six nations[102] plus UNEP was launched to address methane, black carbon, and HFCs.[103] [75, 85, 129] The G8 joined this coalition in May 2012. [9] This list of initiatives is not comprehensive, as there are many large and small efforts emerging around the world.

Most researchers and policymakers are in favor of action on short- and medium-lived pollutants, though reasons for support vary. Frequent arguments have been made in favor of pollutant reductions that have health co-benefits, such as reducing respiratory ailments [88, 130] and improving food security via higher crop yields [88]. Some see adding these pollutants to the discussion as a means to bring more parties to the climate negotiating table. [71] Others see reductions of these pollutants as a way to slow the rate of near-term climate change [15, 131, 132] and "buy time" [15, 50, 71] – either for adaptation to be done, for negotiations to progress, or for new technologies to be developed. Some perceive reducing these pollutants to be a fast way to reduce climate change. [133] As mentioned in section 4.5, reducing these pollutants has not yet proven to be fast or easy, even though the effect of their removal on the climate would indeed be fast due to their short lifetime. Finally, since wide uncertainties on the RF of aerosols contribute to the wide uncertainty on climate sensitivity, some scientists support reductions in short-lived pollutants as a way to refine climate sensitivity estimates and improve projections of future climate change. [134]

Despite growing popularity, there is some resistance to reducing short- and medium-lived pollutants, or even focusing research attention on them. One line of argument is that if attention is given to short- and medium-lived pollutants, it will be drawn away from CO_2. In 2009, a Nature editorial noted that "Some fear that even talking about such subjects [black carbon, methane, hydrofluorocarbons] could distract from the main problem, which is CO_2." [135] Another line of argument was published in 2011 by Myhre et al. [16] , who expressed their concern that near-term climate change may be needed to provoke action and expressed their fear that reducing near-term climate change via mitigation of short-lived pollutants will reduce action on CO_2.

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[102] United States, Bangladesh, Canada, Ghana, Mexico, Sweden. Note the mix of developed and developing nations.

[103] See discussion of HFCs in section 4.1. The current RF of HFCs is very small relative to other short- and medium-lived pollutants (0.01 W/m^2, relative to 0.84 W/m^2 for CH_4 emissions or 0.35-0.85 W/m^2 for black carbon's direct effect – see Figure 4-11). HFCs are included in the cited campaign because they are growing rapidly, and without intervention, the UNEP HFC report estimates that their RF could be 0.1-0.4 W/m^2 in 2050. Note that HFCs have a range of lifetimes, many not short-lived: HFC-23: lifetime 270 years; HFC-125: lifetime 29 years; HFC-134a: lifetime 14 years; HFC-152a: lifetime 1.4 years.

The Climate Boxes Framework sheds light on these opposing positions. While CO_2 is the "main problem" for long-term climate change and ocean acidification [56], concern about near-term climate outcomes (Box 1 (delay) or Box 2 (avoid 1.5-2°C)) is consistent with support for reductions of short- and medium-lived pollutants. As we will see in Chapter 13, not reducing these pollutants would make an extremely challenging mitigation task even more difficult. Concern about long-term climate outcomes and a priority on avoiding 3-4°C (Box 3) is consistent with a push to focus almost entirely on CO_2. In short, arguments about whether or not to address short-lived pollutants and to research near-term climate change (see Chapter 8) can be mapped to the different boxes, including differences in time horizon priorities.

7.3 Arguments For and Against Geo-engineering via SRM

Arguments about geo-engineering, especially via solar radiation management (SRM), are far more complicated than those regarding short- and medium-lived pollutants

SRM, particularly via stratospheric sulfate particles, has three factors in its favor. It is the only known option that can materially change the climate within a matter of years. It is the only known option that has the potential to produce near-term cooling (not just slow warming). And it is inexpensive relative to mitigation options and carbon capture. These strong positives are complicated by many downsides, which lead most scientists to describe SRM as an "emergency measure" or "last resort". [96, 136]

Among the downsides, there are concerns about whether SRM would work as planned and about the spatial distribution of its effects. One mechanism by which SRM via stratospheric sulfate particles could backfire would be by increasing the Antarctic ozone hole (more sulfates to interact with existing CFCs to consume ozone), which drives changes in atmospheric circulation (the Southern Hemisphere Annular Mode, or SAM), which strengthens the Southern Ocean winds, which reduces the efficiency of the Southern Ocean carbon sink, which increases CO_2 in the atmosphere and increases climate change. [137] The magnitude of this feedback has not yet been quantified, and is provided as an example of unintended climate consequences. Several scientists have cautioned about the potential for a variety of unintended consequences due to incomplete knowledge of earth system interactions [137, 138] and noted examples of past environmental interventions that went awry due to incomplete understanding [139].

Existing knowledge shows that SRM would not be able to fully replicate "a low CO_2 climate in a high CO_2 world" [140] and that global averages of temperature, precipitation, and sea ice could not all be restored simultaneously [141]. Regional patterns of temperature and precipitation would change [97, 142] and many models predict a slow-down of the global hydrological cycle with lower average precipitation [143]. Significantly, the regional patterns would be different depending on the approach taken to implement SRM [97], leading researchers to caution policymakers on the political implications.

Political concerns about SRM revolve around the question of whose climate would get optimized, based on whose preferences, and how this authority would be assigned and maintained. These political issues have been suggested to lead to the potential that climate alteration may be seen as an "aggressive act", potential for a consequently longer negotiation process for SRM than for CO_2 mitigation [137], the potential for "mutually assured destruction" [144], and the need for "centuries of trusted global climate-controllers… [who] operate continuously, reliably, and by consensus" [145]. Outcomes will depend on many factors, including the motives of those in charge [146] and differences between the "selfish geoengineer" and the "benevolent geoengineer" have been noted [147].

Additional concerns revolve around direct and indirect side effects of SRM, particularly via stratospheric sulfates. Direct effects are numerous and include the following examples: Sulfate particles would combine with remaining CFCs in the stratosphere to deplete ozone – expanding the Arctic ozone hole, delaying recovery of the Antarctic ozone hole[104], and thinning mid-latitude stratospheric ozone – increasing ultraviolet radiation reaching the earth's surface and increasing risk for skin cancer and cataracts. [148, 149] Skies would be whiter and brighter by day due to scattering by sulfate particles [148, 150] and stars would be less visible at night, impacting both human enjoyment and Earth-based optical astronomy [151]. Electricity generation from concentrated solar plants would be reduced, as particles would scatter the incoming sunlight and reduce the amount of direct (versus diffuse) solar radiation. [148, 152][105]

Indirect effects would arise if implementation of SRM led to reduced concern about climate change and continued high emissions of CO_2. In that case, atmospheric CO_2 would continue to rise and ocean acidification would continue to increase, threatening the survival of corals and shellfish and the structure of marine ecosystems. [153] There is long-standing concern about the moral hazard that even the possibility of a geo-engineering option will lead to less mitigation of emissions [96, 154]

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[104] By 30-70 years, per Tilmes, Muller, and Salawitch 2008.

[105] Per Murphy 2009, "Each 1% reduction in total sunlight reaching the earth from enhancement of stratospheric aerosols will cause a 4-10% loss in output from concentrated solar power applications…." Smaller losses would be experienced by flat solar hot water and photovoltaic panels, which utilize diffuse light, but not as efficiently as direct sunlight. Per Robock 2008, a 1.8% reduction in incoming solar would approximately compensate for a doubling of atmospheric CO_2. In that case, concentrated solar power generation would drop 7-18%.

In short, “engineering the climate strikes most people as a bad idea” and is often described as a “last resort”. [136] Nonetheless, many scientists, starting with Paul Crutzen [155] and Ralph Cicerone [154] in 2006, have stated their support for geo-engineering research. Reasons to support research range from affirmation of the freedom of inquiry [154], to concern that any major intervention be given sufficient study first [139], to the sense that research will be done regardless and the best research should be encouraged [154].

While computer-based research on SRM is accepted in the scientific community, fieldwork experiments and actual deployment are highly controversial due to the concerns listed above. Deployment of geo-engineering is described by a limited few as “the most effective and efficient solution”. [156] More typically, support for deployment of geo-engineering, at some undefined point in the future, is supported by the “buying time” argument [96, 157] – for all of the “buying time” reasons discussed in sections 6.3 and 7.2. Other tentative support for deployment comes from an explicit desire to minimize near-term climate change and provide “palliative care” for the planet [158], reducing near-term impacts on ecosystems [159].

7.4 Summary

There is relatively little debate over the net positive benefit of reducing short- and medium-lived warming pollutants and the side effects of pollutant reductions are generally considered positive (e.g., improved health); the debate that does exist can be traced back to different implicit positions on the Climate Boxes Framework (Box 1 “delay” versus Box 2 “avoid 1.5-2°C” versus Box 3 “avoid 3-4°C”).

In contrast, the side effects of SRM are acknowledged to be largely negative, and concerns have been raised about the political, societal, personal, and environmental consequences of the SRM approach. While support for SRM is consistent with Box 1 (reducing near-term climate change and buying time for mitigation), support for Box 1 does not imply or require support for SRM.

In Chapter 8, I will explore the future research needs on mitigation of near-term climate outcomes.

Chapter 8 Scientific Research Needs on the Topic of Mitigating Near-Term Climate Change

This chapter summarizes the gaps in scientific study on near-term climate change, particularly research that would inform mitigation decisions regarding delay (Box 1), and provides suggestions for future research.

Knowledge of the widest possible range of near-term climate options is essential to informing mitigation policy, informing adaptation planning and costing, and furthering climate modeling skill. The near-term is particularly worthy of significant and explicit research attention because:

1) The near-term horizon (20-40 years) is the window that most of the adult population will live to see. This fact alone makes the near-term of personal relevance to decision-makers and members of the public.
2) Technologies that provide options for delaying, but not avoiding, climate outcomes exist (Box 1; see Chapter 5). Explicit study of near-term scenarios is required to understand what climate outcomes are delayed, by how long, by what levels of adoption of these technologies.
3) Policy arguments are made that the delay approaches in Chapter 5 will “buy time” for adaptation and mitigation. [50, 71] Closer comparison of the mitigation actions required to “buy” a given amount of time, and the value of what is gained by that time, will inform policy.
4) Focusing attention on the near-term focuses attention on the benefits of delay, which in turn focuses attention on rates of climate change. Greater understanding of the relationship between specific rates of climate change, climate feedbacks, and ecological impacts (as discussed in section 6.2) will both improve climate models and inform mitigation policy.
5) Focusing attention on near-term nuances may accelerate advances in the young field of decadal prediction, and in turn, create unanticipated advances in other related climate sub-fields.
6) Near-term scenario comparison is presently a large, and largely unacknowledged, gap in climate science knowledge (see statistics in the introduction to Section II). Scientific curiosity beckons.

8.1 Gaps in Near-Term Scenario Comparisons

The coordinated global climate modeling effort for the most recent and the forthcoming IPCC assessments (CMIP3 for AR4 and CMIP5 for AR5) largely excludes scenarios with major near-term climate action. All of the RCP and SRES scenarios, except RCP3-PD, actually have 2050 emissions higher than those in 2010 (see Figure 2-1 and Figure G-1). RCP3-PD is the only scenario that would achieve the international policy objective of the Copenhagen Accord [3] and the G8 [9] of keeping global temperature below 2°C (see Figure 2-5).

The limitation of these standard scenarios to a single scenario that avoids 1.5°C and 2°C creates significant information gaps about delay. E.g., RCP 4.5 will cross 1.5°C in ~2040 and 2°C in ~2060 (see Table 2-5). RCP 3-PD never crosses those thresholds. The delay between 2040 or 2060 and “never” is infinite. What delay could be achieved by scenarios that lie between RCP 3-PD and RCP 4.5? Additional low-emission scenarios are needed to answer the question.[106]

Higher scientific priority on scenarios that achieve the stated international policy goals is also needed. The RCP3-PD scenario has been identified by the CMIP5 team as not “core” [160], which means it is optional for modeling groups to run it for the upcoming IPCC assessment report (AR5). This sentiment is consistent with the 2011 publication of a set of ultra-high emission scenarios (above A1FI) with the concerned comment from its authors that these scenarios were being overlooked as “recent literature has been devoted to low emissions futures”. [161]

In addition to low emission scenarios, bounding and control scenarios would be particularly informative for understanding what is “committed” in the near-term (see section 2.4). Bounding scenarios situate choices relative to extremes and include: emit nothing starting today[107] (i.e., zero emissions) or burn all fossil fuels. The zero emission scenario provides decision-makers with information about which outcomes cannot be changed by any means. Control scenarios are characterized by some variation on “no treatment” and include: zero emissions (emit nothing), constant emissions (no change in emissions), steady growth (no change in emissions trajectory), or constant atmospheric concentrations (no change in concentrations).

Bounding and control scenarios are largely absent from typical climate modeling results. While a handful of teams have recently started to publish articles with the zero emission scenario as a bounding scenario [55], most modeling teams do not publish the bounding, control, or low-emission scenarios. The constant concentration control scenario was run by some teams for

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[106] Limitations in decadal modeling skill can make scenario differences statistically insignificant. If statistical insignificance is the result of low modeling skill, then that insignificance may disappear as skill increases.

[107] See footnote 36 for a lower possibility.

CMIP3 (see Figure 2-2), but is not included among the scenarios run for CMIP5.[108] The lowest bounding scenario, zero emissions, is not included in either CMIP3 or CMIP5.

Additionally, scenarios that test the near-term climate outcomes with or without major mitigation of short- and medium-lived pollutants are also not included among the standard scenarios.[109] The material near-term difference on temperature that inclusion or exclusion of mitigation of these pollutants could make (up to 0.5°C ± 0.3°C) is illustrated in Figure F-1.

For impacts, it is common practice to present the result of only a single scenario for the near-term horizon. In the Technical Summary of Working Group II in the most recent IPCC assessment report (AR4), two boxes summarize the impacts by system and sector and by region with a total of 155 bullet points. Of these, only 25 points (16%) specify which scenario the impact is associated with and only 7 points (5%) make a comparison of impacts across different scenarios. [101]

The concept of calculating the benefit of delay is largely absent from the mainstream adaptation literature. The World Bank 2010 assessment of the costs of adaptation for developing countries through 2050 includes only a single scenario (A2), with no quantification of the differences in adaptation costs between different mitigation approaches. [162, 163] Hof, den Elzen, and van Vuuren do consider the relative adaptation costs of avoiding 2°C (Box 2) versus avoiding 3°C (Box 3) and find differences of 2-3x. [164] The global benefit of delay (Box 1) for adaptation has not been calculated.

8.2 Progress Being Made

Despite the gaps, significant progress is being made. Transient changes are particularly difficult to model (e.g., [165]), and comparison of delays in near-term climate outcomes between scenarios requires sophisticated modeling of transient changes. Knowledge of decadal natural variability is evolving, knowledge of transient dynamics is growing, and the field of decadal prediction is beginning to establish itself. [166, 167]

"Near-term climate" is also starting to enter the research mainstream. The introduction to Section II noted that only 233 articles on "near-term climate" are found in Web of Science versus 16,557 articles on "long-term climate". The first paper with "near-term climate change"

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[108] Running the constant concentration scenario with the CMIP5 models would provide a control run to easily see model-related differences between CMIP3 and CMIP5.

[109] Standard scenarios include all pollutants, but the mitigation of non-CO_2 pollutants is assumed to be correlated with the mitigation of CO_2. (see Appendix F)

in its title appeared in 2006. [168] Thus, it is noteworthy that the IPCC's AR5 will have a chapter for the first time on "near-term climate change" in Working Group I [169], including detailed climate modeling for the near-term period through 2035 for the first time. [52] It will also include a sub-section in Working Group III on "integrating long- and short-term perspectives" on mitigation. [169]

Mentions of *mitigating* near-term climate change have been even scarcer in the literature, and ground-breaking publications on the topic have only recently emerged. The UNEP 2011 Integrated Assessment of Black Carbon and Tropospheric Ozone [36] and the related Shindell et al. 2012 Science article [88] present the very first published comparison of near- and medium-term temperature with and without aggressive mitigation of short- and medium-lived pollutants (Figure F-1). This approach breaks from the conventional practice of assuming that the magnitude of reductions of short- and medium-lived pollutants is correlated with the magnitude of reduction of CO_2 (e.g., section 9.3.a and Appendix F).

The titles of these documents are noteworthy in their adoption of the language of *mitigating* near-term climate change. The UNEP Science Policy Brief accompanying the integrated assessment is titled, "Towards an *Action Plan for Near-term Climate Protection* and Clean Air Benefits" [15] and Shindell et al.'s paper is titled "Simultaneously *Mitigating Near-Term Climate Change* and Improving Human Health and Food Security." [88] (italics added)

Finally, there may be a shift in sentiment underway on the topic of bounding scenarios, with Sanderson et al 2011 [161] arguing (in this case for high scenarios) that: "There is … an argument for exploring the climate consequences of emissions scenarios that may appear to be implausible. First, determining the bounds of plausibility is subject to high uncertainty, so a conservative approach would argue for at least testing the outcomes of scenarios that remain within physical constraints, but that otherwise are not much constrained by judgments of plausibility."

8.3 Next Steps for Research on Mitigation of Near-Term Climate Change

While this dissertation and many climate publications focus primarily on temperature, global temperature is a proxy for a wide range of specific climate outcomes that do not change linearly with temperature and whose outcomes are not geographically homogeneous (e.g., freshwater availability). Informed decisions about mitigation policy and adaptation policy rely on an understanding of the impacts that accompany any climate change.

The next research step in fully understanding delay (Box 1) would generalize from temperature to near-term climate outcomes, answering the following research question:

> Will a given emissions trajectory (of all pollutants) delay or avoid an undesirable climate outcome? If delay, by how long?

Figure 8-1 sketches what a graph of this information might look like for a given climate outcome under the comparative cases of two low bounding scenarios (zero emissions and constant concentration) and four other hypothetical scenarios.

Adaptation researchers could suggest the impacts for which Figure 8-1 would be the most informative, by first asking whether the costs and resources required for a given type of adaptation (e.g., disease prevention, ecosystem resilience, human resettlement) differ materially with the time available for adaptation. Adaptation and mitigation planners could then use the results of Figure 8-1 to understand the mitigation that would be required to "buy" that additional time and the benefits of delay.

8.4 Summary

Mitigation of near-term climate change is an under-explored topic, and there is much interesting research to be done. Advances in this field would better inform both adaptation and mitigation policy and more adequately inform box choices.

The next section turns to a much more commonly discussed topic: the mitigation requirements to avoid a 1.5-2°C temperature increase above pre-industrial levels (Box 2).

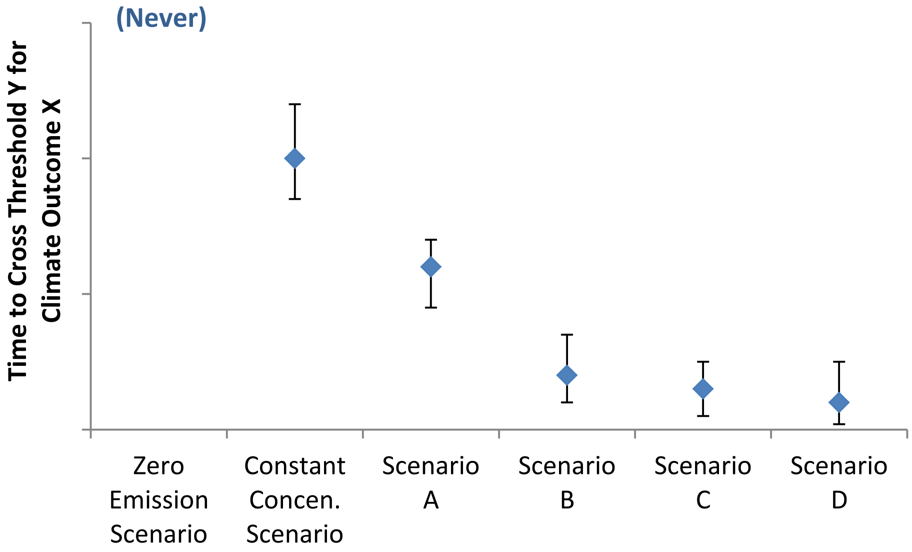

Figure 8-1: Illustrative Sketch of How Different Scenarios Delay or Avoid a Climate Outcome

Section IV Mitigation Required to Avoid 1.5°C or 2°C

Section II and Section III focused on near-term climate change. Section II established that mitigation of near-term climate change involves a greater focus on short- and medium-lived pollutants than mitigation of long-term climate change and a focus on mitigation in different sectors. It also reviewed evidence that significant mitigation of short- and medium-lived pollutants is technologically possible, though not yet globally demonstrated, and that maximum technically feasible mitigation of these pollutants can delay near-term temperature increases of 1.5-2°C by 5-35 years. Aggressive mitigation of a combination of long- and short-lived pollutants can delay these increases by 5-55 years. (Box 1)

In Section IV, I now shift to Box 2, which straddles the near-term and long-term with the goal of permanently avoiding a 1.5°C or 2°C increase in global surface temperature above pre-industrial levels. As presented in Chapter 2, these temperatures will be exceeded by 2050 across a range of scenarios that modelers consider plausible (see Table 2-5), so avoiding these temperatures affects both the near-term and long-term. The goal of avoiding 2°C (and re-visiting the possibility of avoiding 1.5°C) is included in the 2009 Copenhagen Accord and is a common way that the goal of climate change mitigation is framed.

As we also saw in Chapter 2, temperature projections for a given emission trajectory come in ranges, not in precise numbers, due to uncertainties in physical processes. It therefore makes sense to discuss the likelihood of avoiding 1.5°C or 2°C, and the language of likelihoods will be used throughout the section. Throughout Section IV and Section V, I primarily present results that achieve a 50% likelihood of avoiding a given temperature. This choice is made in order to present a bounding scenario; mitigation requirements for 50% likelihood reflect the least demanding mitigation that would be required to have positive odds of avoiding the given temperature. The choice to present 50% likelihood is also made in order to focus attention on the best scientific estimates, which correspond to these odds. A decision-maker must evaluate what level of risk is acceptable and what likelihood of avoiding a given temperature is required, and I am intentionally refraining from suggesting a level of risk that I consider appropriate.

Chapter 9 covers the combinations of peak year, plateau year, and CO_2 emission reduction amount that can achieve 50/50 odds of avoiding 2°C, with the requirements for other likelihood levels provided for comparison. Chapter 10 explores the implications of these emission trajectories for Annex I versus non-Annex I (developing) nations and the implications for the fossil fuel industry, specifically natural gas. Chapter 12 compares the Box 2 need for near-immediate peaks and rapid emission declines with the actual CO_2 emission trajectories to-date of regions, nations, and sources to-date and reviews the precedents for discontinuous peaks. Chapter 13 considers the role that non-CO_2 pollutants can play in improving the likelihood of avoiding 2°C and introduces a curve showing the likelihood of avoiding 2°C versus RF.

By the end of Chapter 13, I will fill in the mitigation required for Box 2 (see Table 8-1). Box 2, avoiding 1.5°C or 2°C, is the strictest of the four boxes. It involves a small finite CO_2 budget from now through equilibrium, which implies rapid emissions reductions in the developed world and flat emissions in the developing world. Reductions of non-CO_2 warming pollutants can increase the likelihood of avoiding transient temperature peaks under certain conditions (Chapter 13).

Chapter 14 will close the section with a look at the existing arguments for and against making the effort to avoid 1.5°C or 2°C (Box 2).

	Most concerned about climate outcomes in the next 20-40 years	**Most concerned about long-term climate outcomes**	**Not concerned**
In general	Reduce all warming pollutants (CO_2 and non-CO_2)		n/a
Delay or slow down climate change	Box 1: Reduce emissions of all warming pollutants in proportion to the desired delay, and /or Geoengineering (SRM)	n/a	n/a
Avoid 1.5°C or 2°C	Box 2: Limit CO_2 to finite budget: Developed world: immediate CO_2 drop, with 80-100% reduction by 2030-2040 Developing world: immediate CO_2 plateau Reduce non-CO_2 as needed to avoid transient temperature peaks		n/a
Avoid 3°C or 4°C	n/a	Box 3	n/a
Don't delay or avoid climate change	n/a	n/a	Box 4

Table 8-1: The Climate Boxes Framework, with Box 1 and Box 2 Mitigation Identified

Chapter 9 Global CO_2 Target Setting to Avoid 2°C

This chapter lays a foundation for understanding the mitigation required for Box 2 (avoiding 1.5°C or 2°C), the most challenging of the four boxes (see Table 8-1). It describes the mitigation required to avoid a global temperature increase of 2°C above pre-industrial levels (Box 2), and while 1.5°C is not specifically discussed, the reader can surmise that it is commensurately more difficult.

I start by reviewing the theory that underlies the analysis, summarize methods, re-frame carbon budgets into compatible emission paths, and characterize the global CO_2 emission paths that are aligned with different likelihoods of avoiding a 2°C global temperature increase above pre-industrial levels. I find that the CO_2 emission reduction requirement through 2050 varies significantly depending on how soon a global peak is achieved. Reduction requirements also differ significantly based on the decision maker's desired level of certainty in avoiding 2°C (e.g., 50% likely versus 75% likely). After diving into the details of assumptions on non-CO_2 emissions, I close by reviewing the current international CO_2 pledges versus the emissions required to avoid 2°C.

This chapter provides an analytical extension of Meinshausen et al. 2009 [170], synthesizes the highly cited works of the carbon budget theorists and the language of policymakers, and provides actionable information for Box 2.

9.1 Background: The Carbon Budget Theory

The carbon budget theory posits that the trajectory of emissions does not matter for equilibrium temperature increase, and that trajectories with the same cumulative CO_2 emissions will have the same equilibrium temperature outcome. In 2009, four papers written by two research teams introduced the concept of carbon budgets:

- Group 1: (common authors: Matthews and Zickfeld)
    - Nature 2009 (1): HD Matthews, NP Gillett, PA Stott, K Zickfeld[110] [171]
    - PNAS 2009: K Zickfeld, M Eby, HD Matthews, AJ Weaver[111] [172]
- Group 2: (common authors: MR Allen, M Meinshausen, and N Meinshausen)

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[110] Matthews et al.: "The ratio of temperature change to cumulative carbon emissions is approximately independent of both the atmospheric CO_2 concentration and its rate of change on these timescales [decades to centuries]". This group uses 10-1000 year simulations.

[111] Zickfeld et al.: "[E]stimates of cumulative CO_2 emissions, compatible with a specified temperature stabilization target, are independent of the path taken to stabilization." Runs are through year 2500.

- Nature 2009 (2): MR Allen, DJ Frame, C Huntingford, CD Jones, JA Lowe, M Meinshausen, N Meinshausen[112] [173]
- Nature 2009 (3): M Meinshausen, N Meinshausen, W Hare, SCB Raper, K Frieler, R Knutti, DJ Frame, MR Allen[113] [170]

As a policy tool, the concept is a theoretical departure from targeting atmospheric concentration (ppm), % emissions reductions by certain dates, and defined emissions trajectories. It has been proposed as a policy alternative to all of the above.

The carbon budget theory is consistent with the long-term atmospheric behavior of CO_2. The atmospheric concentration resulting from a given pulse of CO_2 decays steadily for several hundred years, then flattens out between 20-40% above pre-industrial levels (at a fraction defined by the cumulative emissions; see formula in section 15.1.a) and remains there for millennia until it reacts with calcium carbonate and igneous rocks.[114] [68] Given that equilibrium temperature is calculated after CO_2 has stabilized, a difference in timing of emissions on the order of decades does not affect the equilibrium temperature.

The carbon budget theory would not hold if feedbacks were materially dependent on rates of climate change, since feedbacks and equilibrium temperature would then be a function of the rate of emissions rather than only the cumulative total of emissions. To-date, none of the hundreds of citations of the carbon budget articles[115] has challenged the basic premise of carbon budgets. This absence of challenge is consistent with the discussion about rates of change and feedbacks in section 6.2. I found limited scientific evidence to-date supporting the hypothesis that the slower changes in near-term climate (slower rates of change, slower transient feedbacks) would reduce long-term climate change. Rather, they would delay it. Thus, different emission trajectories totaling the same cumulative amount would, in most cases,[116] serve to speed up or slow down climate change rather than change the equilibrium

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[112] Allen et al.: "[T]he relationship between cumulative emissions and peak warming is remarkably insensitive to the emission pathway (timing of emissions or peak emission rate)." Runs are through year 2500.

[113] Meinshausen et al.: "We show that, for the chosen class of emission scenarios… cumulative emissions up to 2050… are robust indicators of the probability that twenty-first century warming [and equilibrium warming] will not exceed 2°C relative to pre-industrial temperatures…." Runs are through 2100.

[114] Note, the fraction that remains is higher with higher cumulative emissions, and can extend above 40%. See the equilibrium airborne fraction for different cumulative emission levels in Table 15-2.

[115] As of April 3, 2012, per Web of Science, the first group of papers has been cited 55 times (Matthews et al. 36 times; Zickfeld et al. 19 times) and the second group has been cited 280 times (Allen et al. 91 times; Meinshausen et al. 189 times).

[116] There are limits to this statement at the extremes. E.g., if emissions were reduced to a low level and sustained at that level for hundreds or thousands of years so that a constant RF were maintained, the climate outcome

result.[117] This is supported by recent modeling work by Zickfeld et al. (of Group 1), who "find that the response of most surface climate variables is largely independent of the emissions pathway once emissions cease…" [174] Zickfeld et al. caveat that their modeling in CanESM1 does not include "all potential sources of hysteresis in the climate system", and that vegetation response or dynamic ice sheets "could introduce path-dependencies…." Further research is needed to identify whether these changes would affect equilibrium climate (or simply change the path to that climate) and at what thresholds of cumulative emissions these dynamics could become material to the climate outcome.

The carbon budget theory could also be compromised if a transient temperature peak exceeded the equilibrium warming associated with the carbon budget. A transient temperature peak could trigger feedbacks that would not otherwise occur and produce a higher equilibrium temperature. A transient temperature peak could result within the confines of a carbon budget in a case with significantly front-loaded emissions, a high transient airborne fraction (before the decline to the equilibrium airborne fraction), and a rapid climate response function (high percentage of temperature response to radiative forcing experienced upfront). Situations that could create transient temperature peaks are described in more detail in sections 13.2.a and 15.1.c.

Accepting that cumulative emissions determine equilibrium climate in most cases, the carbon budget theory faces three limitations in its application:

1. It is focused on equilibrium climate change, whereas the next century will be highly transient.
2. It ignores non-CO_2 pollutants (assumes they are removed from the atmosphere over long enough timescales)[118]
3. It ignores reasons decision makers might care about *delaying* near-term climate changes, for reasons outlined in section 6.3.

Thus, its use should be limited to circumstances where the goal is explicitly to *avoid* a certain climate outcome or to *avoid* a certain equilibrium temperature.

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would be different than the same amount of emissions released in a single century so that the RF steadily decayed over the ensuing centuries. The carbon budget theory implicitly assumes that emissions cease at some point in the next few centuries and that the RF a thousand years in the future is approximately the same given the same cumulative emissions, regardless of the emission path.

[117] A transient temperature peak (above equilibrium warming) may occur with extreme variations on emission paths, as discussed in section 6.2.b.ii.

[118] Exception: Meinshausen et al. include them in their model, assuming high CO_2 emissions are correlated with high non-CO_2 emissions and vice versa; see Figure 9-4

In the next few chapters, we consider a situation where carbon budgets can be applied – one in which policymakers have the goal of *avoiding* 2°C. Since there is a chance that this temperature will be exceeded by 2050 (see Table 2-6), the discussion is relevant to both the near-term and long-term. In section 9.3.a, I will show the assumptions that are made about non-CO_2 pollutants. And in Chapter 13, I will show how the framework can be used in a way that incorporates the non-CO_2 pollutants that Chapter 3 and Chapter 5 showed are so influential in the near-term horizon. I will continue to apply the carbon budget theory to the topic of avoiding a temperature increase of 3-4°C in Chapter 15.

9.2 Methods

This chapter explores the CO_2 constraints imposed by a 2°C temperature ceiling. This ceiling was noted in 2009's Copenhagen Accord, in which 100+ nations agreed to constrain global warming to 2^oC and to consider a 1.5^oC goal by 2015. [3] The 2°C goal was re-affirmed by the G8 in May 2012. [9]

Because the climate is not perfectly predictable, climate models provide a range of climate outcomes that may result from any given emission trajectory. This means that for any given emissions trajectory, there is a probabilistic chance of exceeding 2°C.

This chapter builds on the work of Meinshausen et al.'s Nature 2009 paper [170]. In that paper, the authors presented the likelihood of exceeding 2°C versus cumulative CO_2 emissions (years 2000-2049), based on the results of the MAGICC model across a wide range of published climate sensitivities.[119] This graph is reproduced in Figure 9-1 with several additions: a second x axis (CO_2 ppm in 2050) and blue blocks denoting the x axis location of several scenarios: the RCP scenarios, the SRES marker scenarios, zero CO_2 emissions (ZCE), constant emissions (CE), and constant concentration (CC).

What is shown in Figure 9-1 is technically the probability of exceeding 2°C before 2100, but Meinshausen et al. have structured their scenarios, as described below, in such a way that "[u]nder scenarios [that] will probably lead to a global surface warming below 2°C… temperatures have stabilized or peaked by 2100." [170] As shown in Figure 6-4, about half of equilibrium warming is nearly simultaneous with emissions and two-thirds (global) to three-quarters (Northern Hemisphere) of equilibrium warming is seen within 100 years. This means

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[119] The team ran the MAGICC model, a simple climate model, with 600+ parameterization combinations to reflect 19 distributions of climate sensitivity and 6 distributions of transient climate response and to reflect the range of outputs of 18 major climate models (CMIP3 and C4MIP emulation). These parameterizations were run on 900+ scenarios to produce the figure replicated in Figure 9-1. For more information on MAGICC, see Appendix H.

that the remaining third of global warming attributable to 21st century emissions will occur beyond the 100-year horizon. However, for most scenarios with a high probability of avoiding 2°C, Meinshausen et al. have structured the scenarios to have negative emissions by the 2090s and implicitly beyond (this is true for all scenarios with a 75% likelihood of avoiding 2°C and half of scenarios with a 50% likelihood). [175][120] This means that the additional warming that would have occurred is avoided by reducing the cumulative emissions.

I consider net negative emissions to be theoretically possible but technically unproven and I do not rely on them in my analysis. Instead, in section 9.3.b, I calculate the total CO_2 budget, for pre-industrial through equilibrium, for the 75% and 50% likelihood of avoiding 2°C of equilibrium warming. Then I subtract the actuals for 1800-2000 and the Meinshausen et al. emission scenarios for the 21st century and discuss the implications of the emission budget that remains for years 2100 through equilibrium. The total carbon budget is a function of equilibrium climate sensitivity (°C per W/m^2), radiative efficiency (RF per ppm), and the equilibrium airborne fraction (ratio of CO_2 airborne (ppm) to CO_2 emitted). The radiative efficiency and equilibrium airborne fraction are well-constrained. The equilibrium climate sensitivity (ECS) has a fairly wide range of uncertainty, with a best estimate of 3°C per 3.7 W/m^2 (denominator defined by the RF from a doubling of CO_2). For ECS, I use the distribution from Rogelj et al. 2012 that is derived in Figure 13-1, which has 50% likelihood of ECS below 3°C per 3.7 W/m^2 and 75% likelihood of ECS below 4.1°C. More detailed methods for the total carbon budget calculations will be discussed in detail in Chapter 15.

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[120] I examined a sample of 11 scenarios for 25% likelihood and 9 scenarios for 50% likelihood; see caption of Figure 9-4 for methods.

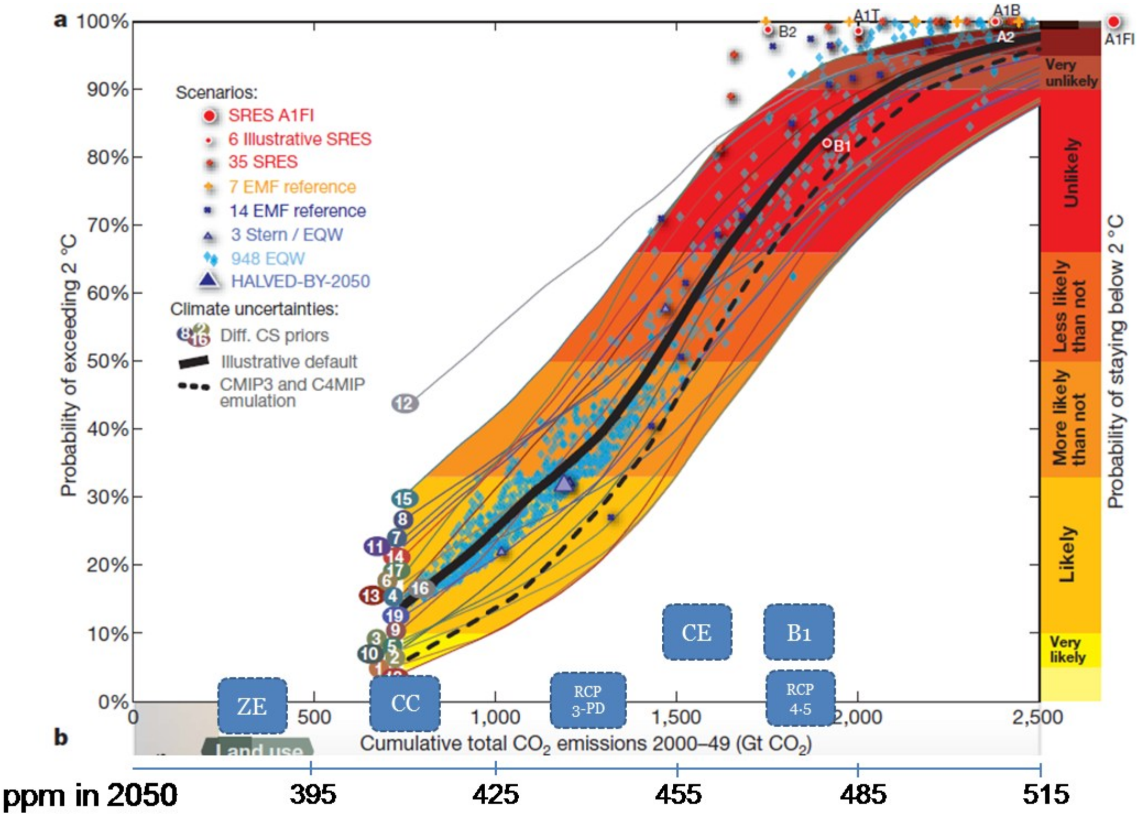

Figure 9-1: Probability of Exceeding 2°C by 2100 versus Cumulative CO_2 Emissions (2000-2049)[121]

Reprinted by permission from Macmillan Publisherrs Ltd: Meinshausen et al., Nature 2009. [170] CO_2 emissions include both fossil and non-fossil sources. Note, the "illustrative default" distribution for climate sensitivity is similar to the IPCC AR4 estimate. Assumptions for non-CO_2 pollutants and post-2050 pollutants are shown in Figure 9-4. The lower x axis (ppm in 2050) has been added, calculated as the year 1999 concentration (367 ppm) [29] + CO_2 emissions * 46% airborne fraction (see Appendix J) * 7.92 Gt airborne CO_2 per ppm.[122] The blue boxes, denoting the 2000-2049 carbon emissions of different scenarios, have also been added. RCP and SRES scenario emissions are summed directly from the RCP database [26] and SRES database (marker scenarios) [30]. The zero CO_2 emissions (ZCE) scenario assumes no CO_2 emissions after 2010. The ZCE and constant emission (CE) scenarios use actuals for 2000-2005 and averages across the RCP scenarios for 2006-2010. CE assumes emissions constant at 2010 levels through 2049. The constant concentration (CC) scenario requires CO_2 emissions to fall by 54% immediately and then to fall linearly to 80% below 2010 levels by 2050 [42, 65] (see trajectory and details in Figure 2-12).[123]

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[121] For reference, cumulative CO_2 emissions from 1800-1999 were ~1,535 Gt CO_2, per the RCP database.

[122] Calculation: 7.92 Gt airborne CO_2 per ppm = (1.8×10^{14} mol CO_2/ppm * 44.01 g/mol) / 10^{15} g/Gt.

[123] See footnote 43 for details on constant concentration scenario.

9.2.a Alternate Trajectories for a Carbon Budget

A given 2000-2049 carbon budget can result from a variety of emission trajectories with different peaking years and levels of reduction. I construct a set of 70 emission trajectories that follow RCP4.5 until their peaks in 2015, 2020, 2030, and 2040. Post-peak, their emissions decline linearly to 0%, 10%, 20%, 30%, 50%, 70%, or 90% below 1990 global emission levels (denoted R0, R10, R20, R30, R50, R70, R90; the R-scenarios) by 2020, 2030, 2040, or 2050. The base year of 1990 is used for consistency with the base year used in the Kyoto Protocol. [176] After reaching the target level, emissions plateau to 2050, with further declines thereafter that will be discussed in section 9.3.b. The linear decline is both a simple assumption and a reflection of the lack of foreseeability of the shape of the emissions curve. (Chapter 12 will present observed data with both gradual and discontinuous declines.) The curves are shown in Figure 9-2. Cumulative CO_2 is a simple summation of annual emissions.

Table 9-1 shows the translation between the R-scenarios, the corresponding percentage reduction below 1990 emission levels (the baseline used for the Kyoto Protocol [176]), and the percentage reduction below current (2008) emission levels (the most recent data available in the EDGAR 4.2 database [46]).

	CO_2 Emissions @ Plateau	
	vs. 1990	**vs. 2008**
R0	0%	-23%
R10	-10%	-30%
R20	-20%	-38%
R30	-30%	-46%
R50	-50%	-61%
R70	-70%	-77%
R90	-90%	-92%

Table 9-1: Reduction Scenarios (R0-R90): CO_2 Emission Reductions below 1990 and 2008 Emission Levels

Reductions versus 1990 are by definition; Reductions versus 2008 are calculated from EDGAR 4.2 [46].

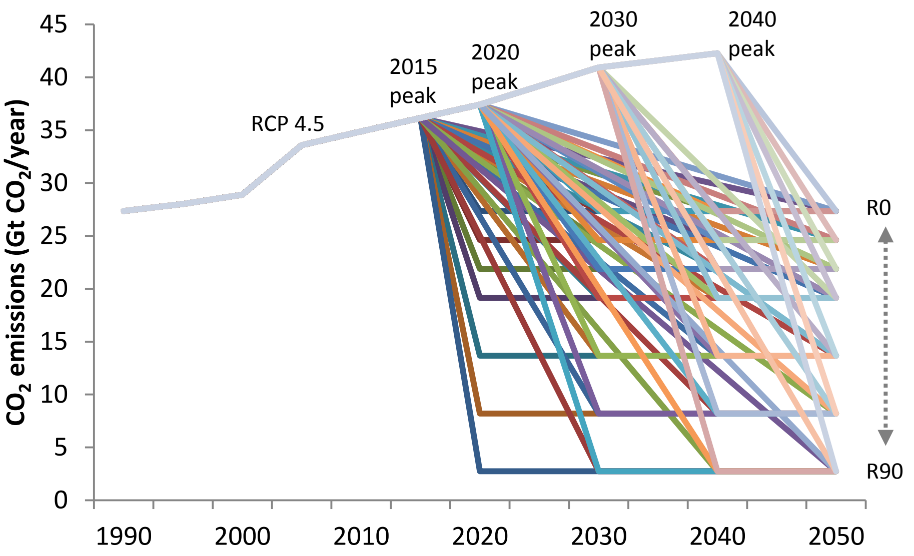

Figure 9-2: Stylized CO_2 Emission Trajectories (R-Scenarios), through 2050
All emission trajectories follow RCP4.5 (gray line) [26] until starting their linear declines.

9.3 Results and Discussion

Global, national, state, and local emission reduction targets are regularly framed as an X% (CO_2 or greenhouse gas emission) reduction (relative to 1990 or 2000 levels) by X year (e.g., the G8 target of an 80% global emissions reduction vs. 1990 by 2050 [177]). Because "emission reduction by deadline" has been the standard framework for policy for two decades, it is useful to re-frame cumulative CO_2 budgets and the results of the Meinshausen likelihood study in these terms.

Figure 9-3 shows the cumulative CO_2 resulting from the 70 emission trajectories shown in Figure 9-2. Note that the x axis of cumulative CO_2 is the same as the x axis in the Meinshausen figure (Figure 9-1). A second x axis shows the likelihood of avoiding 2°C, which decreases with higher cumulative CO_2 emissions.

A handful of conclusions emerge from this figure.

First, there is a fairly wide variety of options that have better than 50/50 odds of avoiding the 2°C temperature ceiling, ranging from R10 to R70 depending on peak and plateau year. The levers of peak year, plateau year, and emission reduction amount can be traded off to some extent to choose the most doable path.

Second, the time window for actions that produce a high likelihood of avoiding a 2°C temperature increase above pre-industrial levels is short and the likelihood falls each year in which the emission peak has not occurred. Scenarios with a likelihood of up to 90% of avoiding 2°C are still physically possible[124] within the climate system today (whether societally feasible is a different question). Within five years, scenarios with a likelihood of only up to ~80% of avoiding 2°C will be physically possible (unless peaking occurred by 2015). In the 2020s, scenarios with a likelihood of only up to ~60% will still be physically possible (unless peaking occurred by 2020). And in the 2030s, scenarios with a likelihood of only up to ~30% will still be physically possible (unless peaking occurred by 2030).

Third, there are very few options today with better than 75% likelihood of avoiding the 2°C temperature ceiling. These options would require massive, almost immediate emission reductions:

- R60 (-60% vs. 1990, -69% vs. 2008) with a 2015 peak and 2020 plateau
- R70 (-70% vs. 1990, -77% vs. 2008) with a 2015 peak and 2030 plateau
- R80 (-80% vs. 1990, -85% vs. 2008) with a 2020 peak and 2030 plateau

As shown by these options, slightly smaller reductions are required if action is more rapid.

Fourth, peaking soon (2015 or 2020) produces a higher likelihood of avoiding 2°C than peaking later (2030 or 2040), across a wide range of reduction levels. E.g., a reduction of R10 by 2020 with a 2015 peak produces lower cumulative 2000-2049 CO_2 emissions and provides a higher likelihood of avoiding 2°C than a reduction of R90 by 2050 with a 2030 peak (see purple and brown dashed hexagons in Figure 9-3). The difference between peaking early (2015) or late (2040) for a given reduction level and plateau year is 10-40 percentage points.

Fifth, for a given peak year and target plateau year, the range of cumulative emissions is fairly narrow, and becomes increasingly so for later peaks. E.g., the range of cumulative emissions for a 2015 peak with 2050 plateau is 430 Gt CO_2 (1,185-1,615 Gt) and the range for a 2040 peak with 2050 plateau is 120 Gt CO_2 (1,725-1,845 Gt).

The key levers for policymakers are thus the peak year and the target/plateau year, even more than the target % reduction level.

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[124] A physically possible scenario is one that can be achieved within the constraints of the laws of physics and chemistry. In other words, there are no physical limits within the climate system that would prevent its occurrence (though there may be technological, societal, or other limits).

Sixth, the smallest arithmetically-possible emission reduction that still avoids 2°C with 50/50 odds is R10 (10% emission reduction vs. 1990; 30% reduction vs. 2008) with a 2015 peak and 2020 plateau (see dashed purple hexagon). Flat versus 1990 (R0) or versus 2008 is not an option for preserving 50/50 odds.

The option for trading off speed of reductions with the magnitude of reductions is a potentially powerful one, and deserves further exploration. From Figure 9-3, it appears that a quick modest reduction such as R30 done quickly (peak in 2015, plateau by 2030) (see solid brown hexagon) is the better option by 10-15 percentage points of likelihood than a massive reduction (R90) delayed and done slowly (peak in 2030, plateau in 2050) (see dashed brown hexagon). In section 9.3.b, we will see that this conclusion is contingent on emissions in the second half of the century.

Seventh, climate sensitivity (temperature response per unit of radiative forcing) matters significantly for the likelihood calculations, as reflected in the likelihood error bars at the bottom of Figure 9-3. If we consider 50/50 odds, then if climate sensitivity is at the low extreme (right end of error bar), the 50/50 line would sit around 1700 Gt CO_2, and a wide range of scenarios that peak in the 2030s (even R0) could still achieve 50/50 odds. Vice versa, if climate sensitivity is at the high extreme (left end of error bar), the 50/50 line would sit around 1150 Gt CO_2, and only a few scenarios that peak in 2015 or 2020 and have high reductions (R50-R90) could achieve 50/50 odds. The vertical lines reflect the current best estimates (the solid line in Figure 9-1), and the discussion in the following sections and chapters refers to the best estimates unless otherwise noted.

So far, we have been examining the *CO_2* budget for only the *first half* of the 21st century, consistent with the presentation of the Meinshausen results. However, the climate outcome is a function of multiple pollutants and of assumptions for the second half of the century and beyond. The next two sections explore these additional assumptions and their impact on the above conclusions.

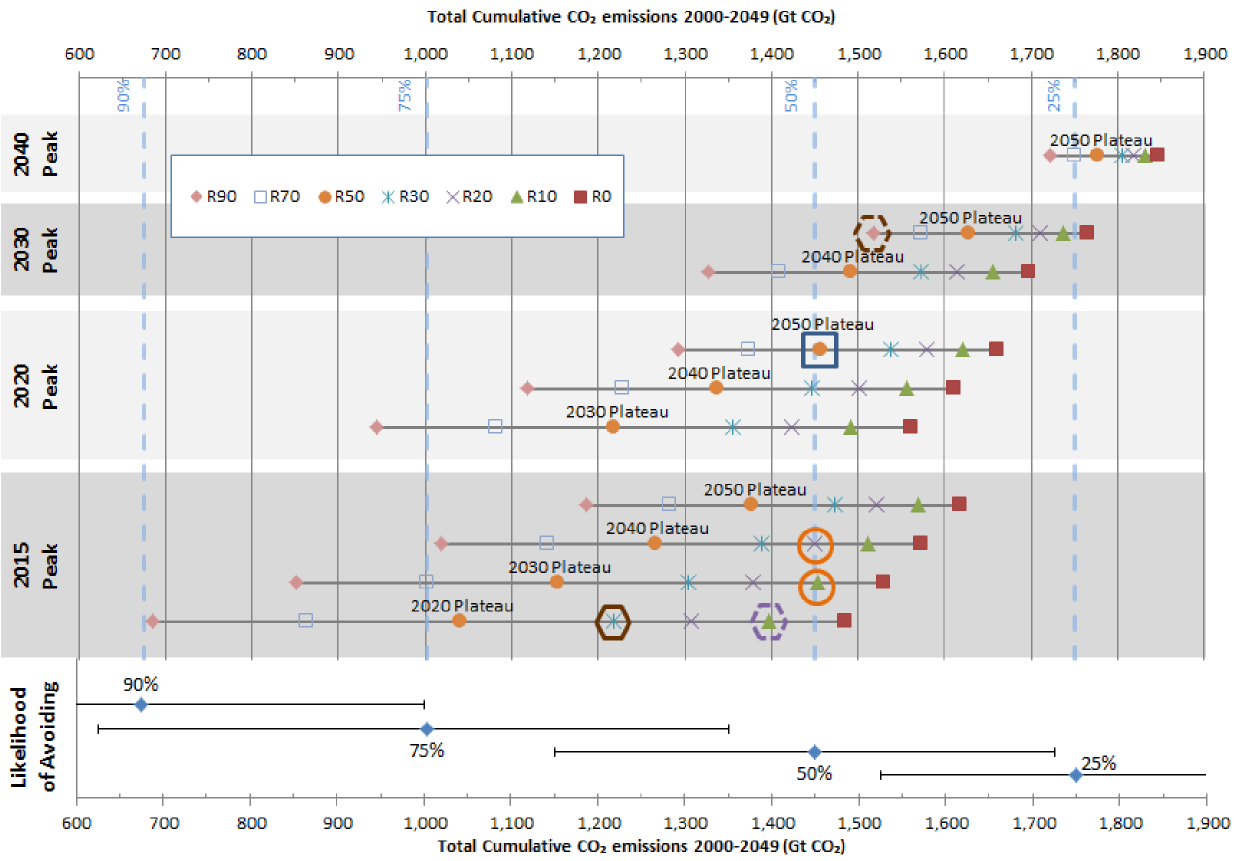

Figure 9-3: Mapping Emission Trajectories to Cumulative CO_2 Budgets
R0, R10, R20, R30, R50, R70, R90: "R" stands for "reduction"; number is % reduction relative to 1990; Vertical lines represent 25%, 50%, 75% and 90% likelihood of avoiding a global temperature increase of 2°C above pre-industrial levels; Blue square indicates G8 target [9]; Brown and purple hexagons indicate scenarios discussed in section 9.3; Orange circles indicate scenarios discussed in section 10.1. Cumulative CO_2 emissions from each scenario are calculated based on 2000-2005 actuals from the RCP database [29], RCP4.5 until the peak of each scenario (RCP4.5 from [26]), linear emission reductions from peak year to plateau year, and flat emissions ("plateau") from plateau year until 2049. Note that a higher emission trajectory (RCP8.5) to the peak (shown in Appendix H) would increase the cumulative 2000-2049 emissions by 57-94 Gt CO_2 for the orange circles and 176 Gt CO_2 for the blue square – taking both to worse than 50/50 odds. The likelihood of avoiding 2°C is visually interpolated from Figure 9-1 [170]. Likelihood assumes further reductions in 2050-2100 (see Figure 9-4). The vertical likelihood lines reflect the "illustrative default" in the Meinshausen study [170], which closely reflects the best estimate climate sensitivity in AR4. The likelihood range for the full range of climate sensitivity reflected in Figure 9-1 and a range of assumptions about non-CO_2 emissions and CO_2 emissions in the second half of the 21st century (see Figure 9-4) is shown in the bottom portion of the figure above. The likelihood estimates in general assume that aggressiveness of mitigation of CO_2 in the second half-century and of non-CO_2 pollutants in the full century correlates with aggressiveness of first half-century carbon budgets. (see Figure 9-4).

9.3.a Non-CO_2 Pollutants

In section 4.4.b, we saw that the difference between CO_2 mitigation with and without near-maximum technically feasible mitigation of short- and medium-lived pollutants may be up to 0.5°C (0.2-0.8°C) in this century. In a discussion of avoiding 2°C, 0.5°C is a material amount of temperature change. Thus, we now turn to the assumptions about short- and medium-lived pollutants that are embedded in Meinshausen et al. 2009 [170].

Figure 9-4 shows the first half-century (2000-2049) and second half-century (2050-2099) CH_4 and SO_2 emission assumptions that are assumed to accompany low, medium, and high levels of first-half CO_2 emissions in Figure 9-1 [170, 175]. As shown in Chapter 4, mitigation at the maximum feasible levels of these pollutants would produce material changes in radiative forcing (Figure 4-11).[125]

Several patterns stand out. First, there is a narrow range of emission assumptions for a given non-CO_2 pollutant within each CO_2 budget level (i.e., the bars are small). Second, the propensity for reductions is correlated across pollutants – i.e., aggressive CO_2 mitigation correlates with aggressive CH_4 and SO_2 mitigation, and vice versa. The same pattern holds for the RCP scenarios (see Figure G-2 and Figure G-3). Third, the general propensity for reductions in the first half-century (aggressive or not-so-aggressive) is assumed to be similar to the propensity for reductions in the second half-century.

If we compare the CH_4 and SO_2 assumptions in Figure 9-4 with the maximum technically feasible reductions (MTFRs) shown in Figure 4-10 for today's technology (15-45% for CH_4 and 70-80% for SO_2), we see that the most aggressive scenario ("L") assumes minimal CH_4 reductions in the first half-century and achievement of MTFR (on average) in the second half-century.[126] The same scenario assumes about half of the MTFR for SO_2 in the first half-century (on average) and reductions in excess of MTFR for SO_2 in the second half-century.

In Chapter 13, I will return to the role that non-CO_2 pollutants can play in improving the likelihood of staying below 2°C and the value of decoupling them from assumptions about CO_2 mitigation. In that chapter, I find that reductions of short- and medium-lived pollutants can improve the likelihood of avoiding 2°C of transient warming by a maximum of 8-11 percentage points.

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[125] Black carbon would also produce a comparable change in radiative forcing, at its central RF estimate, but black carbon was not included in the Meinshausen dataset used to produce Figure 9-4.

[126] Figure 9-4 shows the average emissions over each time period. From 2050-2099, the average CH_4 emissions fall within the MTFR range. Some emission trajectories that are consistent with the CH_4 emissions shown for 2050-2099 include CH_4 emissions in 2099 that exceed MTFR.

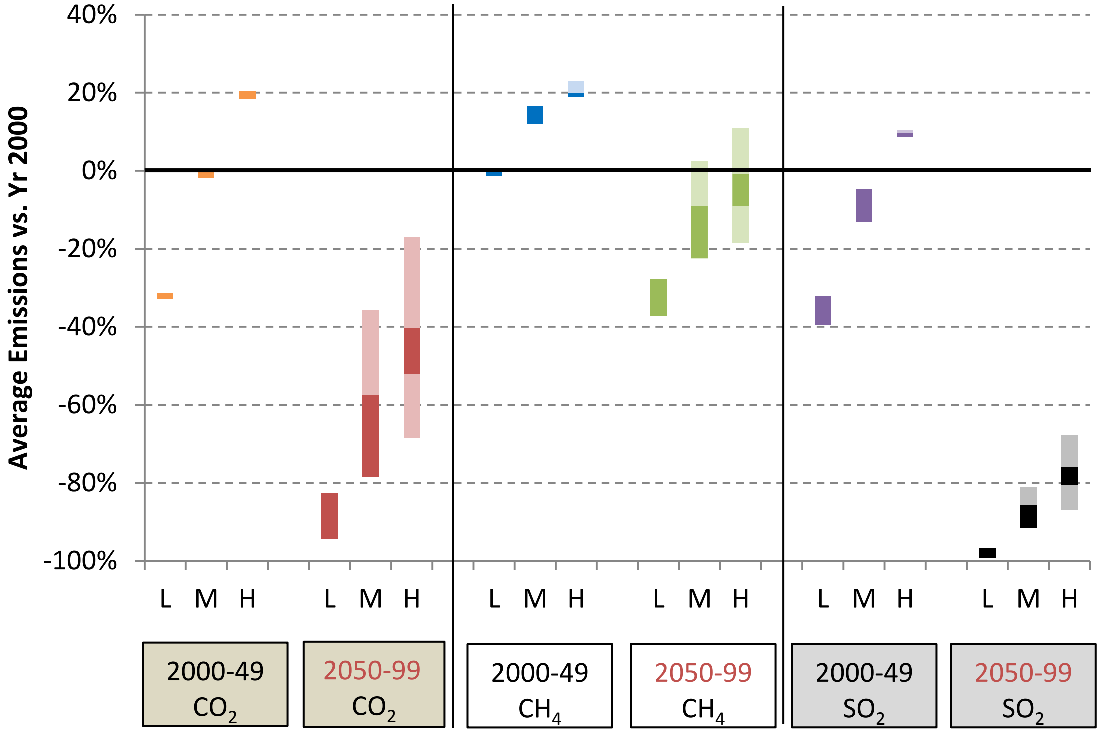

Figure 9-4: Emissions relative to Year 2000 for Low, Med, and High Scenarios in Meinshausen et al. 2009 [26]

(L=1000 Gt CO_2, M =1450 Gt, H=1750 Gt emitted in 2000-2049)

I have designated the Low (L), Medium (M), and High (H) scenario groups to correspond to 1000 Gt CO_2, 1450 Gt CO_2, and 1750 Gt cumulative CO_2 emitted in the first half of the 21^{st} century. These emission levels, on average, correspond with 75%, 50%, and 25% likelihoods of avoiding a global temperature increase of 2°C above pre-industrial levels, as shown in Figure 9-1 and Figure 9-3. Emissions for each pollutant for each scenario group (L, M, H) were extracted from the data used to produce Meinshausen et al. 2009 [170, 175]. The closest scenarios to 1000 Gt, 1450 Gt, and 1750 Gt CO_2 emissions for 2000-2049 were selected: 11 scenarios with 998-1002 Gt CO_2 emissions from 2000-2049, 12 scenarios with 1435-1465 Gt CO_2 emissions during that period, and 8 scenarios with 1730-1770 Gt CO_2 emissions during that period. For each scenario, the emission reduction percentage for each pollutant for each time period was calculated by taking the average emissions over the given time period compared to year 2000 emissions in EDGAR 4.2 [46]. The range of reductions within each scenario group (L, M, H) for each pollutant for each time period is shown in the graph (e.g., for the Low group, the bar shows a range across 11 scenarios). Note that in all cases, the reduction at the end of the time period (not shown) is greater than the *average* reduction over the time period (shown). For the Low group, all scenarios assume negative CO_2 emissions in 2100 (reductions greater than 100%); for the Medium group, 4 of the scenarios make this assumption. Some bars include sections that are lightly shaded; these correspond to scenarios that fell outside 5 percentage points of the likelihood associated with the scenario group (e.g., lightly shaded scenarios for High (H) have a likelihood less than 20% or more than 30% of avoiding 2°C; darkly shaded scenarios are within 5 percentage points of 25%.) All scenarios in the Low (L) scenario group fall within 5 percentage points and are fully shaded.

9.3.b CO_2 Emissions in the Second Half of the 21st Century

So far we have discussed CO_2 emissions in the first half of the century and non-CO_2 emissions throughout the century. Now we turn to the CO_2 emission quantity in the second half of the century.

First, we observe from Figure 9-4 that more aggressive first-half CO_2 emission reductions are correlated with more aggressive second-half CO_2 reductions in the Meinshausen model. Low (1000 Gt) emission paths in the first half assume 85-95% average emissions reductions relative to 1990 in the second half century (88-96% reductions vs. 2008) and Medium (1450 Gt) emission paths in the first half century assume 35-80% average reductions relative to 1990 in the second half century (50-85% reductions vs. 2008).

As with non-CO_2 emission assumptions, making different assumptions about second-half CO_2 emissions could significantly change the likelihood of avoiding 2°C, shifting the vertical likelihood lines and horizontal likelihood bars in Figure 9-3 to the left or right. [127]

Second, we observe that average reductions of ~60% or more below 1990 levels (70% below 2008) are required in the second half-century to achieve better than 50/50 odds after following a Medium path (1450 Gt CO_2) in the first half-century (see dark shaded bar, 2nd from left in Figure 9-4). Average reductions of 85% of more below 1990 levels (90% below 2008) after following a Low path (1000 Gt CO_2) in the first half-century would provide a 75% likelihood of avoiding 2°C (leftmost bar in Figure 9-4).

If we look at Figure 9-3, there are many first-half scenarios (R10-R50) that meet the Low (L) and Medium (M) cumulative carbon limits and involve less than 60% reductions in the first half-century. For these scenarios, reaching 60% or higher reductions will require continued reductions in the second half-century (as opposed to stabilized emissions) in order to stay below 2°C.

Third, a given level of average emissions over the second half of the 21st century offers a variety of options for emission trajectories. E.g., a 60% average emission reduction (relative to year 1990) can be produced by a linear path from 30% reduction in 2050 to 90% reduction in 2099. Or, it can be produced by constant emissions from 2050-2099 at a level 60% below 1990. Similar to the findings for the first half of the century (section 9.3), earlier reductions in the

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[127] The case of negative *average* CO_2 emissions in the second half-century (sinks in excess of emissions) is an extreme example that would shift the likelihood lines and bars in Figure 9-3 to the right.

second half century enable less aggressive targets for 2099 than later reductions while satisfying the same 21st century carbon budget.[128]

Beyond the 21st century, there is a finite carbon budget from now through equilibrium that corresponds to each temperature limit and its corresponding stabilized atmospheric concentration of CO_2 (see Figure 9-5). This budget is finite because after the atmosphere and ocean equilibrate, a fixed fraction of emissions (the equilibrium airborne fraction) stays airborne for millennia awaiting chemical weathering. [68] Beyond equilibrium, emissions must approach near-zero, since a fraction of a percent of today's emissions would offset the millennial weathering.

In the context of a goal to permanently avoid a temperature increase of 2°C above pre-industrial levels, the question for both the 21st and 22nd centuries is how to spread the remaining finite budget over time. Again, there are advantages to an early peak, since more budget is then available for future years. Figure 9-5 shows the CO_2 budgets just discussed for the 21st century in context with past emissions and future emissions under the total CO_2 budgets that avoid 2°C with 50% and 75% likelihood. Depending on emissions in 2050-2099, the remaining budget is sufficient to support annual emissions in year 2100 and beyond at a level equivalent to 6% of year 2000 emissions (94% reduction) with 50% likelihood of avoiding 2°C and 3% of year 2000 emissions (97% reduction) with 75% likelihood of avoiding 2°C. With various assumptions about time to equilibrium, non-CO_2 pollutants, and 21st century emissions (as described in the Figure 9-5 caption), the annual emission budget for years 2100-2500 could range from 1-9% and 2-16% of year 2000 emissions (84-99% reductions), for 75% and 50% likelihood respectively. This is consistent with findings by other authors that CO_2 emissions must be reduced by 80-100%. [29, 42, 66, 178].[129]

The next section turns again to the 21st century and talks further about the trade-offs that are possible between the timing and magnitude of emission reductions in the first and second halves of the century.

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[128] Note, the Meinshausen et al. 2009 study assumes that Low and Medium scenarios take a steady emission reduction path and reach emission reductions of 95% to over 100% by 2099.

[129] The RCP database assumes -91% for RCP 4.5, -89% for RCP 6.0, and -80% for RCP 8.5 for 2500 CO_2 emissions relative to 1990 levels.

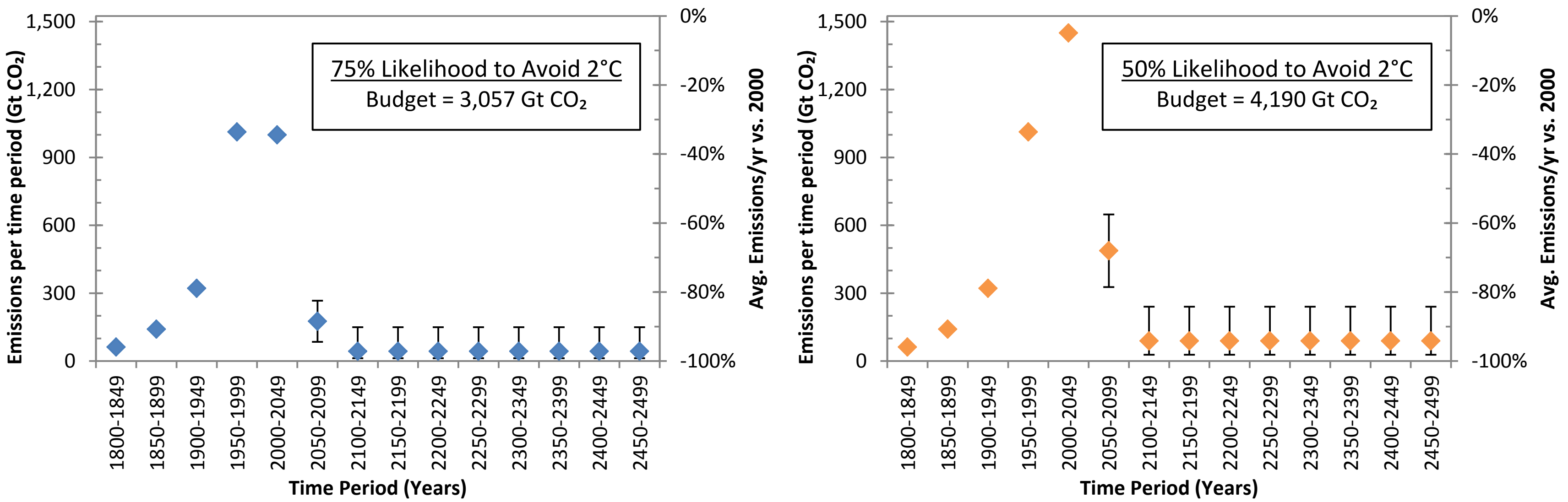

Figure 9-5: Time Course of Emissions corresponding to a Total CO_2 Budget (yrs 1800-2500) for 75% and 50% Likelihood of Avoiding 2°C

This chart summarizes the total CO_2 budget, from year 1800 through equilibrium, that would result in 75% and 50% likelihoods of avoiding 2°C of equilibrium warming (the warming would be avoided at all points in time). This total quantity is finite, with the main decision being the allocation of emissions over time. Actual emissions from the RCP database are shown for 1800-1999. [26, 29] Emissions for 2000-2049 are those presented by Meinshausen et al. [170] as the best estimate of those that would provide 75% and 50% likelihood of avoiding 2°C. Emissions for 2050-2099 are also from Meinshausen et al. and correspond to those shown in Figure 9-4. Emissions after 2100 are the total budget minus emissions from 1800-2100, and are assumed to be the same in each 50-year time period. The main estimate assumes 400 years from 2100 to equilibrium and average emissions for 2050-2099. The error bars reflect the possibility that it may take longer to reach equilibrium (1000 years), the possibility the non-CO_2 emissions may account for 0-20% of radiative forcing at equilibrium, and the upper and range of emissions for 2050-2099. The total CO_2 budget is calculated based on an equilibrium climate sensitivity of 4.1°C and 3°C for 75% and 50% likelihood of avoiding 2°C (see Figure 13-1). The value shown (4,190 Gt CO_2 for 50% likelihood and 3,057 Gt CO_2 for 75% likelihood) assumes that non-CO_2 emissions account for 20% of radiative forcing at equilibrium (approximately the assumption for the RCP scenarios in year 2500). If this percentage were zero, the CO_2 budget would be larger. Zero non-CO_2 RF is reflected by the upper end of the error bar for years 2100 and beyond. Historical CO_2 emissions include ~525 Gt CO_2 emissions from non-fossil sources from 1800-1999 [29], primarily from anthropogenic forest fire [46]. An unquantified fraction of these emissions will be captured by re-vegetation of the land over many hundreds of years. If a fraction of these emissions were not counted toward the equilibrium budget, it would slightly increase the budget available in future centuries, but the change in the dots on the graph would be barely visible: (525 Gt CO_2 / 400 years) * 50 year increment = 65 Gt CO_2. The secondary y axis shows the average annual CO_2 emissions in each 50 year period relative to the CO_2 emissions in year 2000 from the EDGAR database. [46]

9.3.c Comparing a Quick R30 Scenario with a Slow R90 Scenario

Earlier in this section, I showed that peaking quickly was a more powerful lever for improving the likelihood of avoiding 2°C than the magnitude of near-term emission reduction. In this section, I examine that observation in more detail, with the case of a quick peak followed by 30% (R30) reduction (46% reduction vs. 2008) versus a slow peak followed by a 90% (R90) reduction (92% vs. 2008) in the first half-century.[130] Taking these two first-half-century scenarios, I examine the role of second-half CO_2 emissions.

The atmospheric concentration at 2050 is lower for a quick peak R30 versus a slow peak R90 by up to 500 Gt CO_2 (cumulative, 2000-2049), as shown in Table 9-2. But, sustaining a 30% reduction would clearly involve much higher second-half emissions than sustaining a 90% reduction. From the right column of Table 9-3, we can see that R90 would emit 820 Gt CO_2 less than R30 in the second half of the century (orange cells). For the full century, slow peak sustained R90 would be better than quick peak sustained R30 by 315-840 Gt CO_2.

In order for the slow peak R30 to maintain its first-half advantage or break even, R30 in the first half-century must be followed in the second half-century by a 55-90% *average* reduction relative to 1990 (65-92% reduction vs. 2008) to be comparable to a slow peak R90 in the likelihood of avoiding 2°C. Note that the range (55-90%) reflects differences in first-half timing. The low end reflects the earliest peak (2015) and earliest 30% plateau (2020) compared with the latest peak (2040) before a 90% plateau (2050); the high end reflects a later peak (2020) and late 30% plateau (2050) compared with an earlier peak (2030) before a 90% plateau (2050). This example re-emphasizes the benefits seen in section 9.3 and section 9.3.b of peaking early and plateauing early, enabling the same carbon budget for the 21st century to be achieved with a smaller emission reduction target.

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[130] Obviously, quick peak R90 would produce better climate outcomes than quick peak R30 (same peak with a smaller reduction) and better outcomes than slow peak R90 (same reduction with a later peak).

Difference in Cumulative CO_2 Emissions between R90 and R30 (Gt CO2, 2000-2049)

	90% reduction with 2050 plateau			
30% reduction (2020-2050 plateau)	**Peak 2015:** 1,186 Gt CO_2	**Peak 2020:** 1,292 Gt CO_2	**Peak 2030:** 1,518 Gt CO_2	**Peak 2040:** 1,723 Gt CO_2
Peak 2015: 1,218-1,473 Gt CO_2		(181) - 74	45 - 300	249 - 505
Peak 2020: 1,355-1,538 Gt CO_2			(20) - 163	184 - 367
Peak 2030: 1,573-1,682 Gt CO_2				40 - 149
Peak 2040: 1,805 Gt CO_2				

Table 9-2: Advantage of an Early R30 Trajectory Relative to a Late R90 Trajectory (Gt CO_2, 2000-2049)
Cumulative CO_2 emissions (2000-2049) are calculated by the same method as Figure 9-3. Differences between R90 and R30 are calculated by simple subtractions. Gray boxes indicate comparisons in which R90 has lower cumulative CO_2 emissions than R30. R90 is assumed to reach the 90% reduction level in 2050. The boxes outlined in bold compare a quick peak R30 trajectory with a late peak R90 trajectory.

Average emissions vs. 1990, 2050-2099	**Avg. emissions/ year, 2050-2099 (Gt CO_2)**	**Cumulative CO_2 emissions, 2050-2099 (Gt CO_2)**	**Add'l cumulative CO_2, relative to -90% (Gt CO_2)**
-30%	19.1	957	820
-40%	16.4	820	684
-50%	13.7	684	547
-55%	12.3	615	479
-60%	10.9	547	410
-70%	8.2	410	273
-80%	5.5	273	137
-90%	2.7	137	-

Table 9-3: Cumulative CO_2 Emissions, 2050-2099, for Different Reduction Levels
Emission reductions are calculated versus 1990 CO_2 emissions from the RCP database [29]. Cumulative emissions multiply average annual emissions by 50 years. Orange cells indicate the emissions that would result if R30 or R90 were sustained through the second half of the 21st century. Green cells indicate reduction levels in the second half century that would maintain the advantage calculated in Table 9-2 for "early R30" versus "late R90" (i.e., the difference in cumulative emissions above -90% in the second half century (rightmost column) in the green cells is smaller than the difference in cumulative emissions in Table 9-2 for the first half century).

9.4 Summary and Comparison to Pledges

In summary, avoiding a global temperature increase of 2°C involves a finite budget from now through equilibrium (~500 years) (Figure 9-5), per the carbon budget theory. Significant emission reductions are required in the next several decades in order to have any budget remaining for the rest of the time period. Mitigation requirements become more stringent if better than 50/50 odds are desired or if the goal is to avoid an increase of 1.5°C rather than 2°C.[131]

Peaking early (2015 or 2020) improves the likelihood of avoiding 2°C by 10-40 percentage points relative to peaking later (2030 or 2040), for a given reduction level and plateau year. An rapid 30% emission reduction now, paired with emissions in the second-half century averaging 60-85% below 1990 levels, can produce better than 50/50 odds of avoiding 2°C and a higher likelihood of avoiding 2°C than a later 90% reduction.

In both half-centuries, the more rapid the reductions are, the less aggressive the magnitude of the reduction targets needs to be to satisfy the same half-century carbon budget. In the case of less aggressive targets, additional reductions would need to follow in the early 22nd century to bring total emission reductions to 80-100% to stabilize the CO_2 concentration and avoid further temperature increases. However, while peaking early expands emission reduction options, policies are not currently in place for global peaking to occur until the late 2040s at best (Figure 9-6).

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[131] An assumption of major future advances in CO_2 removal technology that would enable negative emissions in the future would ease near-term mitigation requirements somewhat.

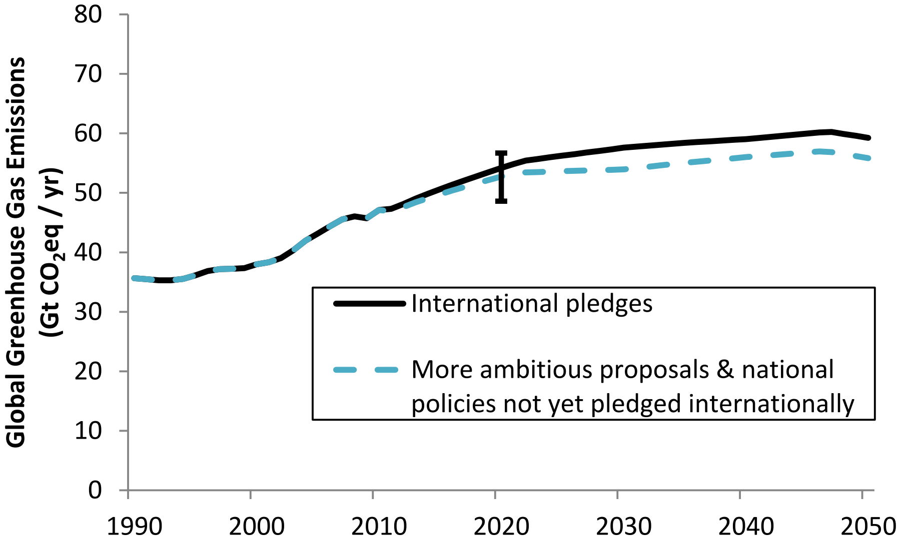

Figure 9-6: Global Emissions Trajectory Based on Pledges To-Date

Emission estimates for the pledges were made by Climate Action Tracker (CAT) [35] and include the six Kyoto gases, in CO_2-equivalent based on GWP100 from the IPCC's Second Assessment Report. Black error bar shows the range of emissions for 2020 estimated by ten modeling groups under the international pledges, with lower emission estimates under strict accounting rules and higher emission estimates under lenient account rules. The width of the range also reflects different interpretations of pledges by different modeling groups. [44] CAT estimates, which assume lenient accounting rules and sit in the upper half of estimates, are shown here because they are available through 2050.

Chapter 10 Implications for Developing Nations

This chapter and the next one translate the somewhat abstract global targets of Chapter 9 into specific requirements for developed nations, developing nations, and the natural gas industry, in a way that is intended to provide a vivid, intuitive description of the mitigation implications of Box 2 (avoiding 1.5°C or 2°C). Box 2 is indeed the most challenging of all boxes, and all players discussed in these chapters would have a tough mitigation path to follow to produce emissions aligned with the goals of Box 2.

Chapter 9 established the importance for Box 2 of peaking early and presented a range of CO_2 emission path options. Figure 9-3 showed that the least aggressive global CO_2 emission reductions with 50/50 odds of staying below 2°C would require a 2015 peak followed by a reduction of 30% below 2008 levels (10% below 1990 levels; R10) by 2030 and additional reductions in the second half of the century. Higher reductions would be required for slower peaking timelines.

In this chapter, I explore the implications of these global targets for Annex I nations and developing (non-Annex I) nations – specifically addressing the question of how much, if any, the developing nations can grow their emissions and still keep the planet under the 2°C temperature ceiling. I then consider the energy infrastructure requirements, the timing mismatch between demand growth and build-out of non-CO_2-emitting infrastructure, and the implications for offsets.

The analysis in this chapter focuses entirely on CO_2, assuming that non-CO_2 emissions follow roughly the medium (“M”) trajectory presented in Figure 9-4, which corresponds to 50/50 odds of avoiding 2°C. Variations in non-CO_2 emissions are considered in Chapter 13.

10.1 Annex-I and Developing Nations

Reduction of emissions poses a host of financial and technical challenges in the developing world. The incremental cost of mitigating climate change has been estimated to be 2-3% of global GDP [179] and $140-175 billion/year in developing countries[132] [180], due to the typically higher cost (excluding externalities) of non-polluting infrastructure vis-à-vis conventional polluting infrastructure. Additionally, introduction of new technologies at scale requires a workforce equipped with the skills needed to implement the roll-out and requires attention to the climate challenge in the midst of other inter-related development challenges such as clean

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[132] These figures are estimated for 2030 and are net of the savings from lower operating costs of new technology.

water, sanitation, and food security. At the same time, the benefits of mitigation are high since climate change impacts are expected to be the greatest in developing nations [10, 39, 162] and the process of development offers the opportunity to build non-polluting infrastructure first, leapfrogging conventional technologies.

In recognition of the disparity of financial capacity and technical capacity among nations, as well as the disparity in vulnerability to the impacts of climate change and the disparity in the historical responsibility for emissions [181, 182], international climate agreements treat developing and developed nations differently. The 1992 UN Framework Convention on Climate Change (UNFCCC) [2] included the following language in Article 3: "The Parties should protect the climate system … on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof." Developing countries were identified as "non-Annex I" countries and developed countries and economies in transition were identified as "Annex I" countries.

In this section, I will explore the extent to which it is arithmetically possible for the CO_2 emission reductions identified in section 9.3 (consistent with 50/50 odds of avoiding 2°C) to be shouldered by Annex I nations and the implications for developing countries (non-Annex I).

Annex I emissions, combined with international aviation and shipping, represented only 43% of global CO_2 emissions in 2008 (see Figure 10-1). This sets an upper limit of 43% on global emission reductions if developing nations held emissions flat and Annex I nations reduced emissions by 100%.[133] In other words, any global emission reduction target greater than 43% arithmetically requires emission reductions in developing nations. As shown in Figure 9-3, there is a limited range of options remaining with global reductions under 43% (vs. 2008; 26% vs. 1990) that still maintain 50/50 odds of staying below 2°C. These options are indicated by orange circles in Figure 9-3 and denoted as Avoiding Absolute Reduction in the Developing World (AAR) trajectories:

- **AAR 1**: 2015 peak with -30% vs. 2008 by 2030 (-10% vs. 1990; R10)
- **AAR 2**: 2015 peak with -38% vs. 2008 by 2040 (-20% vs. 1990; R20)

Both of these options would still require absolute reductions below 2008 levels in both the developing world and the developed world in the second half of the 21st century to further reduce global CO_2 emissions on average by at least 70% (vs. 2008; 60% vs. 1990) to maintain 50/50 odds of avoiding 2°C, as discussed in section 9.3.b.

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[133] International aviation and shipping accounted for 3% of global CO_2 emissions in 2008. Throughout this chapter, I assume that any reductions applied to Annex I nations are also applied to international aviation and shipping.

The 2030 or 2040 deadline for emission reduction required by AAR1 and AAR2 is sooner than typically discussed. The current G8 target (blue square in Figure 9-3) achieves 50/50 odds with a later emission reduction deadline of 2050. [177][134] But, its 50% global reduction target would require absolute emission reductions in developing nations of -48% versus 2008 (assuming 80% reductions in Annex I) (see R50 row in Table 10-1). In this chapter, I work from the assumption that avoiding absolute reduction requirements in the developing world is a more politically palatable goal – if this is true, the earlier reduction deadlines of 2030 or 2040 (combined with a 2015 peak) would be required to avoid 2°C with 50/50 odds.

Table 10-1 shows the combinations of Annex I emissions and developing country emissions that would achieve AAR1 and AAR2 (see rows for R10 and R20). We see that even if Annex I nations were to eliminate 100% of their emissions, non-Annex I countries could only grow their emissions by 9-23% relative to 2008 levels. If Annex I nations reduce their emissions by 80% (the G8 target), developing nations would need to hold their emissions roughly flat (7% growth to achieve R10, 7% *reductions* to achieve R20).

For the rest of the chapter, calculations will assume the AAR1 path, with 80% reductions in Annex I by 2030[135] and developing world emissions in 2030 equal to 2008. This means that even with the most aggressive possible mitigation by developed and transitional nations, developing nations have virtually no room to grow emissions in the first half of the century while maintaining 50/50 odds of staying below 2°C. Because these requirements are so stringent, there is little room for a given nation to negotiate to do less, because it would be extremely difficult for any other nation to do more in exchange, although financial negotiations remain possible.

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[134] The "G8 target" refers to the 2009 G8 endorsement of greenhouse gas (GHG) emission reductions of at least 50% globally and at least 80% in developed nations by 2050. The G8 did not specify whether the 50% reduction was versus 1990 or 2008. They did specify that the 80% reduction in developed nations is versus "1990 or more recent years". For the rest of the chapter, I will assume that both G8 reductions are versus 1990.

[135] Developed nation emissions were fairly flat from 1990-2008, so an 80% reduction versus 1990 is equivalent to a 79% reduction versus 2008 (see Table 10-1). For the rest of the chapter, I will not specify that year of comparison for developed nation emissions.

			Annex I 2050 emissions								
			vs. 1990	-33%	-42%	-52%	-62%	-71%	-80%	-90%	-100%
Name	Global CO_2 Reduction Target (vs. 1990)	Global CO_2 Reduction Target (vs. 2008)	vs. 2008	-30%	-40%	-50%	-60%	-70%	-79%	-90%	-100%
R0	0%	-23%		-17%	-10%	-2%	6%	13%	20%	29%	36%
R10	-10%	-30%		-31%	-23%	-16%	-8%	0%	7%	15%	23%
R20	-20%	-38%		-44%	-37%	-29%	-22%	-14%	-7%	1%	9%
R30	-30%	-46%		-58%	-50%	-43%	-35%	-28%	-21%	-12%	-5%
R50	-50%	-61%		-85%	-78%	-70%	-62%	-55%	-48%	-40%	-32%
R60	-60%	-69%		-99%	-91%	-84%	-76%	-68%	-61%	-53%	-46%
R70	-70%	-77%		-106%	-98%	-90%	-83%	-75%	-68%	-60%	-52%
R90	-90%	-92%		-126%	-119%	-111%	-103%	-96%	-89%	-80%	-73%

Table 10-1: Developing Country (non-Annex I) CO_2 Emissions relative to 2008 Emissions, as a function of Global Reduction Targets and Annex I Reductions

CO_2 emissions data (1990 and 2008) are from the EDGAR 4.2 database [46]. Calculations are made arithmetically. Emissions from international aviation and shipping (not shown; 3% of 2008 emissions) are assumed to be reduced by the same percentage as Annex I emissions. Pink cells indicate absolute emission reductions relative to 2008 emissions; gray cells indicate impossible combinations (reductions > 100%). Yellow cells and bold outlines highlight examples discussed in the text.

10.2 Implications for Energy Technologies in Developing World

The magnitude of the infrastructure challenge to maintain flat CO_2 emissions in the developing world should not be underestimated. Figure 10-1 provides a history of emissions, aggregated for Annex I and Non-Annex I nations. Since 1990, developing nation emissions have increased by 70% while Annex I nations have been roughly flat (down 4%). As we will see in Chapter 12 , the required magnitude and speed of reduction in emissions over the next few decades is unprecedented, in both Annex I and non-Annex I and even in individual countries and sectors. Global emissions have continued to grow since the last available nation-level data (2008), so the challenge is likely to look even more difficult once nation-level data on 2012 emissions become available.[136]

Non-Annex I nations are by definition in the process of development, which means that their need for energy will continue to grow.[137] [183] Holding CO_2 emissions in these nations flat to 2008 would imply satisfying all of that growth with non-emitting energy infrastructure. The International Energy Agency (IEA) [33] projects that non-OECD nations[138] will have growth in

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[136] Year 2008 nation-level data are the most recent available in EDGAR. From Figure 2-6 and Figure 2-7, we can see that global emissions continued to rise through 2010 from aggregate data published by the Global Carbon Project.

[137] As noted by Martinez and Ebenhack 2008, the human development index (HDI) is closely correlated with per-capita energy consumption for energy-poor nations; small increases in per-capita energy are correlated with large increases in HDI. In places where HDI is high, additional per-capita energy is not correlated with HDI changes.

[138] There are 41 Annex I nations (plus the European Union) and 34 OECD nations, with 30 overlapping nations. All OECD nations are part of Annex I except Chile, Israel, Korea, and Mexico. Eleven nations are part of Annex I but not part of OECD: Belarus, Bulgaria, Croatia, Latvia, Liechtenstein, Lithuania, Malta, Monaco, Romania, Russian

total primary energy demand of 54% between 2009-2030, an addition that exceeds (by 1.5 times) the whole world's current energy use from non-fossil fuel (non-FF) sources (see Figure 10-2 for additional comparisons).

In order to avoid a global increase of 2°C above pre-industrial levels, a sustained and unprecedented level of global growth in non-CO_2-emitting infrastructure would be required. Because infrastructure is long-lived and expensive and because 79% of global CO_2 emissions are energy-related (remaining 16% from forest and peat fires, 5% from other) (see Figure 10-3), minimizing the need for early obsolescence is central to economically efficient climate policy-making. One of the best ways to measure mitigation progress is by measuring the fraction of energy produced by non-CO_2-emitting infrastructure. As of 2009, 19% of worldwide energy was provided by non-CO_2-emitting sources (10% from biomass and waste, 6% from nuclear, 2% from hydro, 0.5% from geothermal, and 0.3% from wind and solar). [33] This fraction has been fairly steady between 19-20% since 1986 and was previously lower. [184]

Avoiding 2°C with 50/50 odds on the AAR1 trajectory would require ~60% of all energy in 2030 to be produced from non-CO_2-emitting sources (~85% of energy in developed nations, ~50% of energy in developing nations)[139] – a fraction three times higher than ever before.[140] When growth in energy demand is taken into account, this would require 14% annual growth of installations of non-CO_2-emitting infrastructure in non-OECD nations and 24% annual growth of these installations in OECD nations. This contrasts with 2000-2009 annual growth of non-CO_2-emitting infrastructure installations of 2% in non-OECD nations (3% in China) and 1% annual growth in OECD nations. [184]

These large required additions of non-CO_2-emitting infrastructure would be somewhat smaller if non-energy-related CO_2 emissions (e.g., fire) were decreased in the developing world, if existing energy sources in developing nations were replaced by lower-emission sources, if non-

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Federation, and Ukraine. The Russian Federation is the only large nation that is not part of both – it is part of Annex I and is non-OECD.

[139] Calculation assumes that fossil fuel energy is reduced by 80% versus 1990 usage in developed nations and that fossil fuel energy usage is held flat to 2009 levels in developing nations, while energy demand in developed nations grows by 8% and demand in developing nations grows by 54% from 2009-2030.

[140] Note, the goal advocated by Sustainable Energy for All is 30% renewables by 2030 (wind, water, solar, geothermal, and biomass). (http://sustainableenergyforall.org/objectives; Sustainable Energy for All was launched by UN Secretary-General Ban Ki-Moon in 2011) That is only half of the non-CO_2-emitting energy that is required by 2030 to be on a path with a 50/50 chance of avoiding 2°C. If 30% is the renewable target achieved, the other 30% must be supplied by nuclear or a technology yet-to-be-developed/demonstrated (e.g., CCS with 98% capture).

CO_2 warming pollutants (e.g., methane, black carbon) were reduced more than assumed[141], if CO_2 emissions in the second half-century were more than assumed,[142] or if energy demand were lower than projected by the IEA. Vice versa, requirements for non-CO_2-emitting infrastructure would be higher if better than 50/50 odds of avoiding 2°C were desired (see the scenarios that sit left of the 50/50 line in Figure 9-3).

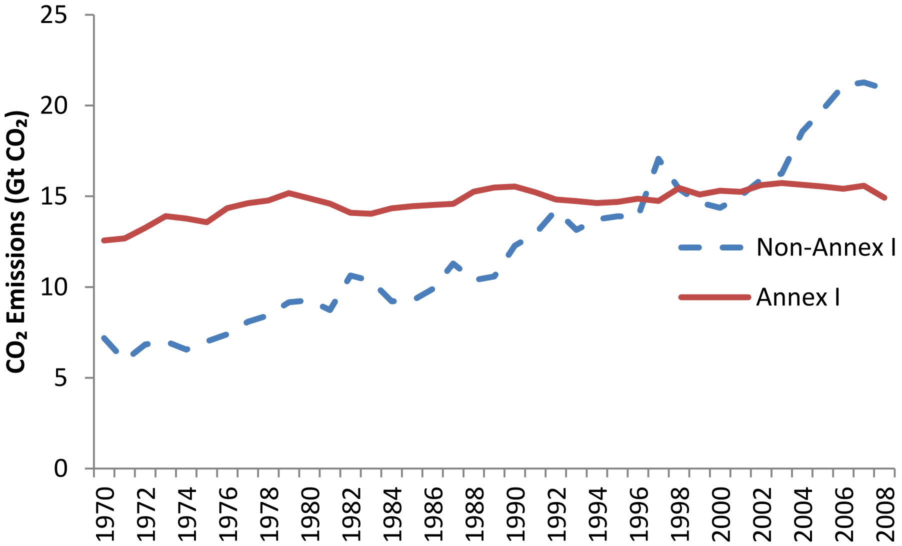

Figure 10-1: CO_2 Emissions, Annex I Nations and Developing (non-Annex I) Nations, 1970-2008
Data source: EDGAR 4.2 database [46].

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[141] In the Medium (50/50 odds) scenario (Figure 9-4) that applies here for AAR1, CH_4 is assumed to grow in the first half-century and be reduced by 9-22% (relative to year 2000) in the second half century. This is at the very low end of maximum feasible reductions (7-28% vs. 2000; 16-43% vs. 2005, as shown in Figure 4-10). Minimal changes are assumed for CO and NMVOC in the first half-century, followed by half to two-thirds of their maximum technically feasible reductions in the second half century (not shown). SO_2 (cooling) is assumed at its maximum technically feasible reduction in the second half century. In brief, there is upside for stronger mitigation of the short- and medium-lived warming pollutants. No assumptions for black carbon and organic carbon are specified in the Meinshausen analysis.

[142] Analysis assumes emissions over the second half-century average roughly 60-80% below 1990 levels (see section 9.3.b).

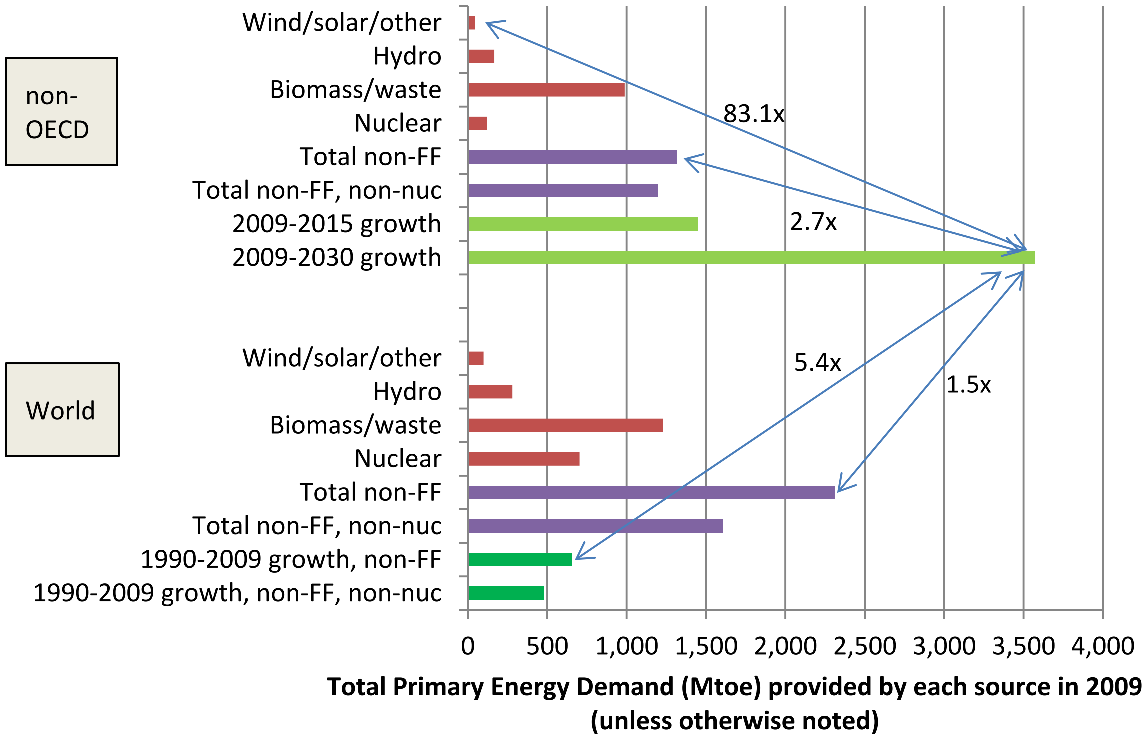

Figure 10-2: Non-OECD Energy Growth Projections Compared to Energy Supplied in 2009 by Non-Fossil Fuel

Data source: IEA World Energy Outlook 2011 [33]. FF = fossil fuel.

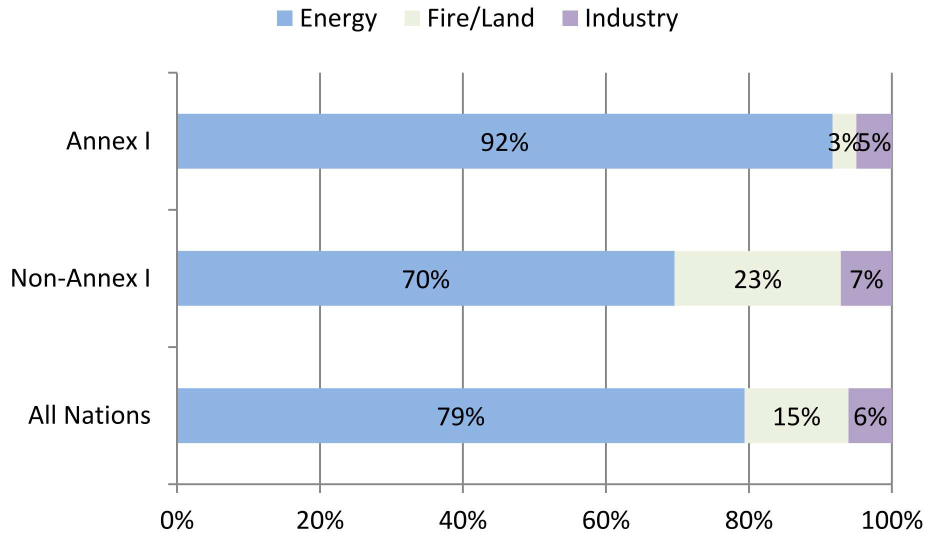

Figure 10-3: CO_2 Emission Sources, for Annex I, Non-Annex I, and All Nations, 2008

Data are from EDGAR 4.2 [46]. I have grouped 29 sources into three categories: Energy, Fire/Land, and Industry. Energy includes all uses of energy – e.g., electricity, heat, transportation, manufacturing and construction, residential and commercial. Fire/Land includes emissions from fires, post-fire decay, and direct soil emissions. Industry includes direct emissions from the production of cement, chemicals, metals, minerals, lime; the use of solvents; and waste incineration.

10.2.a Timing Issues in the Developing World

One of the most significant dimensions of the challenge of holding emissions flat in developing nations is that the energy demand growth is front-loaded (63% of projected growth from 2009-2030 is expected before 2020[143]) and the deployment capacity of non-fossil fuel technology is back-loaded, with the non-fossil fuel industries growing exponentially. This means that there is likely to be insufficient non-fossil fuel capacity to meet near-term energy demand growth (through 2015) in developing nations, even though it is possible for the non-fossil fuel capacity by 2030 to be sufficient to meet the demand.

Let us assume that roll-out of non-CO_2-emitting infrastructure does indeed grow by 14% per year in non-OECD nations (up from the current 2% growth rate), as required to reach a cumulative total in 2030 such that CO_2 emissions equal those in 2008. (see Figure 10-4) Given the small current numbers, the absolute magnitude of the modeled roll-out in the 2010 decade at this exponential growth rate would be relatively small in comparison to the absolute magnitude of the growth in energy demand predicted by the IEA for non-OECD nations over the decade. [33] This gap between supply and demand would reach its peak in 2020, when the

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[143] Growth is also front-loaded in the very near-term, with 64% of 2009-2020 growth expected before 2015.

cumulative new energy demand exceeded the cumulative non-CO_2-emitting supply by 1500 Mtoe. In a bounding case, if new non-CO_2-emitting energy were limited to wind and solar (excluding nuclear, hydro, and geothermal)[144], the magnitude of the gap would widen to 2200 Mtoe in 2023. The gap would then close in the late 2020s as capacity caught up with demand.

The exponential growth rate shown in Figure 10-4 (versus a faster curve shape) reflects physical and logistical constraints in building a new industry. Even if costs equilibrated among technologies and political will materialized overnight, expansion of non-CO_2-emitting energy industries on a scale that meets demand could not happen overnight. It takes time to train large numbers of highly educated engineers and factory workers, build well-functioning companies, and produce consistently high-quality products. An oft-cited precedent is the rapid and successful increase in U.S. aircraft production for World War II (23x increase in production from 1940-1943) [185]. An example of mixed success was the even more rapid U.S. ramp-up of World War II ship-building (50x increase in production from 1940-1943) [186], in which the Liberty Ships were designed to last only five years, an eighth had major fractures, and a few sank at sea due to hull defects. [187] Such trade-offs of speed and quality would not be publicly acceptable for technologies such as nuclear, hydro, CCS, and vehicles, and shorter-than-usual lifetimes for any energy technology would be financially burdensome.

As another point of comparison, the natural gas industry is currently growing at what is considered to be a very rapid pace, with the advantages of incumbency, favorable political winds, and new shale gas technologies. Global natural gas usage increased by 52% from 1990-2009 and non-OECD usage increased by 56%. [33][145] The IEA projects that under current policies, global natural gas use will increase by another 52% from 2009-2030 and non-OECD natural gas use will increase 81%. [33] These rates are more than three times slower than the required growth in developing world non-fossil fuel generation growth of 270% from 2009-2030 under the AAR1 scenario.

There are three possible ways to address the timing gap between up-front growth in demand and back-loaded availability of supply. First, the gap can be reduced by implementing the most energy efficient technologies as demand grows, hence lowering the demand line. Second, the gap can be reduced by growing supply even more quickly than the exponential rate indicated in

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[144] There is opposition in some regions to construction of nuclear plants (due to waste disposal and security issues), large-scale hydro facilities (due to environmental impacts), and geothermal facilities (due to seismic concerns). In the bounding case, I assume that these technologies are unavailable, which increases the challenge considerably, since the projected demand growth from 2009-2030 is 83 times 2009 wind and solar capacity in the non-OECD nations and only 2.7 times the total non-fossil fuel capacity in non-OECD nations (see Figure 10-2).

[145] Usage here is defined as total primary energy demand.

Figure 10-4 effectively raising the supply line. Finally, any remaining gap can be filled with new CO_2-emitting production. The latter option requires an explicit understanding that an equivalent quantity of CO_2-emitting infrastructure will be taken off-line in the late 2020s, an agreement that could be expensive due to early obsolescence (unless older generation infrastructure can be retired) and politically difficult to achieve. The roll-out and obsolescence of CO_2-emitting generation that would fill the gap between the red solid and green dashed lines in Figure 10-4 is shown on the left side of Figure 10-5. Note that obsolescence in the context of power generation includes not only generation facilities, but also transmission lines, since non-fossil fuel sources have different siting criteria and transmission lines must be routed to different places.

Figure 10-4 makes it clear that a requirement for developing nations to immediately meet all additional demand needs with non-CO_2-emitting infrastructure would pose extraordinary logistical challenges given the rapid pace of development. A well-defined roadmap that combines energy efficiency, explicit growth plans for aggressive roll-out of non-CO_2-emitting technologies, and explicit obsolescence plans for CO_2-emitting technologies is perhaps a more viable option for avoiding the 2°C temperature ceiling.

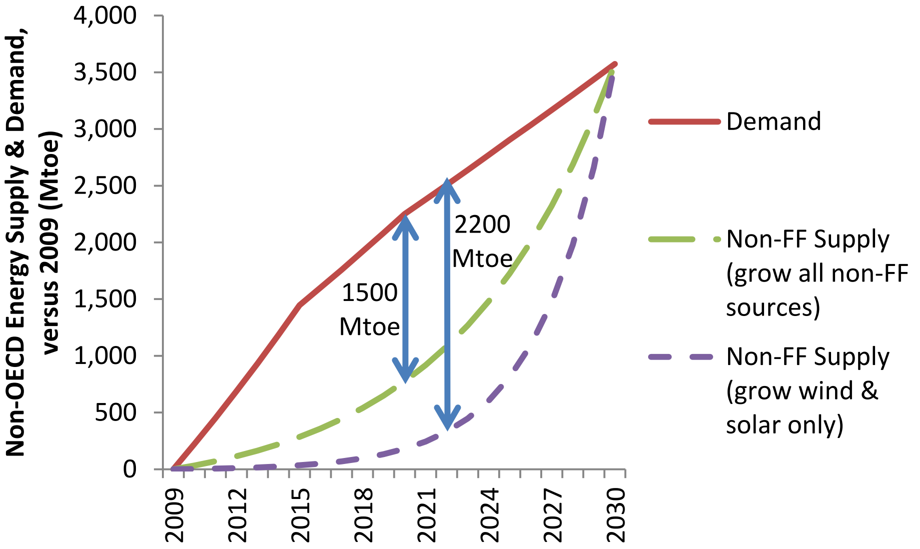

Figure 10-4: Non-OECD Energy Supply and Demand, relative to 2009, with Exponential Growth of Non-Fossil Fuel Energy Supply

Primary energy demand is from the IEA World Energy Outlook 2011's central (New Policies) scenario [33]. Baseline is 6,900 Mtoe total primary energy in 2009 and 23 Mtoe growth in 2009 of non-CO_2-emitting supply, including 4 Mtoe growth in 2009 of wind and solar. Supply additions are calculated with a smooth exponential growth rate to match demand in 2030 (14%/yr using all non-FF sources; 34%/yr using only wind and solar).

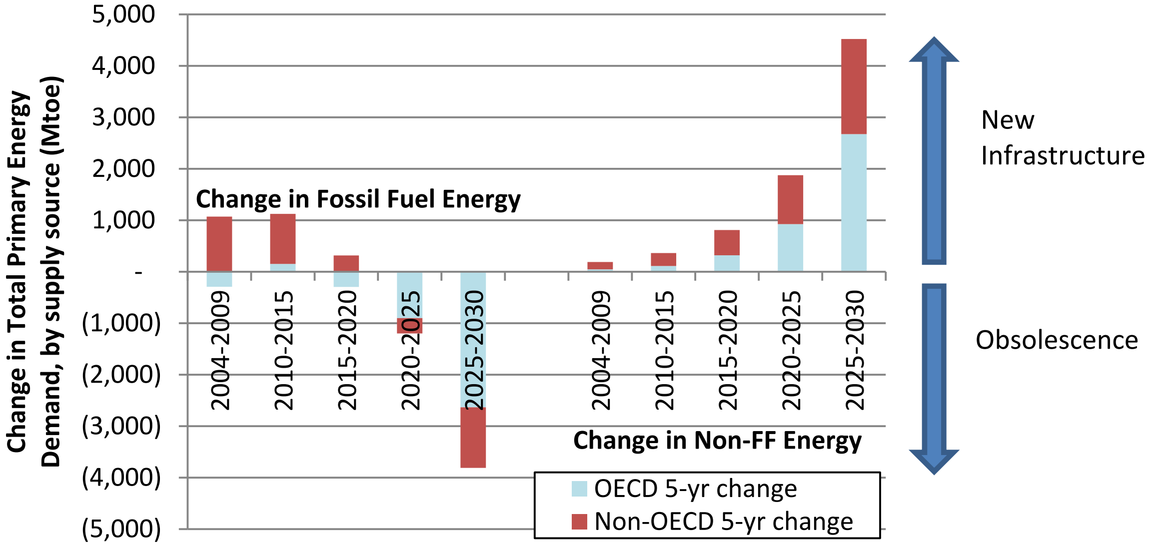

Figure 10-5 Five-Year Changes in Fossil Fuel and Non-Fossil Fuel Energy

FF – Fossil Fuel. Non-FF could include FF use with 98% carbon capture and sequestration (CCS).[146] Historical data and total projected energy demand from IEA World Energy Outlook 2011's central (New Policies) scenario. [33] Calculation assumes that fossil fuel energy in 2030 is reduced by 80% versus 1990 usage in OECD nations and that fossil fuel energy usage in 2030 is flat to 2009 levels in non-OECD nations (per the AAR1 scenario), while energy demand in OECD nations grows by 8% and demand in non-OECD nations grows by 54% from 2009-2030 (the growth rates projected by IEA 2011 [33]). Non-fossil fuel targets for 2030 are the difference between total demand and fossil fuel usage in 2030. For each year, non-FF installations are assumed to grow at a smooth exponential rate in OECD and Non-OECD from 2010-2030 to hit their 2030 target (see Figure 10-4). Annual FF energy is the difference between total energy demand in that year and non-FF supply. Levels of FF usage and non-FF usage at the end of each 5-year period are compared to the totals at the end of the previous 5- year period and the changes are plotted in this graph.

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[146] Feasibility of 98% efficiency in new CCS units by 2050 is assumed by Williams et al. Science 2012.

10.3 Implications for 2050-2100 and Conclusions for non-Annex I

The timing mismatch identified in section 10.2.a and illustrated in Figure 10-4 would result in approximately 50 Gt CO_2 emissions in the first half century above the level assumed for the AAR1 trajectory to have 50/50 odds of avoiding 2°C.[147] Several options for minimizing this timing mismatch were discussed in section 10.2.a, including energy efficiency to delay demand and a more rapid build-out of non-CO_2-emitting supply. If the 50 Gt CO_2 gap persisted, a ~13% average emission reduction in 2031-2049 in developing nations (relative to 2008 levels)[148] would be needed in order for the first half-century carbon budget to be at the level consistent with 50/50 odds (1450 Gt CO_2).

If developing world emissions were to remain flat during the 2030-2049 period, another option would be to increase the developing world reductions in the second half-century. As we saw in section 9.3.b, first-half emission reductions must be followed by larger second-half emission reductions in order maintain 50/50 odds of avoiding a temperature change above 2°C, regardless of the timing mismatch.

Without the extra emissions from the timing mismatch and assuming the AAR1 trajectory just discussed, global CO_2 emissions in the second half-century must be reduced on average[149] by at least 70% below 2008 levels (60% below 1990 levels). Turning back to Table 10-1, if Annex I emissions were reduced by 80%, a minimum of 61% average reductions in non-Annex I nations (vs. 2008 emissions) would be required. If Annex I emissions were completely eliminated, developing country emissions would still need to be reduced on average by 46% (vs. 2008 emissions). An effort to offset the extra emissions from the timing mismatch would add ~5 percentage points to the required reduction,[150] bringing developing country reductions to 66% (with Annex I emission reductions of 80%) or 51% (with Annex I emission reductions at 100%).

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[147] This calculation takes the total fossil fuel generation from 2009-2030 that corresponds to Figure 10-4 and subtracts the total fossil fuel generation from 2009-2030 that would result from flat fossil fuel (2009 fossil fuel generation multiplied by 22 years) to find the amount of over-generation. This overage is divided by the total target fossil fuel generation (OECD + non-OECD) for the 2009-2030 period (flat non-OECD, 80% reduction in OECD), producing a result of 10% overage. The target emission level for the 2000-2049 period (1450 Gt CO_2, from Figure 9-3) is then scaled to 22 years (22/50) and scaled by the energy fraction of emissions (79%), then multiplied by 10% to produce an estimate of ~50 Gt CO_2 of overage.

[148] This calculation takes 50 Gt CO_2 , divides by 19 years, and divides by the 2008 non-Annex I emissions from the EDGAR 4.2 database (20.9 Gt CO_2), finding a result of 13%.

[149] Average reduction equals average emissions over the 50 years, relative to emissions in 2008.

[150] This calculation takes 50 Gt CO_2 , divides by 50 years, and divides by the 2008 non-Annex I emissions from the EDGAR 4.2 database (20.9 Gt CO_2), finding a result of 5%.

In summary, emission reductions in developing countries during this century are arithmetically unavoidable for scenarios that stay below 2°C.[151] The AAR1 trajectory that allows developing nations' CO_2 emissions to stay roughly flat for the first half-century requires very fast action in the current decade both to halt developing world emission growth and to rapidly reduce Annex I emissions. Developing country emission reductions below year 2008 emissions are required in the second half-century in all cases that stay below 2°C. To the extent that there is a timing mismatch that takes developing world emissions above 2008 levels before returning to those levels in 2030, the required reductions in the developing world in the second half-century would be higher. Beyond the 21st century, both developed and developing nation emissions must eventually be reduced to near-zero in order to fit within the finite millennial budget that corresponds to temperature stabilization at any level (see section 9.3.b and Figure 9-5).

Returning to the trade-offs discussed in section 9.3 and section 10.1, decision makers have the option to make trade-offs between speed and level of emission reductions in the present century. If more time is needed, deeper emission reductions can be chosen. For example, the G8 target mentioned earlier peaks soon (assume 2020) and then reduces emissions by at least 50% globally (R50) and at least 80% in developed nation by 2050 (relative to 1990). As shown in Figure 9-3, this trajectory provides 50/50 odds of staying below 2°C. It has the advantage of a less demanding timeline than AAR1 (2050 versus 2030) but the disadvantage of requiring larger reductions (50% versus 30%, relative to 1990). Table 10-1 shows that achieving the G8 goal of a 50% global reduction relative to 1990 (61% reduction vs. 2008) [152] requires 48% reductions in developing nations relative to 2008 if Annex I countries reduce emissions by 80% (35% reductions in developing nations if Annex I countries reduce by 100%).

Davis et al. [63] captured the magnitude of this challenge from another angle. They found that even if all existing infrastructure is retired at the end of its useful life and all new infrastructure is carbon-free, the planet will still warm by ~1.3°C above pre-industrial levels (see section 2.4). This is another way of saying that the vast majority of both new and replacement infrastructure around world must be near-zero emission technology in order to stay below 2°C.

If neither rapid action nor deep reductions are achieved, in both developed and developing nations, then the 2°C ceiling is unlikely to be avoided.

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[151] In absence of geo-engineering (see sections 5.4 and 7.3).

[152] See footnote 134. This chapter assumes the G8 reductions are relative to 1990. If the G8 intended 50% global reductions vs. 2008 (-35% vs. 1990), then Figure 9-3 shows that the G8 target (assuming peaking in 2020 and achieving target in 2050) would not satisfy 50/50 odds.

10.4 Implications for Offsets and Cap and Trade

Offsets are policy instruments that are used to exchange emission reductions in one region or sector for reductions in another region or sector. Most offsets are purchased by companies and individuals in developed nations and supplied by organizations in developing nations. [188] Offsets in the Clean Development Mechanism and many voluntary programs are required to represent "additional" reductions below a theoretical baseline of future emissions. In practice, what is purchased is often an *avoided increase* of emissions rather than a *reduction* of emissions, and assessing the integrity of the baseline is a significant challenge to ensuring the integrity of offsets. In fact, the additionality of offsets has been an on-going point of contention. [189]

Baseline determination could become much simpler in the context of the 2°C trajectories discussed in the prior sections. In the AAR1 scenario, developing nations must hold emissions roughly flat, even if Annex I nations rapidly reduce their emissions by at least 80% by 2030-2040. In this case, there is no such thing as an offset that is an avoided increase of emissions. If we consider offsets in aggregate, let us say that Annex I entities wish to purchase offsets equivalent to 10% reductions in their emissions so that they only need to reduce their own emissions by at least 70%. Emissions in Annex I countries would thus be higher under the offset program than without it, and so emissions in developing nations must be lower under the offset program than without it. Without any offset program, developing nation emissions must be flat. Thus, under the offset program, there would need to be absolute declines in developing nation emissions in order for total global emissions to meet the target.

In the new situation just described, the baseline for environmental additionality in developing nations would equal 2008 emissions, and would no longer be a theoretical construct. An offset would only be sold if the supplier could prove that they were retiring or reducing an existing emission source and that this emission source was not being replaced elsewhere. This would be difficult to prove, though perhaps easier to evaluate than today's offsets. [190]

A global emission permit system – i.e., global cap and trade, rather than offsets – would have the potential to make counting even easier under the more stringent requirements of a 2°C ceiling, provided that the caps were binding in a way that resulted in a emission trajectory such as AAR1 (for lessons learned in past programs, see [191] and [192]).[153] Such a global system would require participation of all nations to avoid issues such as emissions leakage to non-participants.

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[153] McAllister 2009 describes past issues with stringency in cap and trade and makes recommendations for environmentally effective caps. Sovacool 2011 reviews the flaws in eight markets for tradable credits.

To date, there has been no political appetite for capping developing nation emissions (or emissions of some developed nations, for that matter). The acknowledgement that developing nation emissions must be flat in order to stay under 2°C, together with Annex I commitments to reductions of at least 80%, would be a major watershed in international climate politics. This watershed is a necessary step to designing workable policy instruments such as next-generation offsets or global cap and trade that would achieve the 2°C goal.

10.5 Summary

Decisions that are consistent with 50/50 odds of avoiding an increase in global temperature of 2°C above pre-industrial levels involve CO_2 emission reductions of 80-100% in Annex I nations by 2030-2040[154] and roughly flat CO_2 with near-immediate peaking of emissions in non- Annex I nations, and reductions in fossil fuel infrastructure[155] that are consistent with these emission trajectories. Smaller changes such as swapping natural gas for coal in new generation will avoid the higher temperatures of a coal-dominated world, but will not avoid 2°C (natural gas is discussed further in Chapter 11). Higher reductions of short- and medium-lived pollutants will delay climate outcomes, but will not by themselves avoid 2°C (we will see this again in Chapter 13).

If government leaders are committed to avoiding 2°C (Box 2), difficult decisions must be made within the next few years in order to peak emissions by 2015-2020. Alternatively, decision-makers can determine that other factors are more important (e.g., ease and lower upfront cost of doing things the way they are currently done) and accept climate change in excess of 2°C.

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[154] Note, there are other combinations shown in Table 10-1 that allow Annex I nations to reduce less if emissions reductions are pursued in non-Annex I nations

[155] Other alternatives include massive, immediate build-out of nascent carbon capture and storage (CCS) technology or massive, immediate implementation of budding technologies that capture and use CO_2 (e.g., for cement manufacture (http://calera.com/ or http://novacem.com/) or for creation of liquid fuels (http://liquidlightinc.com/). If these technologies become viable, then mitigation progress can be measured in atmospheric concentration of CO_2 instead of only emissions reduction.

Chapter 11 Implications for the Natural Gas Industry

We saw in Chapter 10 that avoiding a global temperature increase of 2°C with 50% likelihood requires the minimum action in the first half of the 21st century of an 80% reduction in Annex I CO_2 emissions relative to 2008 emissions by 2030, combined with roughly flat emissions in developing nations.[156] This type of trajectory implies early obsolescence of fossil fuel sources in the late 2020s (see Figure 10-5).

In this context, I now turn to the question of whether natural gas, as a replacement for coal, is part of the climate solution. This question has become particularly relevant over the past few years, as the technology to develop large shale gas reserves has been refined and implemented in the United States and around the world. Global natural gas usage increased by 52% from 1990-2009, and US usage increased 22%. [33][157] The IEA projects that under current policies, global natural gas use will increase by 66% from 2009-2035 and US natural gas use will increase 8% over that time period. [33]

Natural gas has multiple uses. Most commonly discussed is natural gas used in electricity production, but this accounts for only a fraction of demand. In the US, 31% of natural gas is used for electricity production and the remainder is used for residential and commercial heating and cooking (33%), industrial (27%), and other (9%).[158] [193, 194]

The role of natural gas in climate mitigation depends on whether we are discussing *delays* in near-term climate outcomes, as discussed in Chapter 5 and Chapter 6, or whether we are discussing *avoiding* climate outcomes such as 2°C, as discussed in this chapter. As I will show in the following sections, natural gas does not delay near-term climate outcomes (and may speed some up by eliminating coal's near-term cooling pollutants), but may play a small role in replacing old coal plants in developing nations while still avoiding the 2°C ceiling.

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[156] Alternatively, a 100% reduction in Annex I combined with 23% growth in developing nations.

[157] Usage here is defined as total primary energy demand.

[158] As a point of comparison, ~90% of coal in the US was used for electricity production in year 2000 (up from ~20% in 1950). The equivalent figures in India and China were ~70% and ~54%.

11.1 Natural Gas as a Way to Delay Near-Term Climate Outcomes?

In 2010, US natural gas plants produced ~25% less CO_2 per kWh generated as compared with the overall grid mix and ~60% less as compared with coal plants (calculated from [195] and [196])[159] [197]. For this reason, natural gas has been promoted as a "bridge fuel"[160] for electricity generation for climate mitigation purposes, with the implication that it will be replaced with lower-emission technologies at some point in the future.

While natural gas has less CO_2, it lacks the cooling sulfur dioxide (SO_2) that is emitted by coal plants and also involves more lifecycle methane (CH_4) emissions in some cases.[161] Emitted sulfur dioxide is converted into sulfate aerosols, which play a reflecting role in the atmosphere, masking part of the warming that would otherwise occur in their absence. However, sulfate aerosols also impair respiratory function and contribute to acid rain, so there are public health reasons to minimize SO_2 emissions. Global SO_2 emissions increased by 14% from 2000-2008, reversing a multi-decade decline (see Figure 4-7).[162]

Due to SO_2, the radiative forcing (RF) from coal is less than the RF from natural gas per kWh in the near-term years, before becoming significantly greater than the RF from natural gas in later years, as illustrated in Figure 11-1. Coal RF is driven by the different lifetimes of SO_2 (days) and CO_2 (centuries). The SO_2 does not accumulate and its RF remains constant with steady power production, while the CO_2 does accumulate and its RF increases. Thus, the net effect for steady provision of 1kW from coal begins at negative RF at time 0 and steadily increases. In contrast, the net effect for steady provision of 1kW from natural gas begins at positive RF (from CO_2 and CH_4) and then grows more slowly than coal due to the lower natural gas CO_2 emissions and shorter lifetime of CH_4 relative to CO_2. When the plants shut down, the masking effect of SO_2

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[159] Note, natural gas produces ~45% less CO_2 per Btu of primary energy versus coal, but natural gas plants also produce 33% more electricity per Btu than coal plants on average, due to the use of combined cycle technology (which use the waste heat) versus steam turbines alone. Thus, the CO_2 improvement from natural gas is higher (60%) on average versus coal when measured based on final net electricity generation. The efficiency difference between natural gas and coal is less for newer coal plants that use pulverized coal and super-critical or ultra-super-critical steam (USC) cycle technology. USC is the preferred technology for new coal plants in China.

[160] "National groups such as the Sierra Club, the Environmental Defense Fund and the Natural Resources Defense Council have backed natural gas as a so-called bridge fuel that can help the country move away from coal and oil without waiting for renewable sources of energy, such as wind and solar power, to catch up." – Wall Street Journal, December 22, 2009 (http://online.wsj.com/article/SB126135534799299475.html)

[161] Natural gas production and distribution processes involve methane leakage, as does coal mining. The relative comparison of CH_4 released between the two is dependent on the specific sources and technologies used.

[162] USA SO_2 emissions dropped by 37% from 2000-2008.

disappears and the RF from coal immediately exceeds that of natural gas and remains in excess for centuries.

Shindell and Faluvegi 2010 find that for global coal-generated electricity production in aggregate, the coal line in Figure 11-1 would rise above zero RF after 15-25 years of constant year 2000 emissions. [194][163] [164] Hayhoe et al 2002 find that the global temperature is higher for 25 years after a global switch to natural gas (relative to coal) due to the loss of the aerosol cooling in their base case. [198][165] The temperature advantage of natural gas only appears beyond year 25. For the other scenarios (aside from base case), this window of relative warmth ranges from 0 years to 100+ years.

The shape of the curves in Figure 11-1 and the distance between them varies primarily on the sulfur emissions per kWh of electricity produced, and to a much lesser extent on variations in the methane leakage from a given region's production and distribution of natural gas relative to the methane leakage from the mining of coal. The Hayhoe base case assumes a 1.5% lifecycle loss rate of CH_4 in their base calculation (which finds a higher temperature for natural gas for the first 25 years); if the methane loss rate were 10%, the time would increase by only 5 years to 30 years. [198]

The sulfur emissions per kWh of electricity produced from coal depend on the type of coal used (low-sulfur or high-sulfur), the existence and effectiveness of SO_2 capture technology in place for a given coal combustion facility, and the efficiency of the coal plant in converting primary energy into electricity. The sulfur content of coal varies by a multiple of 6-14 from mine to mine, with typical ranges of 0.5-3% sulfur by weight, and over 7% sulfur in some sources. [198] Capture technologies, if used effectively, can capture up to 50-70% of SO_2 emissions (via boiler additives) or up to 95% (via post-combustion scrubbers). [198] These technologies have been implemented extensively in the US and across Annex I nations, with reductions of SO_2 emissions in the power sector of 61% in the US and 65% in Annex I nations from 1990-2008 (calculated from [46]). Energy conversion efficiency has also increased for coal plants, from 28% for existing plants on average to 45% for the most efficient modern plants. [199] Taking all of these factors into account (coal type, capture technology, and plant efficiency), sulfur emissions per kWh of electricity produced from coal have fallen by roughly 50% globally over the past two

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[163] Assuming the global average SO_2 emissions from a coal plant in year 2000.

[164] Shindell and Faluvegi analysis makes the same uncertainty assumptions about the aerosol indirect effect for sulfates as were discussed in section 4.4.b.i and shown as the solid error bars for SO_2 in Figure 4-11. Wider uncertainty as shown in the dotted error bar would increase the number of years before coal RF rises above zero.

[165] Hayhoe base case assumes global SO_2 emissions/kWh at late 1990s levels.

decades, as illustrated in Figure 11-2. The figure has fallen by 65-75% in Japan and the United States and by 33% in China.

The SO_2/kWh figure is important, because it determines the number of years before the coal RF line in Figure 11-1 crosses zero and the number of years before it crosses the natural gas line. The baseline data (late 1990s / 2000) used in the Shindell and Faluvegi study and the Hayhoe study pre-date more recent improvements in SO_2/kWh, and thus the number of years that an average natural gas plant today would produce higher temperatures than an average coal plant has fallen from ~25 years to a currently undetermined number. Additional research is needed to specify more broadly the relationship between SO_2/kWh and the number of years it takes for coal RF to rise above zero in Figure 11-1 and between SO_2/kWh and the number of years it takes for coal RF to rise above natural gas RF in Figure 11-1. This research, if done using a variety of CH_4 leakage assumptions for natural gas, would also identify if there exists a boundary point at which coal RF exceeds natural gas RF from day one of operation.

In summary, replacement of coal with natural gas in general does not delay near-term climate outcomes and may accelerate them; the specifics vary meaningfully from plant to plant. But, natural gas does have a lower climate impact than coal over the longer-term. The next section discusses the longer-term impact of natural gas.

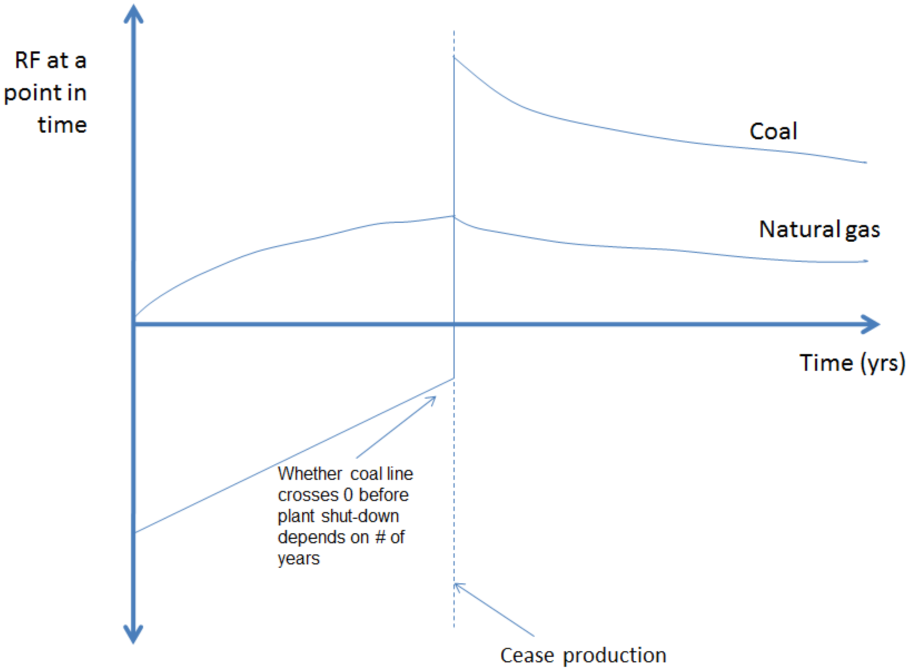

Figure 11-1: Schematic of RF versus Time of Coal and Natural Gas Plants Producing 1kW of Electricity
RF at a point in time is produced by the accumulated pollutants in the atmosphere attributable to the plant since time 0. RF increases as CO_2 and CH_4 emissions accumulate in the atmosphere. Note that this is not cumulative RF (which would be the integral of the RF curve). It is also possible that the coal RF line would exceed the natural gas RF line before the two plants ceased production. The time before the coal line crosses zero and the time before (and whether) the coal line crosses the natural gas line depends primarily on SO_2/kWh and also on assumptions regarding the upstream methane leakage for both coal and natural gas.

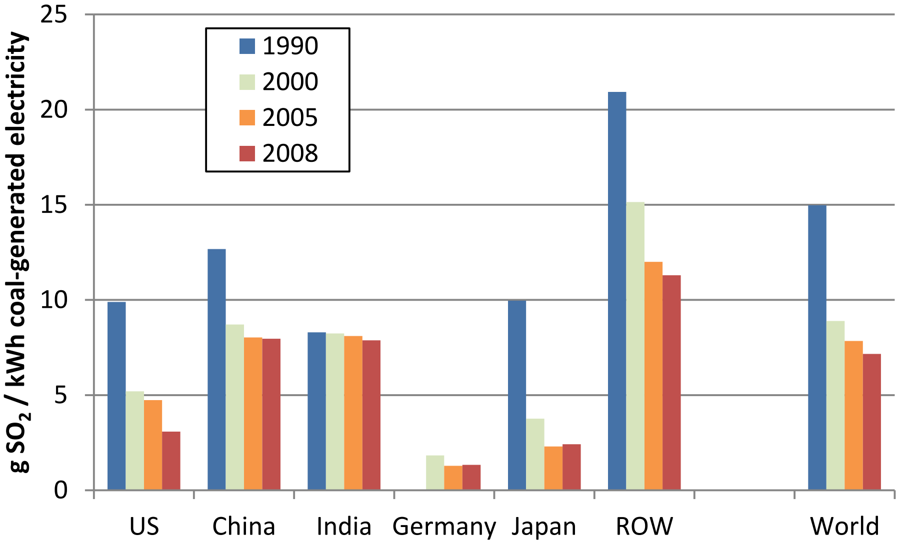

Figure 11-2: SO_2 Emissions per kWh of Coal-Generated Electricity by Nation and Globally
Figure shows the five nations producing the most electricity from coal (73% of total 2008 coal-fired generation), along with the rest of the world (ROW), and the world in aggregate. Coal-fired generation figures are from the IEA World Energy Statistics (2000-2008) and IEA World Energy Outlook 2011 (1990) [33, 200]. Coal-fired generation data for 1990 were not dis-aggregated for Germany, so that bar is missing in the figure. Sulfur emissions for the power sector are from the EDGAR 4.2 database [46]. The minimum technically feasible level is 0.1-3.2 g SO_2/kWh, depending on sulfur content of the coal and plant efficiency (calculated from Hayhoe et al. [198]).

11.2 Natural Gas and the 2°C Ceiling

Whether natural gas has a role to play in longer-term climate mitigation depends on the goal. If the goal is to avoid 2°C (or 1.5°C), the role of natural gas (and all fossil fuels) is quickly diminishing. If the goal is to avoid the higher temperatures that might otherwise occur if coal were to continue as a dominant fuel for electricity and other combustion, then natural gas would play a larger role in achieving that goal.

Natural gas currently contributes 22% of the total CO_2 emissions in Annex I nations (see Figure 11-3). This means that there is no arithmetic option to expand natural gas beyond today's usage and achieve the 80% reduction of CO_2 emissions in Annex I nations that was discussed in section 10.1 and has been established as a goal by the G8 [177]; the minimum reduction required for natural gas in Annex I nations would be 2% if it were feasible to completely eliminate all other CO_2 emissions sources.

The maximum feasible reduction for natural gas in Annex I nations depends on the availability of lower-emission alternatives for each end use. Recall that natural gas in the U.S. is used for electricity production (31%), residential and commercial heating and cooking (33%), industrial purposes (27%), and other (9%) [193], and for this discussion I will assume the split is roughly similar in other Annex I nations. In the electricity sector, maximum feasible reductions of natural gas depend on the availability of a zero-emission technology for load-balancing (ZELB) the electricity grid, a role currently played by natural gas. Such a ZELB could include energy storage or demand-side solutions, or it could include carbon capture and sequestration (CCS) for the natural gas plants. [201] If a ZELB were rolled out, the maximum feasible reduction for natural gas in the electricity sector would approach 100%. The maximum feasible reduction of natural gas in the residential and commercial heating and cooking sector also approaches 100%, since direct use of natural gas can be replaced by electricity for these end uses. The remainder of natural gas is currently used for industrial and other purposes, and a fraction of these end uses may require a quality of heat provided only by natural gas. In summary, assuming a ZELB for load-balancing, a rough estimate of the maximum feasible reduction of natural gas is at least 62% (eliminate use in electricity, heating, and cooking) and perhaps approaching 100% (if industrial and other uses can be replaced).

In terms of where natural gas reductions would need to land in order to satisfy the goal of avoiding 2°C and hence the target of reducing Annex I emissions by 80-100% by 2030 (section 10.1), the difference between minimum reductions of 2% and maximum feasible reductions of 62-100% lies in the assumptions that are made about reductions from all of the other emission sources.

Figure 11-4 provides the year 2008 breakdown of CO_2 emissions in Annex I nations by source. Note that the chart includes several difficult-to-reduce sources such as: manufacturing and construction (12%) (for certain end uses, high-quality heat is required), peat fires (3%) (dry peat is particularly vulnerable to fire), domestic aviation (2%) (alternative fuels are in development), cement production (2%) (lower-emission technologies are in development), production of chemicals and other industrial products (3%), and other fragmented sources (2%). The total of difficult-to-reduce sources adds up to 24%. If no reductions were made in these sectors, the target of 80% would be missed, even if all other source emissions went to zero. Some reductions are feasible from these sources, so the target need not be missed, but it means the reduction requirements are significantly above 80% for the other sources.

The implications for the power sector are illustrated in Table 11-1, which splits emissions into Power, Transportation, and Other. For an 80% Annex I total target, the power sector target is 80-100%, unless both Transportation and Other achieve reductions in excess of 80%. This is consistent with Williams et al.'s finding that in order to achieve an 80% reduction below California's total 1990 CO_2 emissions (90% below 2008 levels), 90% of electricity in California would need to be derived from CO_2-free sources. [202]. It is also consistent with the Global Energy Assessment's finding that "in industrial countries, virtually no new investments in electricity generation should result in the new emission of GHGs". [179]

The implications for natural gas plants of a high target for the power sector is shown in Table 11-2, using U.S. production as an example. At an 80% reduction target for the electricity sector, there would still be room for 7% growth in natural gas above 2010 levels (replacing existing coal), if all other electricity sources were producing zero emissions. At 85% and larger electricity sector reduction targets, natural gas generation would need to shrink, significantly (-46% to -95%) in the case of a 90% or 99% electricity sector reduction target. And in all cases, overall natural gas usage would shrink because end use combustion of natural gas (for heating, cooking, industry, etc.) would be replaced in most cases with electric power. This is consistent with the finding of Williams et al. 2012 [202] that natural gas consumption in California would fall by 86% between 2010-2050 in order to achieve the state's goal of an 80% reduction of GHG emissions (relative to 1990 levels).

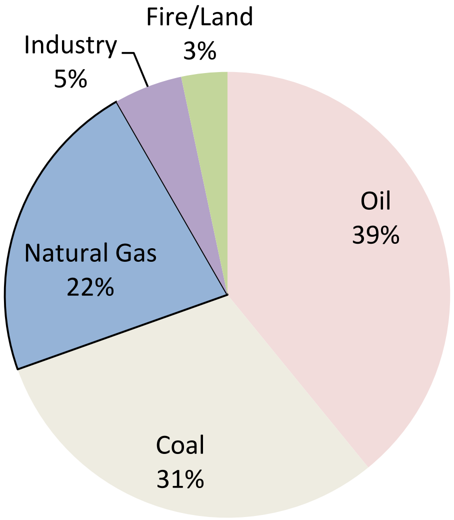

Figure 11-3: CO_2 Emissions from Annex I Nations in Year 2008, by Fuel and Source
Emission data for Annex I for 2008 are from the EDGAR 4.2 database [46]. The proportional split of energy emissions among oil, coal, and natural gas is approximated based on the IEA emission data for OECD nations in 2009 [33] (see section 10.1 for the large overlap between Annex I and OECD nations). Industry includes cement production, production of chemicals, metals, and minerals, lime production, and other smaller sources. Fire/Land includes peat fires, forest fires, direct soil emissions, and other smaller sources.

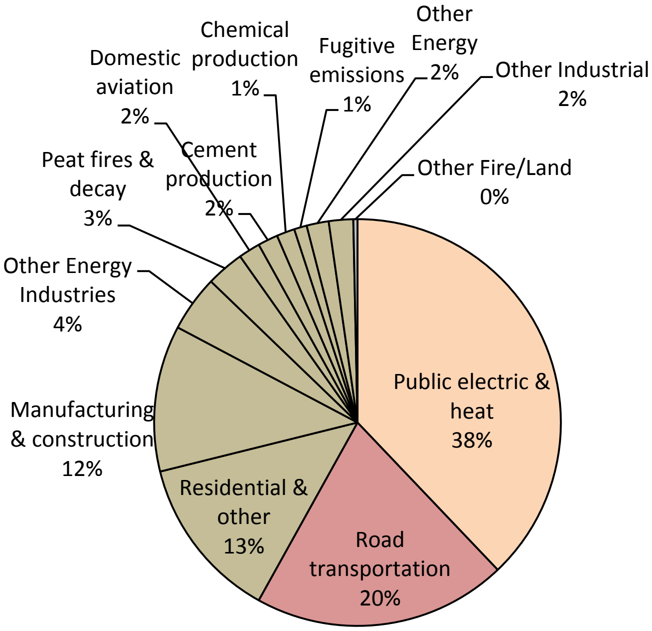

Figure 11-4: CO_2 Emissions from Annex I Nations in 2008, by Source
Data source: EDGAR 4.2 database [46]. Pie slices are color-coded by power sector (orange), road transport sector (red), and other (khaki), to match categorization in Table 11-1.

Power Sector Summary - CO_2 Reductions						
Annex I Total CO_2 emissions vs. 2008	**Other Reduces 0%**	**Other Reduces 20%**	**Other Reduces 40%**	**Other Reduces 60%**	**Other Reduces 80%**	**Other Reduces 100%**
-60%	-103%	-89%	-74%	-60%	-46%	-31%
-70%	-121%	-106%	-92%	-77%	-63%	-48%
-80%	-138%	-123%	-109%	-94%	-80%	-66%
-95%	-164%	-149%	-135%	-120%	-106%	-91%

Power Sector Summary - CO_2 Reductions						
Annex I Total CO_2 emissions vs. 2008	**Other & Transport Reduce 0%**	**Other & Transport Reduce 20%**	**Other & Transport Reduce 40%**	**Other & Transport Reduce 60%**	**Other & Transport Reduce 80%**	**Other & Transport Reduce 100%**
-60%	-158%	-126%	-93%	-60%	-27%	6%
-70%	-185%	-152%	-119%	-86%	-54%	-21%
-80%	-211%	-178%	-146%	-113%	-80%	-47%
-95%	-251%	-218%	-185%	-152%	-120%	-87%

Table 11-1: Annex I Power Sector CO_2 Reductions Required, as a Function of the Total Emission Reduction Target and the Emission Reductions in the Transport and Other Sectors

Required power section CO_2 emission reductions are calculated arithmetically, based on the emissions in Figure 11-4, which were split into three broad sectors for use in this table: Power including public electricity and heat (38%), Transport (20%), and Other (42%). In the top chart, Transport is assumed to reduce by the same percentage as the Power sector. In the bottom chart, Transport reduces by the same percentage as the Other sector. Red shading denotes combinations that cannot achieve the Annex I total target (sector-level reductions of >100% would be required).

Electricity Sector Target (vs. yr 1990)	Max growth in electricity from NG (vs. yr 2010)
-80%	7%
-85%	-19%
-90%	-46%
-95%	-73%
-99%	-95%

Table 11-2: Maximum Growth in U.S. Electricity Production from Natural Gas, assuming all other generation produces zero CO_2 emissions

NG = Natural gas. US electricity sector emissions are from EPA [196]. US electricity generation (MWh) data are from EIA [195]. Calculation is done arithmetically, by multiplying the 1990 sector CO_2 emissions by 1 minus the sector reduction percentage, then dividing by the average 2010 emissions per kWh for natural gas to produce the maximum generation from natural gas, then dividing by the 2010 electricity generation from natural gas to compute the percentage change.

11.3 Summary

Natural gas has lower long-term climate forcing than comparable coal-fired power per kWh, but scenarios with expanded natural gas use still lie above 2°C. Chapter 10 and 10.5 show that current governmental and industry actions to expand natural gas production and usage in Annex I nations are not consistent either with the Copenhagen Accord [3]and G8 [9] goal of avoiding a 2°C (or 1.5°C) increase above pre-industrial levels or with delaying near-term climate change. In fact, natural gas usage in developed nations would likely need to fall by ~85% to achieve 80-100% reductions in Annex I CO_2 emissions, even assuming that other sources are reducing CO_2 and non-CO_2 emissions by the maximum amount feasible.

The situation in non-Annex I countries is somewhat different, if we assume that non-Annex I nations are aiming to stay roughly flat over the first half-century while Annex I nations are aiming to reduce quickly by 80-100% to stay below 2°C (see section 9.3). Since non-Annex I countries can make trade-offs within their existing emissions “budget”, replacing *existing* coal-fired electricity production (or end use coal combustion[166]) with natural gas could allow an expansion of fossil fueled electricity capacity and a decrease in respiratory pollutants while holding electricity emissions flat. However, assuming that electricity production must continue to expand aggressively to meet the needs of development, the majority of new electricity production in non-Annex I nations would need to come from non-fossil fuel sources[167] in order to meet the goal of staying flat with 2008 emissions that is required to stay below 2°C. And, at the end of the useful life for this generation of natural gas plants and pipelines (30-40 years) [33, 63],[168] they too would need to be retired and replaced with non-fossil fuel sources in order to meet the second half-century goal of 65-95% reductions versus 2008 emissions.

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[166] End uses of coal include high-temperature industrial processes, space heating, and other purposes.

[167] In the future, other options may become available, such as large-scale carbon capture and sequestration.

[168] Natural gas plants have an average lifetime of 30-35 years (Davis, IEA WEO 2011) and pipelines have an average lifetime of 40 years (IEA WEO 2011). This means that half of the plants and pipelines built in this decade will still be in service in 2050.

Chapter 12 CO_2 Mitigation Progress and the Role of Discontinuous Peaks

In the context of Box 2 (Avoid 1.5-2°C), Chapter 9 and Chapter 10 emphasized the importance of peaking global CO_2 emissions as soon as possible, optimally in 2015 and no later than 2020, in order to maintain 50/50 odds of staying below 2°C while avoiding the need for emission reductions in developing nations.

This chapter examines the historical data on CO_2 emissions at the sub-global scale to identify if and where CO_2 emissions have peaked and sustained their reductions after the peak. Data are examined first at a regional level, then at a source-level, then at a nation-level. For those peaks that have occurred, I explore the nature of the peaks and the associated economic and political circumstances.

The goal of this chapter is to provide background on where CO_2 emissions have peaked at a sub-global scale in the past and to stimulate thoughts about what it might take to do so again repeatedly at the sub-global, then global, scale. The findings sit within the context that the global CO_2 emissions peak is expected in the 2040s at best under existing international policies and pledges (see Figure 9-6 and Figure A-1).

12.1 A Global Peak and the Accompanying Series of Sub-Global Peaks

The task of peaking global CO_2 emissions that was discussed in Chapter 9 can be segmented into the slightly smaller tasks of peaking CO_2 emissions at the level of each nation and source type. Figure 12-1 illustrates a series of sub-global peaks in which different entities reach their individual peaks in succession; the single global peak is shown on the total line.

At the time that global emissions peak, some sub-global entities will still be increasing and others will have already peaked and be decreasing (see Figure 12-1). The peak occurs when the total of sub-global annual decreases equals the total of sub-global annual increases, assuming that is followed in the ensuing time periods with the decreases exceeding the increases. Mathematically,

Peak: $$\frac{d}{dt}(A(t) + B(t) + \cdots) = 0 \qquad \text{Eq. 12.1}$$

Post-Peak: $$\frac{d}{dt}(A(t) + B(t) + \cdots) < 0 \qquad \text{Eq. 12.2}$$

where A (t), B(t), etc. are the CO_2 emissions from each sub-global entity in time t

This arithmetic fact has important implications for policy. As demonstrated in Chapter 9, an early global peak of CO_2 emissions creates flexibility for the magnitude and timing of reductions over the following decades. Not all nations must peak at the same time in order for a global peak to occur; increases must simply be equal to decreases at the point of the peak. As found in Chapter 10, one way to achieve 50/50 odds of avoiding a temperature increase of 2°C is to peak emissions globally in 2015, reduce Annex I emissions by 80% by 2030, and hold developing nation emissions flat between 2008-2030. I also noted that a flat emission line in the developing world could be difficult to achieve given projections of front-loaded energy demand, and that 2030 emissions from developing nations may need to equal 2008 emissions after an interim increase then decrease (section 10.2). In a modified scenario, by 2015, the limited annual increase in developing nation emissions would need to be offset by an equal or greater amount of decrease in Annex I emissions.

In this chapter, I focus on identifying regions, nations, and sources that show potential for contributing reductions to Eq. 12.1. A peak of global CO_2 emissions requires a series of peaks at the national and source-level.

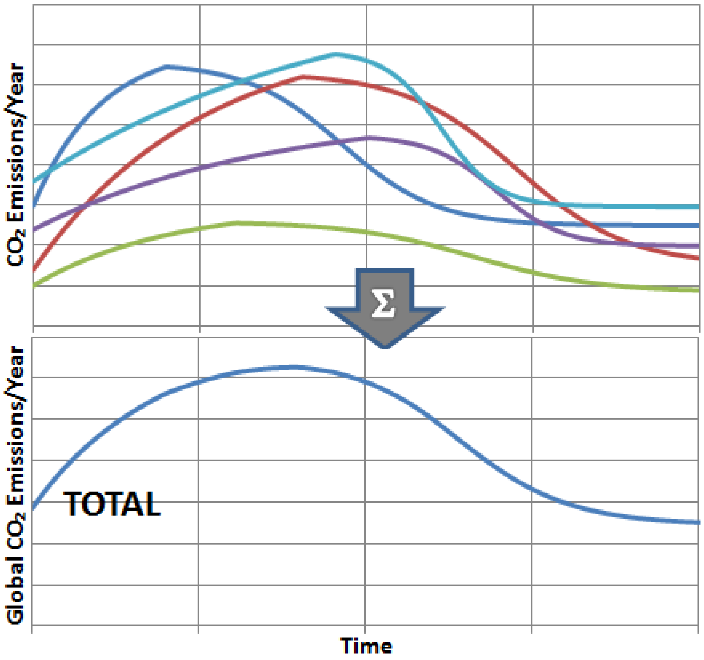

Figure 12-1: Illustration of a Series of Emission Peaks (top) and the Global Result (bottom)
Emission trajectories for the sub-global entities in the top graph are illustrative and do not represent specific nations or sources. The global total is the sum of the sub-global curves.

12.2 Methods

The goal of the chapter is to identify sub-global entities (regions, sources, nations) that have peaked as of 2008 – i.e., emissions are on a downward trend and appear unlikely in the future to exceed their maximum to-date. Identification of peaks is partly quantitative and partly qualitative, as described below.

Data are analyzed first by region (26 regions), then by emissions source (29 sources), then by nation (233 nations and other politically defined geographic units).[169] All graphs show annual emission data from 1970-2008 from the EDGAR 4.2 database [46].

The year of maximum emissions for each entity (region, nation, source) is identified based on a five-year rolling average. For example, the five-year rolling average in 2005 covers the years 2001-2005. The rolling average is used to avoid identification of false peaks, most common for regions and nations whose CO_2 emissions are dominated by anthropogenic fire-related emissions. In highly volatile cases, underlying emissions may be steadily trending up, but a single dramatic fire year can make current emissions look like a drop from a peak. The five-year rolling average helps avoid such false peaks.

For cases where the maximum year is the most recent one (2008), a peak cannot yet be observed. For cases where the maximum year is 2006-2007, peaks are identified as tentative.

For entities that show a maximum year other than 2008, I examine the emission reduction rate since the maximum to assess whether the peak is statistically significant (database uncertainty is ~10% for a given year) and to describe the nature of different peaks. Peaks are described based on the post-peak decline, as “plateau”, “gradual”, or “discontinuous”. A discontinuous peak is characterized by an abrupt and large (15-20% or more) decline within a few years after the peak. A gradual decline is on the order of 1% per year or less over a decade or more. A plateau is characterized by emissions that are sustained within ± 5% of the same level for a decade or more.

For growth and reduction rates, I use a five-year rolling average compound annual growth rate (CAGR) to capture true growth rather than volatility in emissions. Rates are calculated by first

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[169] EDGAR provides data for 233 places, including 231 geographic places plus international aviation and international shipping. This is 25 more places than the 206 sovereign states in the world (http://en.wikipedia.org/wiki/List_of_sovereign_states). I was able to reconcile the EDGAR places with the nations in the UN population database to within 0.4% of global population.

taking five-year rolling averages of emissions (e.g., 2004-2008) and then calculating a five-year CAGR.[170]

Peaks identified by this quantitative process are then subjected to a short qualitative assessment based on stage of national development, economic and social circumstances, and climate and energy policy. This part of the analysis aims to explore whether peaks are associated with adverse circumstances such as the volatility of low development or might be caused by societal crises such as war, civil disruption, or economic collapse. In such cases, peaks are likely to be temporary and not the type of permanent peaks that this analysis seeks to identify. Alternatively, if the nation is known to have an explicit policy in place that could plausibly generate reductions for a given source on an on-going basis, an observed peak is much more likely to be permanent.

As part of the qualitative assessment, current CO_2 emissions per capita of a nation relative to per-capita emissions of developed nations[171] is used as a proxy for stage of national development. While climate mitigation policy aims to break this link by leap-frogging developing nations into low- and zero-emission technologies, that has happened to only a limited extent to-date, so the relationship between emissions per capita and development stage holds for historical data. Emissions per capita are calculated by simple division of CO_2 emissions from the EDGAR database [46] by population from the UN population database [203]. In cases where anthropogenic forest fire and/or peat fire is a significant contributor to emissions, emissions per capita are calculated both with and without fire.

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[170] The five-year CAGR = average of 2004-2008 emissions/average of 1999-2003 emissions)^(1/5)-1.

[171] Developed nations have a range of 2008 emissions per capita (tons CO_2/person/year in OECD Europe: 8.7, Japan 9.9, US 17.7)

12.3 Region-level

Regions can be grouped into three categories: those that have not peaked yet, those that peaked in the 1970s-1990s, and those that peaked in 2006 or 2007 (tentative peaks).[172] I have done the assessment of peaking based on 5-year rolling average emissions.[173]

The first category, those regions that have clearly not peaked yet, is largest, representing 48% of 2008 global CO_2 emissions and 67% of global population. As shown in Figure 12-2, the trend in this group is led by rapid growth in China. Despite the attention paid to China[174], the emissions from other growing regions are, in total, of comparable magnitude.

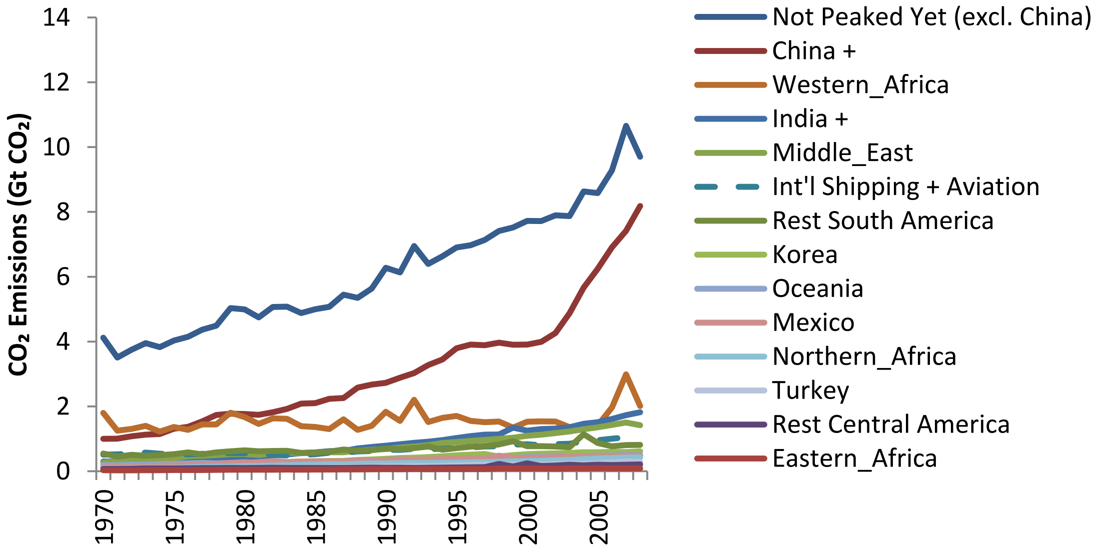

Figure 12-2: CO_2 Emissions for Regions that Have Not Yet Peaked[175]
All graphs in this chapter show annual emissions data (not rolling averages).
Regions in the legend are listed in descending order of 2008 emissions.
Data source: EDGAR 4.2 database. [46]

The second category, those regions that peaked in the 1970s-1990s, represents 23% of 2008 global CO_2 emissions and 17% of global population. As shown in Figure 12-3, this group consists primarily of OECD Europe, the former Soviet Union and Eastern Bloc, and Southeastern Asia. OECD Europe is down only 1% from its peak in 1980, on a three-decade plateau. Southeastern

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[172] There were no regional peaks in 2000-2005.

[173] This means that if I say a region peaked in 2006, it means that the rolling average emissions from 2002-2006 were the highest of any 5-year period in the 1970-2008 period.

[174] See China trends by source in Appendix K.

[175] Note, EDGAR has defined the "China+" region to include China, Hong Kong, Macao, Mongolia, and Taiwan. The "India+" region includes India, Afghanistan, Bangladesh, Bhutan, Sri Lanka, Maldives, Nepal, and Pakistan. The next section addresses emissions at the national level.

Asia is down 5% since its peak in the mid-1990s, with fairly stable emissions over the past decade and relatively low development level such that emissions are likely to rise.[176] Russia, Central Europe, Ukraine, and Asia-Stan emissions are down -26%, -37%, -44%, and -12% versus their respective peaks in the late 1980s and early 1990s. Large emission reductions accompanied the structural economic and social change brought about by the dissolution of the USSR in the early 1990s and these emission reductions have been largely sustained since.[177] This raises interesting potential research questions about characteristics of unplanned emission reductions that are sustained or not, but the social upheaval does not provide a model that other regions can or would desire to readily follow.

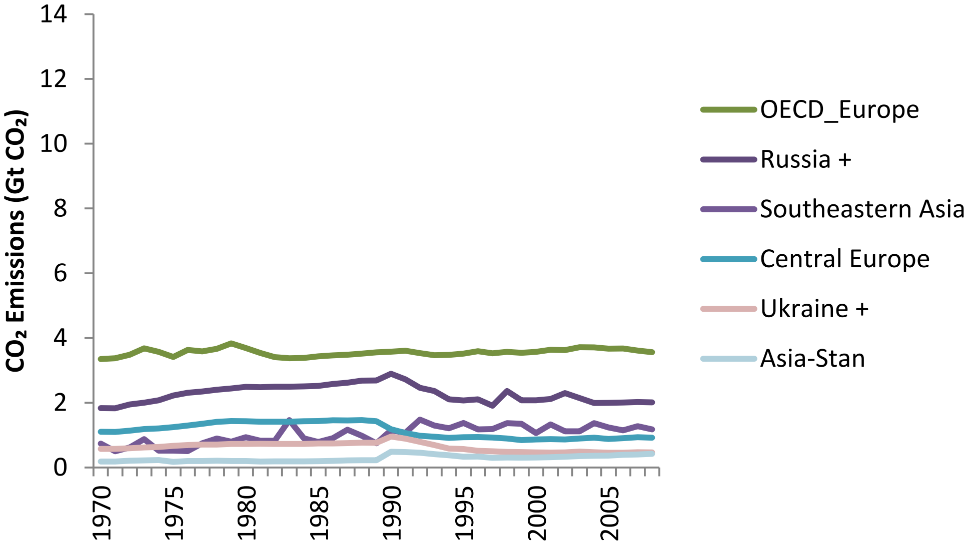

Figure 12-3: CO_2 Emissions for Regions that Peaked in the 1970s-1990s[178]

Note, all region-level and source-level graphs in this chapter have the same y axis range so that differences in relative emissions are visually obvious.

Data source: EDGAR 4.2 database [46].

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[176] Southeastern Asia CO_2 emissions in 2008 were 3.3 tons/person; compare to global average 5.4, China 6.1, OECD Europe 8.7, Japan 9.9, US 17.7.

[177] Aside from Russia+, per capita emissions in these regions are 10-20% below the OECD Europe average (8.7 tons CO_2/person): Russia+, 12.6; Ukraine+, 7.9; Central Europe, 7.2; Asia-Stan, 7.0.

[178] Note, EDGAR has defined the "Russia+" region to include the Russian Federation, Georgia, Azerbaijan, and Armenia (all former republics of the USSR). "Ukraine+" includes Ukraine, Belarus, and Moldova (all part of the former USSR). "Asia-Stan" also consists of former republics of the USSR: Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. "Central Europe" includes former satellite states of the USSR (Poland, Czech Republic, Slovakia, Hungary, Romania, Bulgaria), nations affected by the Yugoslav wars of the early 1990s (Bosnia and Herzegovina, Croatia, Serbia and Montenegro, Slovenia, Republic of Macedonia), the Baltic states claimed by the USSR (Lithuania, Latvia, Estonia), and a handful of other nations (Albania, Cyprus, Malta). "Southeast Asia" includes Brunei, Cambodia, Lao, Myanmar, Malaysia, Philippines, Singapore, Thailand, Timor-Leste, and Vietnam.

The final category, those regions with tentative peaks in 2006 or 2007, is shown in Figure 12-4 and represents 32% of 2008 global CO_2 emissions and 16% of global population. All nations in this category show modest reductions of 1-4% versus the tentative peak (based on rolling averages), with the exception of Brazil (-11%).[179] Uncertainty in the EDGAR database for CO_2 is ~10%, so 1-4% is within the band of data noise for such a short time period.[180] Japan and Canada are stable developed nations whose emissions have dropped 1% and 4% versus their respective peaks. A closer inspection of Canada's emissions variability (see Appendix K) shows that the peak may not be detectable. Southern Africa's decline of 2% likely reflects a slowdown in development rather than a true peak.[181] Indonesia and Brazil are both developing nations whose emissions swing dramatically with forest and peat fires. In both cases, emissions are down versus major peak fire periods in the mid-2000s. However, non-fire emissions are steadily increasing[182] (see Brazil and Indonesia by source in Appendix K).

The most prominent and promising in the category of tentative peaks is the United States (-1%).[183] Despite rancorous internal debate and the absence of Congressional action, US CO_2 emissions may have peaked in 2007, with recent reductions driven by lower emissions from public electricity and heat.[184] According to EPA data, this trend has been sustained through 2010. [196][185] Whether the trend will persist after the recession is not clear. The EIA's reference case[186] [204] projects a gradual small rise of US energy-related CO_2 emissions through 2035, but expects emissions to stay below the 2007 peak. See Appendix K for a breakdown of 1970-2008 US emissions by source.

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[179] If peaking is used as a metric, it will be necessary to determine what level of reduction definitively marks the passing of a peak and what other economic/structural/societal characteristics must also be true. (e.g., can a peak only be declared for an economically advanced, socially stable nation?) (e.g., reduction from a "peak" must be beyond the bounds of observed variability for the nation or source; more difficult to identify a peak in highly erratic emission patterns)

[180] See more detail on EDGAR in Appendix C.

[181] Southern Africa emissions are very low: 2.8 ton CO_2/person; compare to global average 5.4, China 6.1, OECD Europe 8.7, Japan 9.9, US 17.7.

[182] Note, Brazil and Indonesia non-fire emissions per capita are very low: 2.1 and 1.7 tons CO_2 /person, respectively; compare to China 6.1, OECD Europe 8.7, Japan 9.9, US 17.7.

[183] Canada (-4%) may also be promising, but their baseline emissions are much smaller than the United States. Politically, the irony is similar as the United States is the only one among 192 signatories not to ratify the Kyoto Protocol and Canada is the only signatory and ratifier to denounce the protocol (Dec. 2011).

[184] US peaked in 2005 based on annual emissions per EDGAR and in 2007 based on the 5-year rolling average (2003-2007).

[185] US EPA data show that USA CO_2 emissions in 2010 were 7% below 2007.

[186] Note, the EIA's 2012 report adjusted reference case CO_2 emissions for 2035 down by 8% versus the 2011 report. (the 2011 report projected 2035 emissions exceeding the 2007 peak)

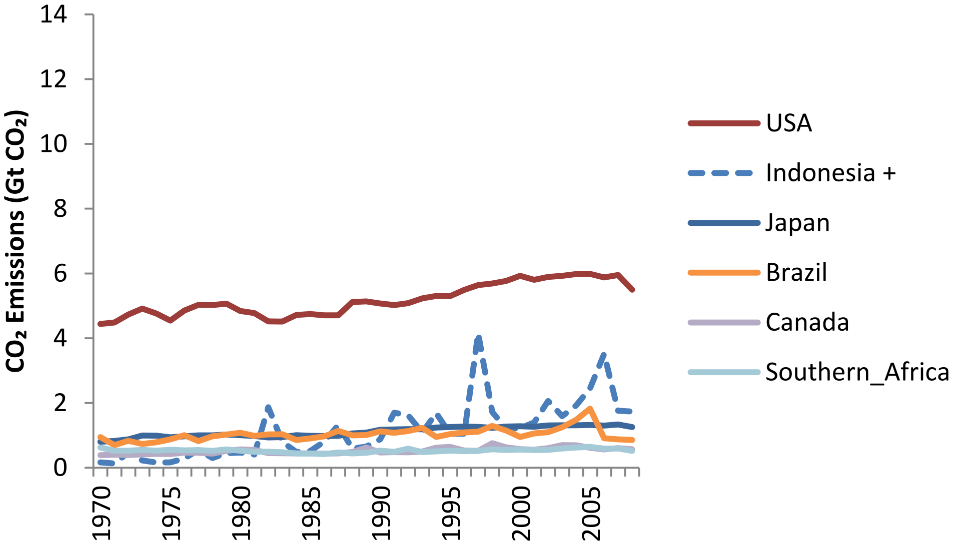

Figure 12-4: CO2 Emissions for Regions that May Have Peaked in 2006-2007.
Data source: EDGAR 4.2 database [46]

12.3.a Region-Level Summary

Emissions are summarized for the three regional groupings in Figure 12-5. The magnitude of the “Not Peaked Yet” category is larger and the slope is steeper than the “Tentative Peaks” and “Peaked before 2006” categories. The slope of the “Peaked Before 2006” category is nearly zero (flat), which means that regions who peaked in the past have tended to plateau. The slope of the “Tentative Peaks” category has recently declined steeply, but its trajectory over the past 15 years has shown significant volatility and the longer-term trend is inconclusive. Recalling the discussion in section 12.1, the sum of the decreases must exceed the sum of the increases in order to pass a global peak. This means a global peak would require that the slope of the Not Peaked Yet category become less steep upward and the slopes of the Peaked Before 2006 and Tentative Peaks categories become steeper downward until the conditions of Eq. 12.1 and Eq. 12.2 are met (shown here as Eq. 12.3 and Eq. 12.4):

Peak: $$\frac{d}{dt}(A(t)+B(t)+\cdots)=0 \qquad \text{Eq. 12.3}$$

Post-Peak: $$\frac{d}{dt}(A(t)+B(t)+\cdots)<0 \qquad \text{Eq. 12.4}$$

where A (t), B(t), etc. are the CO_2 emissions from each sub-global entity in time t

A global peak in 2015 (discussed in section 10.1) would require discontinuities in one or more of the lines of Figure 12-5.

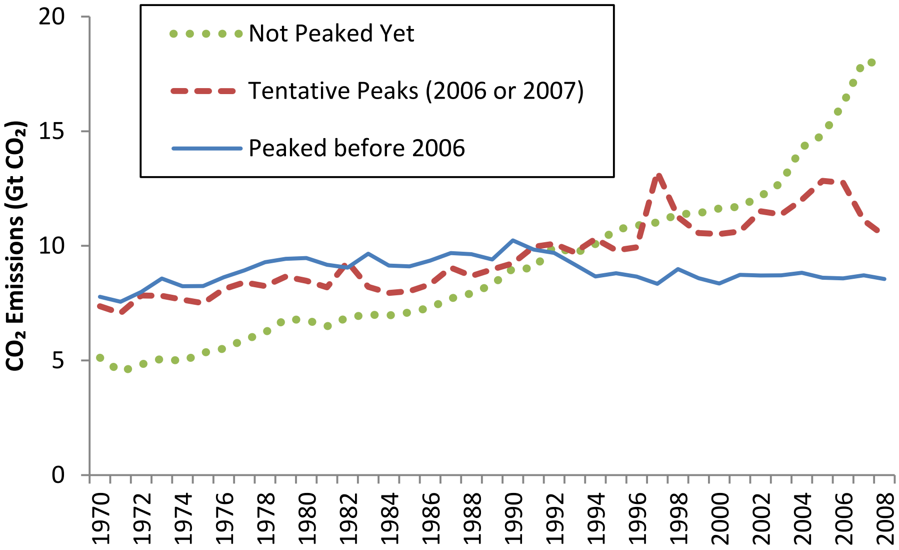

Figure 12-5: CO_2 Emissions by Region, Grouped into Three Peaking Categories
The "Not Peaked Yet" line is the sum of the regions shown in Figure 12-2. The "Peaked in 2006 or 2007?" line is the sum of the regions shown in Figure 12-4. These peaks are tentative. The "Peaked Before 2006" line is the sum of the regions shown in Figure 12-3.

12.4 Source-level

In this section, I will examine peaking behavior by source and start by looking at the breakdown of global 2008 CO_2 emissions by source in Figure 12-6.[187] This shows us that five sources contribute 80% of CO_2 emissions: public electricity and heat production, manufacturing and construction, forest and peat fires, road transportation, and residential and other. We will look at the trendlines for all sources first, and then look more closely at nation-level trends for the top sources on the search for peaks.

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[187] Note, the sum of sources equals the sum of regions equals the global total, to within <0.01%.

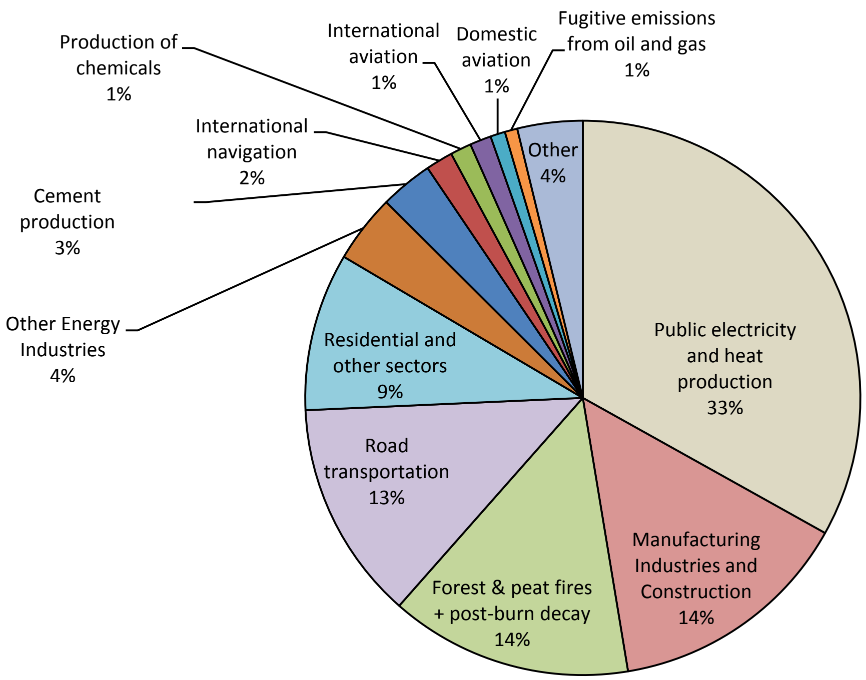

Figure 12-6: Global Anthropogenic CO_2 Emissions by Source, 2008.
Data source: EDGAR 4.2 database [46]

Figure 12-7 shows the opposite of the idealized series of peaks shown earlier in Figure 12-1. We see ~40 years of steady growth in public electricity and heat and road transportation, renewed growth in manufacturing and construction in the past decade, erratic emissions from forest and peat fires on a generally increasing trajectory, and steady growth in road transportation. Residential and other is the only top-5 source that shows a gradual decline and stabilization – likely due to substitution of public electricity and heat for purposes previously served by in-home coal, oil, and biomass burning. Smaller, but still significant, sources also show steady upward trends: other energy industries, cement production, international navigation and aviation, and chemicals production.

Amid the absence of peaks, it is worth noting one exception, too small to be visible in Figure 12-7 and shown separately in Figure 12-8. Fugitive emissions from oil and gas and fugitive emissions from solid fuels (e.g., coal)[188] declined significantly (40-60%) and rapidly in the late 1970s/early 1980s and have been fairly steady over the past decade. This discontinuous change followed technology breakthroughs that used fugitive CO_2 for enhanced oil and gas recovery.[189]

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[188] See footnote 57 for definition of fugitive emissions.

[189] Enhanced oil and gas recovery is a process that injects CO_2 and other gases into a well to increase pressure and thereby increase the flow of oil and gas.

The next few sections take a closer look at individual sources, focusing on three of the top five sources: 1) public electricity and heat, 2) forest and peat fires, and 3) road transportation. Residential and other and Manufacturing and construction can show false peaks due to substitution (between sources) and leakage (between nations), so they are omitted from closer inspection. Residential emissions that decrease may re-appear as public electricity and heat; manufacturing emissions may peak in one nation because the manufacturing shifts to another nation.

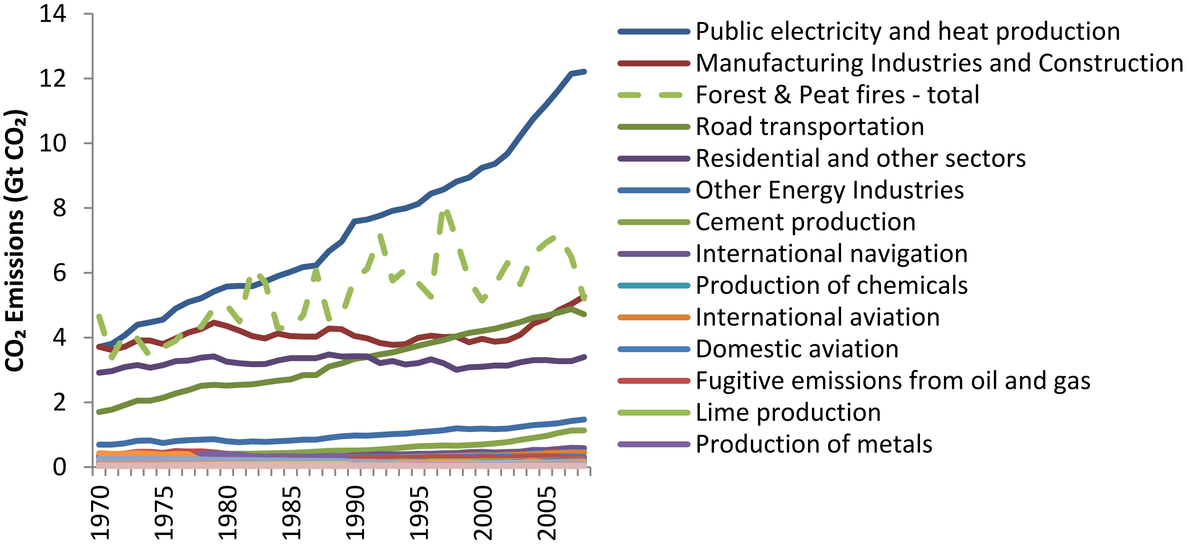

Figure 12-7: Global CO_2 Emissions by Source, 1970-2008.
Data source: EDGAR 4.2 database [46]

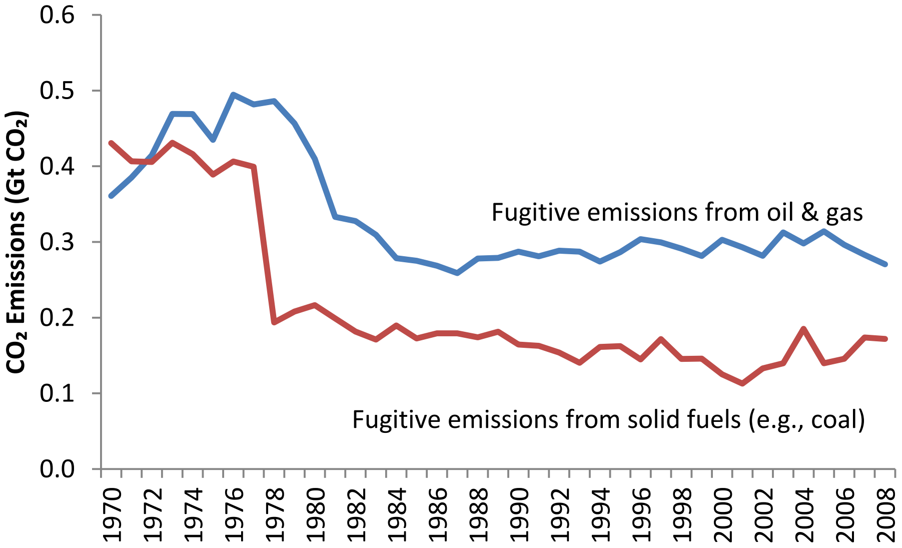

Figure 12-8: Global CO_2 Emissions from Fugitive Emissions, 1970-2008
Data source: EDGAR 4.2 database [46]

12.4.a Source-level: Public electricity and heat

Figure 12-9 shows public electricity and heat production for the 20 nations emitting the most CO_2 from this source. This figure is dominated by the dramatic growth in China, but a few other points deserve mention. First, of the twenty largest electric and heat emitters, only three have had declines over the most recent 5-year window: USA (-0.3%), Canada (-2%), and Ukraine (-2%). Of these, only the Ukraine has declines over both the 5-year and 10-year windows, coincidental with social and economic re-structuring. The US and Canada declines are too small and over too short of a period to be statistically significant. Electricity and heat for all other top-20 emitters, has been either growing or flat over the most recent 5- and 10-year periods.

To find additional peaks for electricity and heat beyond the Ukraine, it is necessary to review much smaller electricity and heat producers, shown in Figure 12-10. Notice that the y axis covers a small fraction of the y axis in the previous figure. The chart includes post-1990 declines from a now-familiar set of nations facing post-USSR and post-Yugoslav War re-structuring. The largest nation demonstrating a durable peak for electricity and heat during a peaceful, prosperous economic period is Denmark; we will return to Denmark in section 12.5.a.

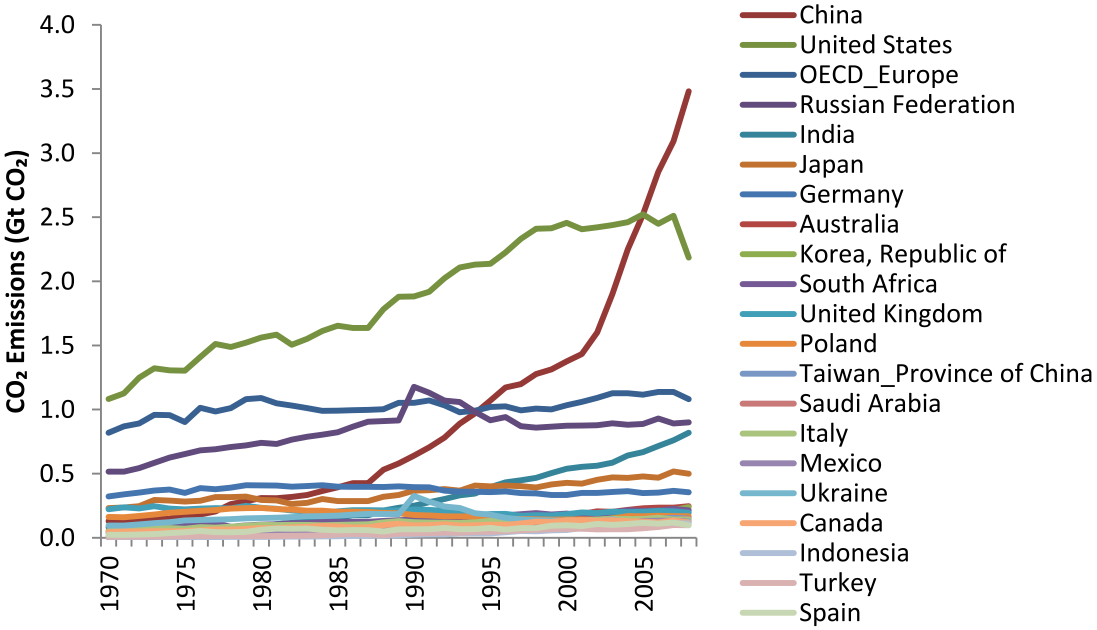

Figure 12-9: CO_2 Emissions from Public Electricity and Heat by Top-20 Nations[190]

Data source: EDGAR 4.2 database [46]. Nations are listed in rank order of their 2008 emissions from public electricity and heat.

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[190] Top-20 as ranked by their CO_2 emissions from public electricity and heat in 2008.

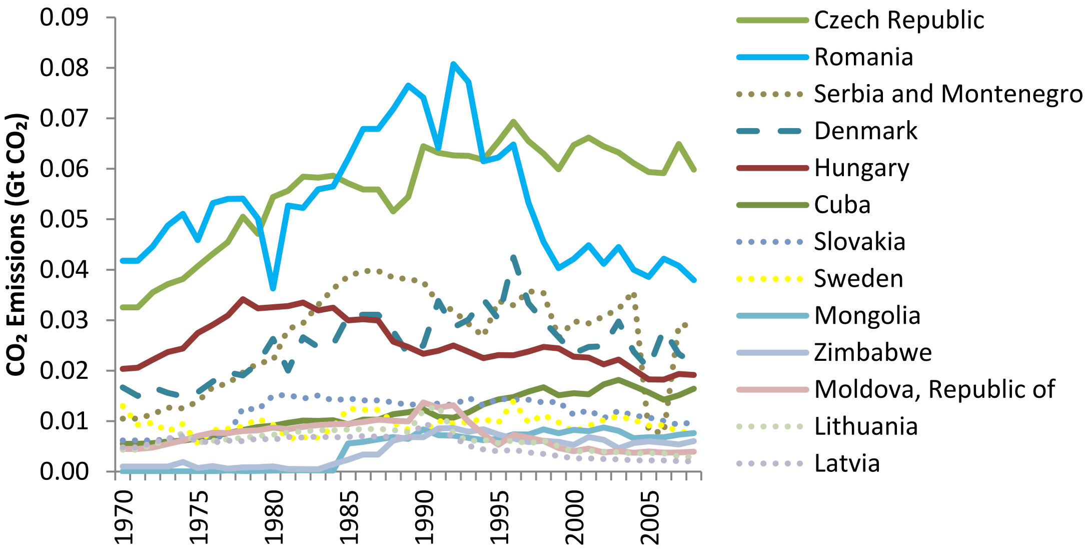

Figure 12-10: CO_2 Emissions from Public Electricity and Heat from Medium-Sized Emitters with Declining Emissions

Data source: EDGAR 4.2 database [46]. Nations are listed in rank order of 2008 emissions from electricity and heat. Dotted lines denote the five nations with the largest 5-year declines.

12.4.b Source-level: Anthropogenic Forest and Peat fires

Forest and peat fire emissions are dominated by a few primary contributors. In 2008, Indonesia accounted for fully 25% of global CO_2 emissions from fire. The Democratic Republic of Congo is in the second spot with 18% of global fire emissions. Third and fourth were Brazil and the Central African Republic. 81% of fire emissions are generated by the 14 nations shown in Figure 12-11.

Amid widespread growth in forest- and peat-related emissions, two nations stand out for steady reductions over ten years from 1998-2008: Myanmar/Burma and the Russian Federation (dotted lines). Myanmar's fire emissions are primarily from forests, and there has been a conscious national effort to reduce deforestation and increase forest cover, captured in the 1995 Myanmar Forest Policy.[205][191] The Russian Federation's fire emissions are primarily from peat burning, and the decline was temporary; massive peat fires returned in summer 2010.[192]

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[191] "The Myanmar Forest Policy 1995 focused on six priorities including protection, sustainability, basic needs, efficiency, participation and awareness. It aimed at managing 30 percent of the total land as Permanent Forest Estate (PFE)."

[192] Many of Russia's peat bogs were drained in the early/mid 1900s and are highly fire-prone. http://www.nytimes.com/2010/08/13/world/europe/13russia.html

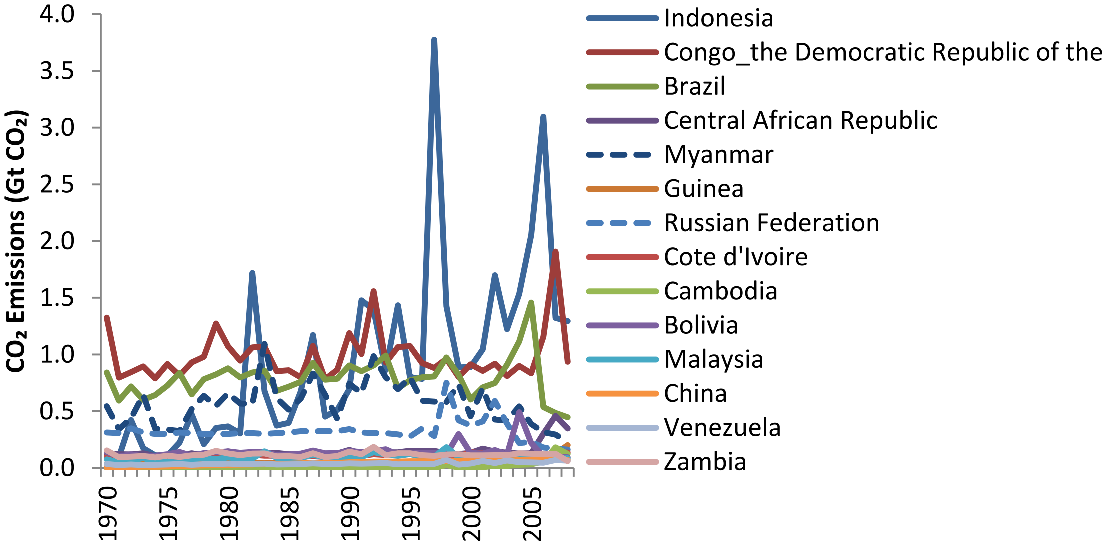

Figure 12-11: CO_2 Emissions from Fire by Leading Emitters

Data source: EDGAR 4.2 database [46]

12.4.c Source-level: Road transportation

Figure 12-12 shows the CO_2 emissions from road transport for the 17 nations who each account for at least 1% of those emissions. The glaring take-away from this chart is that the United States accounts for 28% of global road transport emissions. Second place goes to China, with 6%. Beyond magnitude, though, we are looking for peaks, and they are few and far between. In fact, among the top-100 road transport emitters, only four show declines on a 5- and 10-year rolling average: Japan (-1%, -0%), Germany (-2%, -1%), Lebanon (-1%, -1%), and Hong Kong (-15%, -5%).[193] Hong Kong's road transport emission reductions, shown in Figure 12-13, have come about as the result of conscious urban transportation planning choices, including a Railway Development Strategy in year 2000. This planning has resulted in 90% of trips including public transit and a subsidized switch from diesel to LPG [54][194] for the majority of taxis and public light buses.[195] [206]

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[193] While the US road transport CO_2 emissions declined in 2008, they are up on a 5-year and 10-year rolling average.

[194] Liquefied petroleum gasoline (LPG) emits 15% less CO_2 per Btu than diesel, per EIA.

[195] The Railway Development Strategy 2000 planned for 70% of people and 80% of jobs to be within 1km of a railway station. The plan included 732 footbridges. In the works: high-speed rail to mainland and zero/low-emission zones.

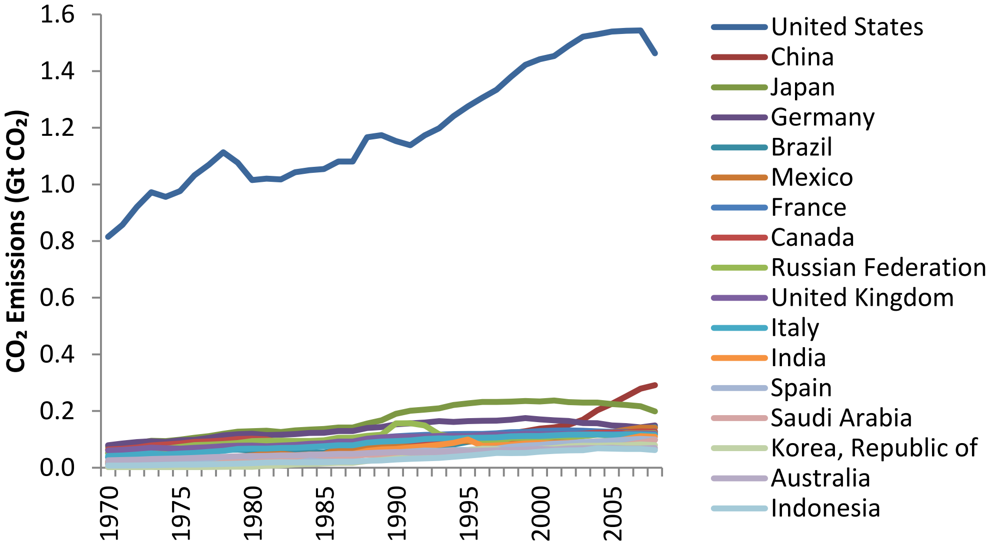

Figure 12-12: CO_2 Emissions from Road Transport by Leading Emitters

Data source: EDGAR 4.2 database [46]

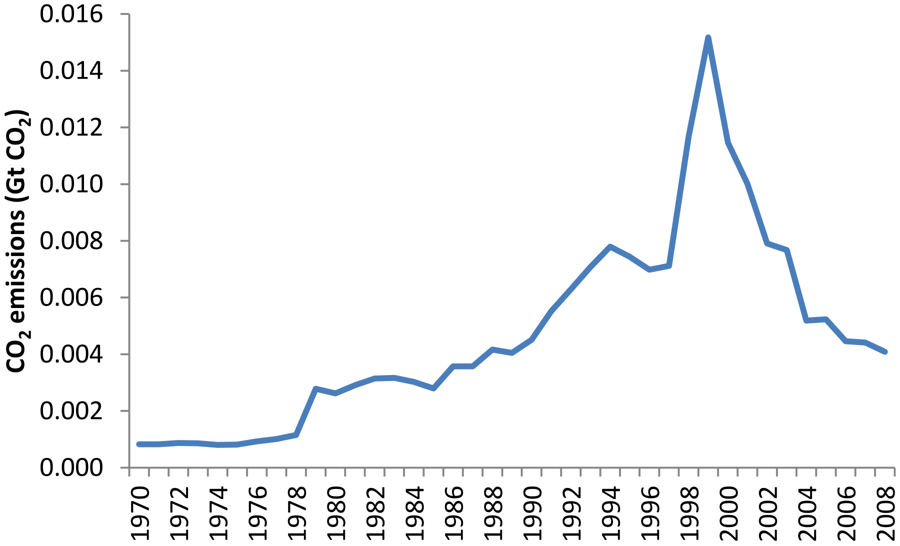

Figure 12-13: CO_2 Emissions from Road Transport in Hong Kong

Data source: EDGAR 4.2 database [46]

12.5 Nation-level

I calculated 5- and 10-year CAGRs for each nation's CO_2 emissions and then graphed all nations that have 5-year declines to visually identify any that are on a clear decline from their peak (28 of the 233 entities).[196] Among the limited examples, two different models of observed emission decline emerged: 1) gradual reductions from a peak and 2) sharp, discontinuous reductions from a peak, followed either by a period of stability or continued gradual decline. The key take-away from this section and this chapter is that discontinuous change is common, and that a future outcome that relies on discontinuity is within the realm of possibility.[197]

Seven nations have experienced a gradual decline in CO_2 emissions over an extended period of time, notably Germany[198] and Myanmar/Burma[199]. These nations are shown in Figure 12-14. Fourteen nations have experienced a discontinuous decline in emissions, most then followed by either a period of stability or of continued gradual decline. These nations are shown in Figure 12-16, Figure 12-17, and Figure 12-18 (each with different scales). Finally, seven nations shown in Figure 12-15 have experienced a recent decline in emissions, that may or may not be permanent (this group includes the United States, which was shown in Figure 12-4 and is omitted from Figure 12-15 due to relative size of the other nations).

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[196] See methods section 12.2. There are 206 sovereign states; the EDGAR database includes additional entities.

[197] Note, despite the observed discontinuities of peaks and the essential role of discontinuities in achieving climate targets, models of emissions scenarios routinely assume smooth changes. Understandably, discontinuities are nigh-impossible to forecast. But, it is important to recognize that the impossibility of a discontinuity in a model does not suggest impossibility of a discontinuity in real life.

[198] Germany and the UK both shifted substantial manufacturing out of country during this time period, so the dotted line that excludes manufacturing excludes the benefits of "substitution" across borders. Germany still shows steady decline on the dotted line, while the UK is fairly stable.

[199] Note, Myanmar's emissions decline coincided with governmental rule by the military from 1989-2011 and accompanying years of unrest. 95% of Myanmar's 2008 emissions were produced by forest and peat fires, and the entire decline is attributable to the reduction in those fires. Non-fire CO_2 emissions in Myanmar have increased steadily for the past 40 years, and at 0.5 tons/person, are currently still far below most nations: China 6.1, OECD Europe 8.7, Japan 9.9, US 17.7.

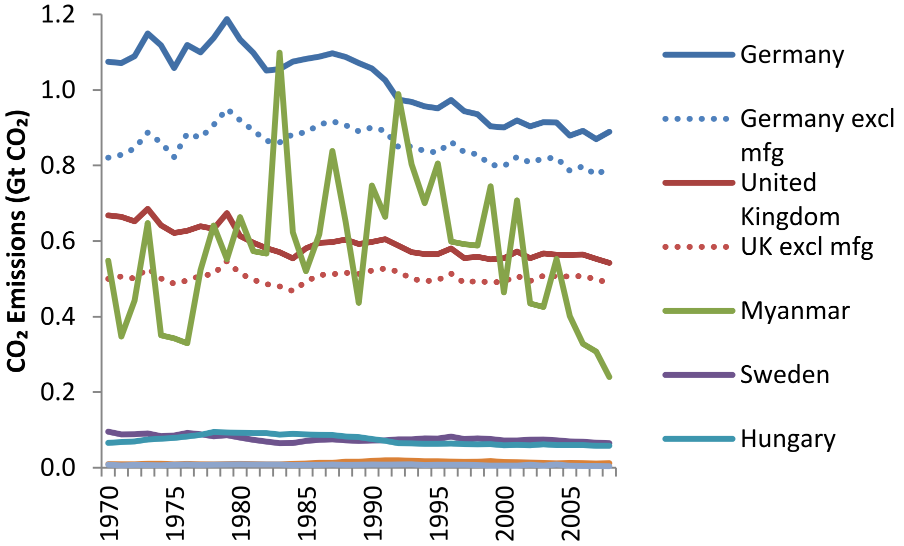

Figure 12-14: Nations with Long, Gradual CO_2 Emissions Declines

Data source: EDGAR 4.2 database [46]

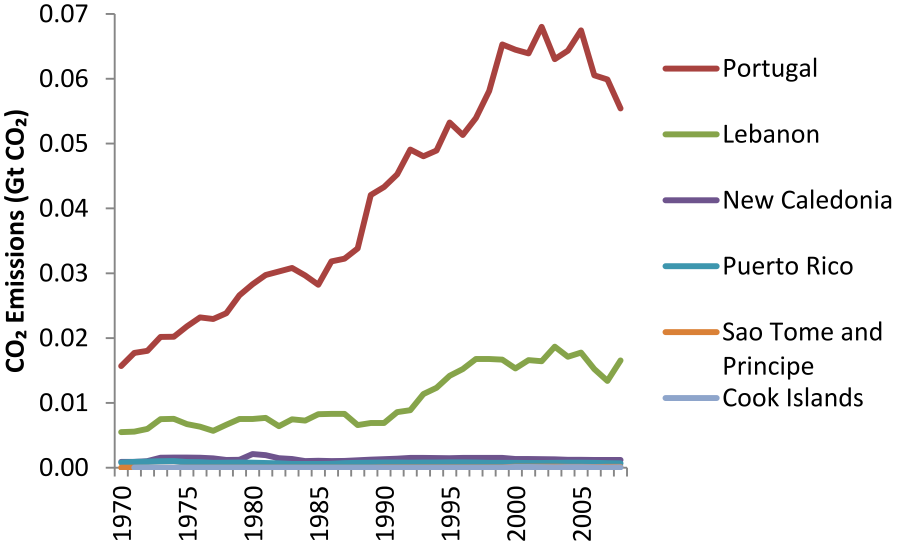

Figure 12-15: Nations with Recent CO_2 Emissions Declines

The USA is not shown due to its much larger emissions; see Figure 12-4 for USA.

Data source: EDGAR 4.2 database [46]

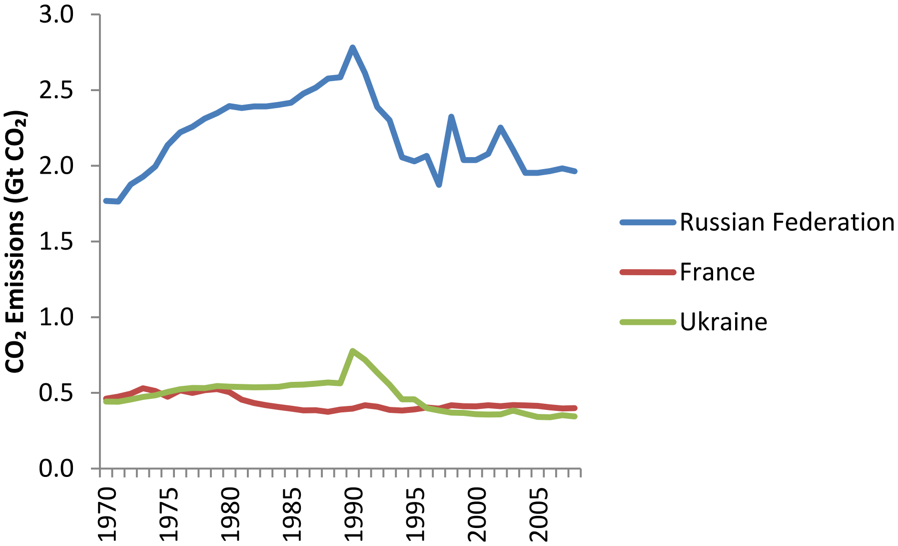

Figure 12-16: Large Nations with Discontinuous CO_2 Emissions Declines
Data source: EDGAR 4.2 database [46]

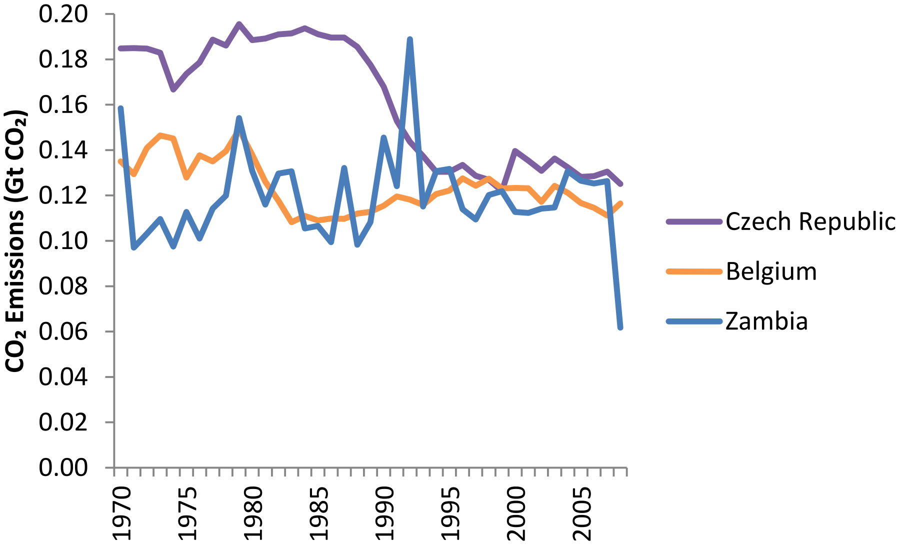

Figure 12-17: Medium Nations with Discontinuous CO_2 Emissions Declines
Data source: EDGAR 4.2 database [46]

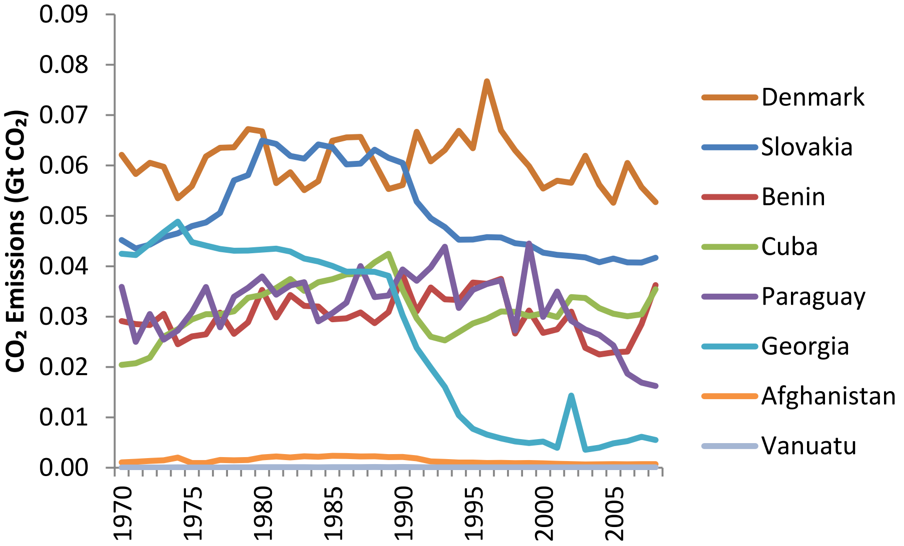

Figure 12-18: Small Nations with Discontinuous CO_2 Emissions Declines
Data source: EDGAR 4.2 database [46]

12.5.a Denmark

Denmark was highlighted as a leader in an earlier section for emission reductions in electricity and heat and also appears in Figure 12-18 as an example of discontinuous change. Figure 12-19 shows the breakdown of emissions by source in Denmark. Denmark has experienced repeated discontinuous reductions, first in residential and other, then in manufacturing and construction, then in inland navigation, and most recently and on the largest scale in public electricity and heat. The most recent change is attributable to Denmark's commitment to zero fossil energy by 2050 and a national commitment to climate change mitigation. [207]

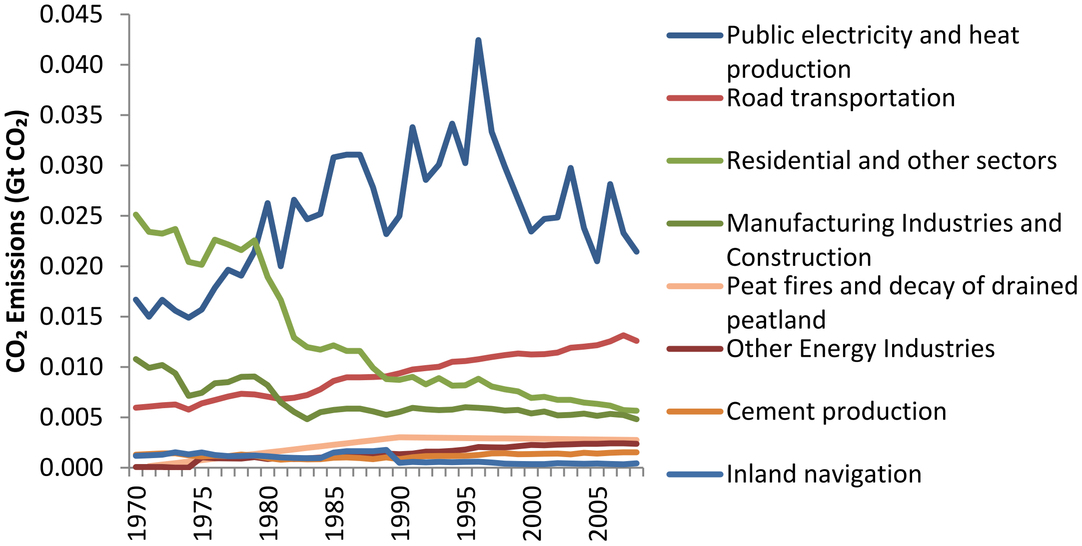

Figure 12-19: Denmark CO_2 Emissions by Source, 1970-2008

Data source: EDGAR 4.2 database [46]

12.6 Summary

In summary, there are not many proven peaks so far – if we define proven peaks as those that are statistically significant and those for which economic and social circumstances do not suggest an imminent rise. While there are few national examples of gradually declining emissions (Germany, UK), the few peaks that have clearly been observed to-date have been dominated by marked discontinuities (i.e., abrupt reductions) – either due to structural economic change (e.g., former USSR and Eastern Bloc), technology introduction (e.g., enhanced oil and gas recovery use for fugitive emissions), or policy intervention (e.g., Hong Kong's transportation plan, Myanmar's forest policy, Denmark's zero fossil fuel plan).

Because there have been few peaks to-date, early peaking for global CO_2 emissions would require a discontinuity in the current trends and a rapid series of peaks. These few examples illustrate that discontinuities can happen and that discontinuities should not be discounted. In fact, as discussed in Chapter 10, discontinuous peaks in Annex I nations and abrupt plateaus in developing nations within the next decade would be required to avoid a global temperature increase of 2°C.

Chapter 13 Improving the Likelihood of Avoiding 1.5°C or 2°C via non-CO_2 Pollutants

In Section II and Section III, I emphasized the influence of short- and medium-lived pollutants on near-term climate outcomes. The goal of avoiding 1.5°C or 2°C (Box 2) straddles the near-term and long-term, since the range of likely[200] temperatures for 2050 is 1.4-2.8°C across a range of scenarios that modelers consider plausible (see Table 2-6). This raises the question of the role that mitigation of short- and medium-lived pollutants can play in avoiding 1.5°C or 2°C.

In this chapter, I examine the extent to which reductions in short- and medium-lived pollutants can improve the likelihood of avoiding 1.5°C or 2°C. I assume that CO_2 emissions are on a trajectory that is likely to avoid 2°C of equilibrium warming and therefore focus attention on the potential for transient temperature peaks. After assessing the limited circumstances in which such temperature peaks could exist, I analyze the potential for reductions of short- and medium-lived pollutants to improve the likelihood of avoiding those transient temperature peaks. This framework of "improving the likelihood" is a conceptually different way of viewing mitigation of short-lived pollutants than the existing frameworks that were presented in Chapter 6 and Chapter 7.

13.1 Methods to Quantify "Improving the Likelihood"

The question that I explore in this section is the extent to which reductions in emissions of short- and medium-lived warming pollutants can improve the likelihood of avoiding a global temperature increase of 1.5-2°C above pre-industrial levels. Since short-lived pollutants and the majority of medium-lived pollutants will be gone from the atmosphere by equilibrium (section 4.1) and since 2°C will be reached by mid-century in absence of very aggressive mitigation (section 2.3 and Chapter 9), the question applies specifically to the next century or so of transient warming.

It is reasonable to expect that temperature will increase steadily from transient to equilibrium (see section 6.2.b.ii.i). In this case, with no intermediate temperature peaks, there is no role for short- and medium-lived pollutants to play in avoiding warming of 2°C. The only role for short- and medium-lived pollutants is in a situation in which transient warming would exceed 2°C. This role is often termed "peak shaving". [42] First, however, there must be a temperature peak to shave. I will use the term "temperature peak" in this chapter to refer to peak warming, to distinguish it from the term "peak" in the previous chapters that referred to peak emissions.

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[200] See footnote 17 for definition of likely.

In the analysis below, I describe the circumstances that could create transient warming above 2°C that would be consistent with equilibrium warming below 2°C and the timing of when that temperature peak might occur. After establishing a limited set of circumstances in which a temperature peak might occur, I then calculate the improvement in the likelihood of avoiding transient warming of 2°C that could be achieved via reductions of short- and medium-lived pollutants.

I use transient climate response (TCR) (°C per 3.7 W/m^2) to calculate transient warming. Transient climate response is, by definition, calculated for the hypothetical experiment in which CO_2 concentration is doubled above pre-industrial by increasing the concentration by 1% a year over 70 years, then stabilized (at an RF of 3.7 W/m^2). The temperature change above pre-industrial in year 70 in that hypothetical experiment is defined as the TCR; the temperature change for the doubled CO_2 at equilibrium is defined as equilibrium climate sensitivity (ECS). [62] As shown in Table 13-1, the TCR is half to two-thirds of the ECS, with an average TCR/ECS ratio of 0.55. The remainder of the temperature increase takes hundreds to thousands of years to appear (recall Figure 6-4).

The cumulative probability distributions for TCR and ECS from three different sources are shown in Figure 13-1. Sources include IPCC AR4 [62], NRC 2011 [42], and Rogelj et al. 2012 [37]. IPCC AR4 and NRC 2011 provide TCR and ECS explicitly. Rogelj et al. 2012 provides ECS implicitly, and these results have been extracted and included for consistency with prior chapters. Rogelj et al. 2012 [37] used similar methods and the same model (MAGICC) as Meinshausen et al. 2009 [170] (discussed in Chapter 9) to present the likelihood of avoiding a given global temperature increase at equilibrium for a given net radiative forcing (RF) (Figure 13-2). I derive the cumulative probability distribution for ECS from Rogelj et al. by taking vertical slices of Figure 13-2, dividing the temperature by the radiative forcing where the temperature vertical crosses each likelihood line. Because the likelihood lines are nearly linear in Figure 13-2, nearly the same ECS distribution results regardless of which temperature vertical is chosen and I took the average across seven temperature verticals. Note that these linear lines imply constant climate sensitivity across the range of RF. For the range of temperature increases discussed in this chapter (1.5-2°C), linearity is likely a reasonable assumption. Feedback-related limitations of this assumption at higher temperatures will be discussed in section 15.1. The TCR is then derived using the average TCR/ECS ratio of 0.55 referenced above. A derived TCR is also calculated for AR4 and a derived ECS is also calculated for NRC 2011 (see Figure 13-1). Hansen et al. 2011 [43] argue that most climate models produce a transient response that is too small relative to the equilibrium response; if that were correct, then the TCR curves in Figure 13-1 would shift somewhat to the right and be slightly less steep, the transient warming curves derived in Figure 13-4 and Figure 13-5 would shift left and be slightly steeper, the likelihood of a transient temperature peak would increase (see section 15.1.c), and results would show a larger impact of short- and medium-lived pollutants on the likelihood of avoiding a transient temperature increase of 1.5°C or 2°C than I show below.

Several observations can be made on Figure 13-1. First, TCR (solid lines) is fairly tightly constrained – both within a given curve and across curves. The TCR curves are relatively steep and they are tightly spaced at the bottom and spaced by only about 0.5°C at the top. The TCR curves are all steeper than their respective ECS curves, which makes sense mathematically (TCR=.55*ECS). All sources have the same best estimate for ECS (3°C), and only Rogelj et al. show a long tail on ECS, though AR4 does not rule it out [62]. Finally, there is a range of steepness among the curves. For TCR, AR4 is least steep (widest confidence interval), a point that will become important in the discussion in section 13.2.

The last step in the process is to calculate the improvement in the likelihood of avoiding transient warming of 1.5°C or 2°C. I create graphs of the likelihood of exceeding 1.5°C and 2°C at different levels of radiative forcing (see Figure 13-5), which enable comparisons with the radiative forcing reductions possible via short- and medium-lived pollutants (from section 4.4). Similar graphs for likelihood versus CO_2 emissions are found in Appendix L for comparability with Chapter 9 and Chapter 15. The likelihood curves are calculated based on the TCR distributions in Figure 13-1. For each curve, I calculated radiative forcing at each likelihood point by the following equation:

$$RF = \frac{T * 3.7 \; {}^{W}/_{m^2}}{TCR} \qquad \text{Eq. 13.1}$$

T is the temperature increase being avoided (1.5°C or 2°C)
TCR is the transient climate response (TCR) at the likelihood point (°C)

Note that for Rogelj et al., this method applied to ECS produces the same result as taking vertical slices of Figure 13-2 (see Appendix L for transient and equilibrium results using the Rogelj et al. data).

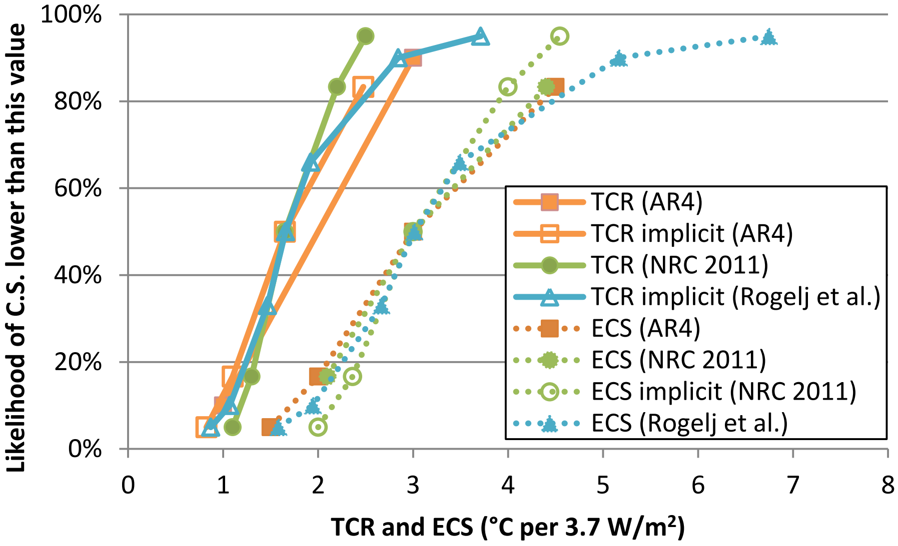

Figure 13-1: Cumulative Probability Distributions of Equilibrium Climate Sensitivity and Transient Climate Response

Solid markers signify data that were provided in the cited source. Outlined markers signify data that were calculated, using the relationship, TCR = 0.55 ECS (see Table 13-1). Two TCR lines are provided for AR4 [62]: the one with solid markers shows the 80% confidence interval provided explicitly for TCR and the one with outlined markers is calculated from the cumulative probability distribution for ECS. Similarly, two ECS lines are provided for NRC 2011 [42]: the one with solid markers shows the distribution explicitly provided for ECS and the one with outlined markers is calculated from the cumulative probability distribution for TCR. ECS data from Rogelj et al. [37] were visually interpolated from Figure 13-2, using an average of multiple points (T/RF) along each likelihood line. Note that the lines in Figure 13-2 are nearly straight, so the average does not differ significantly from any single point.

	Transient Climate Response (TCR)	Equilibrium Climate Sensitivity (ECS)	Ratio (TCR / ECS)
IPCC AR4 2007 [62]	1-3 °C (80% confidence)	2.0 – 4.5 °C (66% confidence)	50-66%
NRC 2011 [42]	1.65 °C (best estimate)	3.0 °C (best estimate)	52%
	1.3 – 2.2 °C (66% confidence)	2.1 – 4.4 °C (66% confidence)	50-62%
	1.1 – 2.5 °C (90% confidence)	na	na
Rogelj et al. 2012 [37] (implicit and derived)	1.5 – 1.9 °C (66% confidence, derived from ECS)	2.7-3.5°C (66% confidence)	55%
	1.1-2.8°C (90% confidence, derived from ECS)	1.9-5.2°C (90% confidence)	55%

Table 13-1: Transient Climate Response and Equilibrium Climate Sensitivity Estimates
Data are reported from the listed reports. NRC = National Research Council of the U.S. National Academy of Science. The 55% ratio used to calculate the implicit TCR is the average ratio from the AR4 models (AR4 Table 8.2) [41], as summarized by NRC 2011 [42]. Note that the TCR/ECS ratio range in this table is generally consistent with Figure 6-4, which showed that roughly 50% of global warming is coincident (within decades) with the change in RF and that global warming 100 years after the RF stabilizes is approximately 60% of equilibrium warming.

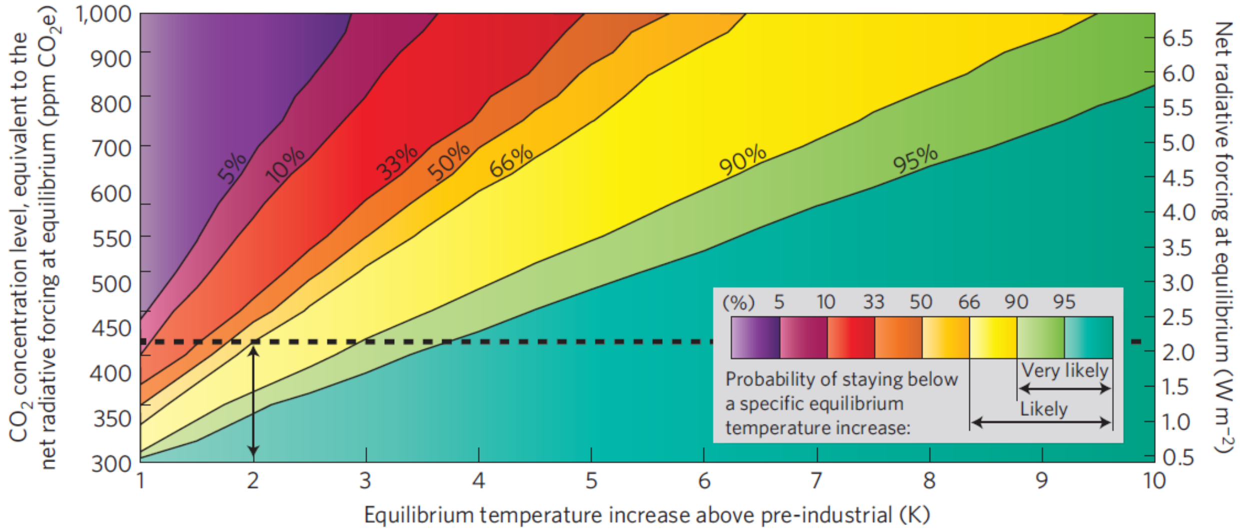

Figure 13-2: Likelihood of Avoiding a Given Global Temperature Increase at Equilibrium for a Given RF
Reprinted by permission from Macmillan Publisherrs Ltd: Rogelj, Meinshausen, and Knutti, Nature Climate Change 2012. [37] Net RF is shown on the right axis. The forcing is translated on the left y axis into the commensurate level of atmospheric CO$_2$ (if all other pollutants cancelled each other out, as they do approximately at present). CO$_2$ eq is defined here as equivalent to net RF at equilibrium, not the more commonly shown global warming potential (cumulative RF).

13.2 Results and Discussion

In this section, I will first describe the circumstances in which a temperature peak could occur on a path with equilibrium warming of less than 2°C, then describe the role short- and medium-lived pollutants could play in avoiding a transient temperature peak.

13.2.a Situations that Could Create a Transient Temperature Peak Above 2°C

If global emissions were on track to stay below 2°C at equilibrium, odds would be good that the transient warming would also stay below 2°C, at least in the near-term. As we will see in Chapter 15, the transient RF from a CO_2 emission budget with 50/50 odds of avoiding 2°C of equilibrium warming would be 3.3 W/m^2 [201] and the best estimate of transient warming corresponding to this RF is 1.5°C,[202] well below 2°C (see Table 15-2). The radiative forcing corresponding to 2°C of transient warming using a best-estimate of transient climate response is 4.5 W/m^2, well above 3.3 W/m^2 and even farther above the actual 2005 radiative forcing of 1.6 W/m^2. [75][203]

There are, however, two situations in which a transient temperature peak could occur. First, front-loaded CO_2 emissions could be combined with a high transient airborne fraction, followed by very low (or negative) future emissions and a low equilibrium airborne fraction. As noted in section 6.2.b.ii.ii, the RF difference between the transient and equilibrium would need to be large to create a temperature peak in the present century. This possibility is discussed in further detail in section 15.1.c.

Alternatively, RF from non-CO_2 pollutants could create a transient temperature peak and their reduction could avoid it. This situation is the focus of this chapter. To create a temperature peak above 2°C, RF from CO_2 plus RF from non-CO_2 must add to more than the RF required for 2°C of transient warming (see Figure 13-3): 4.5 W/m^2 at best-estimate TCR (left chart) or 3.0 W/m^2 at a very high TCR (right chart). In Figure 13-3, this addition is visually apparent from the blue curve (CO_2 RF) and the dotted black line (non-CO_2 RF). If these two lines intersect, then a transient temperature peak above 2°C will occur.

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[201] The CO_2 budget, from pre-industrial through equilibrium, that corresponds to a 50% likelihood of avoiding 2°C of equilibrium warming is 4,190 Gt CO_2, assuming that 20% of the equilibrium RF is contributed by non-CO_2 pollutants (difficult-to-reduce sources of CH_4 and N_2O, plus remnants of halocarbons). The corresponding transient RF, assuming a 46% airborne fraction is 3.3 W/m^2. I will explain the derivation of these budget numbers in Chapter 15.

[202] Calculation: $3.3\ W/m^2 * 1.65°C / 3.7\ W/m^2 = 1.5°C$.

[203] 90% confidence interval: 0.6-2.4 W/m^2

The blue CO_2 curve is RF from the cumulative CO_2 emissions shown on the right side of Figure 9-5, which have 50/50 odds of avoiding equilibrium warming of 2°C. The red line is the not-to-exceed RF line. The distance between the dotted black line and the red line is the current anthropogenic RF excluding CO_2 (0.1 W/m^2, which places it above the red line). CO_2 is thus counting up from zero and non-CO_2 is counting down from the not-to-exceed line; that is why RF will be exceeded and a transient temperature above 2°C will result if the lines intersect.

Clearly the blue curve and black dotted line are far from intersecting today on either the left or right charts in Figure 13-3. If RF from non-CO_2 pollutants remained flat, there would be no transient peak under the TCR best estimate case and over 150 years until the lines crossed under the TCR high estimate case.

However, the magnitude of RF from cooling aerosols is widely uncertain and reductions of these pollutants (especially SO_2) are underway to reduce respiratory illnesses. If cooling aerosols were to be completed eliminated, the dotted black line would move down to join the bottom green line. Full elimination of cooling aerosols is unlikely since maximum technically feasible reductions for SO_2 are estimated at 69-82% (recall section 4.4). Additionally, some warming aerosols are co-emitted with the cooling aerosols, so eliminating both would be a net zero change in the dotted black line. Nonetheless, if the dotted line were to join the green line, transient temperature would exceed 2°C by mid-century under best-estimate TCR and immediately upon the event of the lines joining under high TCR.

As CO_2 emissions are dramatically reduced, many of the co-pollutants will also be eliminated. If all short-lived pollutants were eliminated at some point over the next century, the dotted black line would move down to join the brown line. In this case, transient temperature could exceed 2°C in the late 2200s under best-estimate TCR and immediately upon the event of the lines joining under high TCR.

Another way for the dotted line to move down would be if emissions of non-CO_2 pollutants increased. In the TCR best estimate case, the increase would need to be considerable to move the black dotted line down sufficiently to cross the blue curve. In the high TCR case, a small increase in emissions could push the intersection point from the mid-2100s to the middle of this century.

In summary, if CO_2 is being managed to avoid an equilibrium warming of 2°C, emissions of non-CO_2 pollutants must also be constrained to ensure that the total RF from CO_2 and non-CO_2 does not exceed the RF associated with a transient temperature increase of 2°C. Situations in which this RF amount could be exceeded are discussed further in the next section. Short- and medium-lived warming pollutants have maximum technically feasible reductions of 0.5 W/m^2 (section 4.4.b), and could materially alter the position of the black dotted line in cases where it approaches within that distance of the blue CO_2 curve. The next section describes the potential impact of short- and medium-lived warming pollutants to improve the likelihood of avoiding transient warming of 2°C.

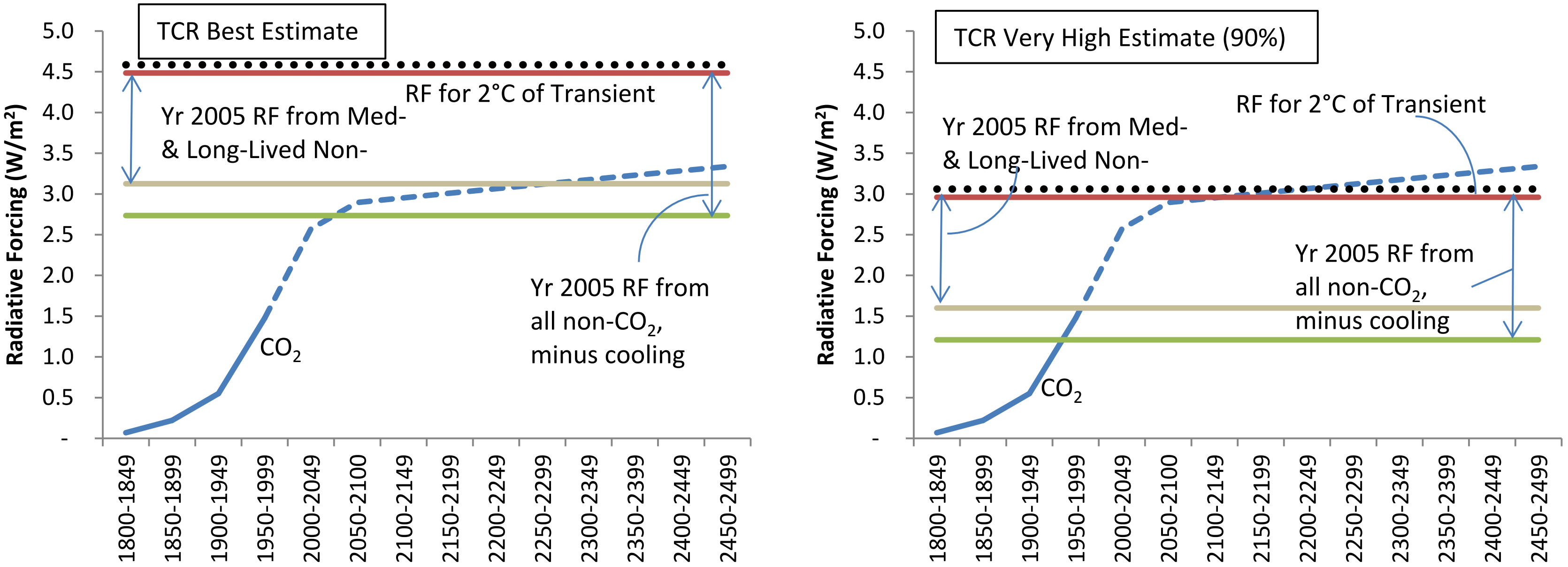

Figure 13-3: Description of Pollutant Combinations and TCR Assumptions that Could Create a Transient Temperature Peak

The left and right graphs are the same, with the exception of the transient climate response (TCR) assumption. The left chart assumes the NRC 2011 central estimate of 1.65°C (per 3.7 W/m^2) and the right chart assumes the high end of the NRC 2011 90% confidence interval with a TCR of 2.5°C (per 3.7 W/m^2). [42] The red top line is the radiative forcing that would produce 2°C of transient warming. The difference between the red line and the black dotted line is the total non-CO_2 anthropogenic climate forcing (1.6 W/m^2 total minus 1.7 W/m^2 CO_2). [75] The brown and green lines are provided for reference. The difference between the red line and the brown line below it is the year 2005 RF from medium- and long-lived pollutants (1.36 W/m^2 from CH_4, N_2O, and halocarbons). [75] The difference between the red line and the bottom green line is the year 2005 RF from all non-CO_2 anthropogenic climate forcing, minus the cooling aerosols (1.6 W/m^2 total minus 1.7 W/m^2 CO_2 plus 1.85 W/m^2 cooling = 1.75 W/m^2). [75] The blue curve is RF from the cumulative CO_2 emissions shown on the right side of Figure 9-5, which have 50/50 odds of avoiding equilibrium warming of 2°C. The airborne fraction is assumed to remain constant at 46%. Note that both the blue CO_2 curve and the red RF line are stylized and that both will actually decline on the approach to equilibrium; the CO_2 curve will decline as the airborne fraction declines toward the equilibrium airborne fraction and the red RF line will decline as the climate response increases (see Figure 6-5). Neither projected decline is well-characterized, and since they are directionally the same, the declines are omitted from this chart. If the blue curve crosses the dotted black line, transient temperature will exceed 2°C. The dotted black line can be moved up or down by changes in non-CO_2 pollutants to avoid (or delay) an intersection.

13.2.b Improving the Likelihood of Avoiding a Temperature Peak

In the previous section, I discussed the conditions for a transient temperature peak over 2°C given specific assumptions for transient climate response. In this section, I consider the likelihood of a transient temperature peak over 2°C, given the distribution of transient climate responses.

The likelihood of avoiding temperature increases above pre-industrial of 1.5^{o}C and 2^{o}C is plotted against RF in Figure 13-4 and Figure 13-5. Figure 13-4 compares the transient and equilibrium likelihoods for 1.5°C and 2°C, based on the explicit TCR and derived ECS values from NRC 2011 [42]. Figure 13-5 compares the transient-only likelihoods for 1.5°C and 2°C across multiple TCR distributions [37, 42, 62]. Note that the y axis shows the likelihood of exceeding a given temperature, so a low percentage is preferable.

There are several points to highlight on these graphs:

First, the transient warming curves sit to the right of the equilibrium warming curves (Figure 13-4). This means that, for a constant RF, the likelihood of exceeding a given temperature in the near-term will be lower than the likelihood of exceeding it in the long-term.

Second, the opportunity to change the likelihood (i.e., marginal improvement in likelihood per marginal mitigation) is the greatest when the likelihood already lies in the steep section of the curve. Some of the curves are steepest in the middle while others have a more consistent slope throughout.

Third, the graphs become less steep as the temperature ceiling goes up (the dashed 2°C curves in Figure 13-5 are less steep than the solid 1.5°C curves). For policy, this dynamic is important because it means that the same RF reduction has less of an effect on improving the likelihood of avoiding a higher temperature (moving leftward down the curve) than on avoiding a lower temperature.

To put this in context, consider an emission reduction of short- and medium-lived pollutants that could improve RF by 0.5 W/m^2. The challenge of achieving such a reduction was described in section 4.4. Current estimates of maximum technically feasible reductions equate in radiative forcing to 0.1-0.3 W/m^2 for methane with narrow uncertainty and 0.2-0.4 W/m^2 for non-SO_2 short-lived pollutants with wide uncertainty that includes crossing zero, so an improvement of 0.5 W/m^2 would require complete accomplishment of maximum technically feasible reductions of these pollutants, based on central forcing estimates. [204]

The improvement in the likelihood of avoiding a transient global temperature increase of 2°C that is possible via a 0.5 W/m^2 reduction depends on the starting point on the transient 2°C curves in Figure 13-5 (dashed lines). This starting point is determined predominantly by the RF from projected CO_2 emissions. If RF would be at 5 W/m^2 without the reduction (steepest point of the curve), a 0.5 W/m^2 reduction would improve the likelihood of avoiding a transient 2°C temperature increase by 8-17 percentage points (see Table 13-2). (The steepest spot on the 1.5°C curves is at 3.5 W/m^2, with maximum improvement of 11-20 percentage points.) Note that this improvement is smaller for less steep curves, such as with the wider AR4 distribution. If RF would be above 6.5 W/m^2 without the reduction, a 0.5 W/m^2 reduction would improve the likelihood of avoiding a transient 2°C temperature increase by only 5-8 percentage points; larger reductions would be needed to significantly improve the likelihood of avoiding 2°C. If RF would be below 2 W/m^2, the likelihood would be so certain that 2^{o}C would be avoided (>90%) that additional reductions would be of minimal added benefit in achieving the goal (less than 5 percentage points). Analogous values for a transient 1.5°C temperature increase are also shown in Table 13-2.

As discussed in section 13.2.a, total anthropogenic RF is currently 1.6 W/m^2 (0.1 W/m^2 below the CO_2 RF due to cooling pollutants). Figure 13-5 shows that the likelihood of exceeding 2°C (or 1.5°C) at this level of RF is below 10%, so there is little improvement in the likelihood to be gained. If we consider the CO_2 emission trajectory shown in Figure 13-3, the RF from CO_2 emissions in 2050 would be approximately 2.6 W/m^2. Figure 13-5 shows that the likelihood of exceeding 2°C at this level of RF is 10% or lower, and a decrease of 0.5 W/m^2 would improve the likelihood by 0-8 percentage points (see summary in Table 13-2). A worst case elimination of all cooling sulfate aerosols without any reductions in short- and medium-lived warming pollutants would produce an RF in 2050 of ~3.7 W/m^2.[205] At this level of RF, the likelihood of exceeding 2°C is 25-30% (Figure 13-5) and a decrease of 0.5 W/m^2 would improve the likelihood by 8-9 percentage points.

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[204] See also discussion of HFCs in section 4.1. Under some reference scenarios, HFCs could increase from 0.01 W/m^2 today to 0.1-0.4 W/m^2 in 2050; eliminating this prospective increase could provide some fraction of the 0.5 W/m^2 discussed in this chapter.

[205] Sulfate forcing of -1.1 W/m^2 corresponds to the black diamond in Figure 4-14 and reflects IPCC AR4 best estimates of the sulfate direct effect (-0.4 W/m^2; -0.6 to -0.2 W/m^2) plus the full aerosol indirect effect (-0.7 W/m^2; -1.8 to -0.3 W/m^2).

Continuing forward in time, the RF from CO_2 emissions on the Figure 13-3 trajectory would be 3.0 W/m^2 in 2150. Figure 13-5 shows that the likelihood of exceeding 2°C at this level of RF is 5-20% and a decrease of 0.5 W/m^2 would improve the likelihood by 5-9 percentage points (see summary in Table 13-2). A worst case elimination of all cooling sulfate aerosols without any reductions in short- and medium-lived warming pollutants would produce an RF in 2150 of ~4.1 W/m^2. At this level of RF, the likelihood of exceeding 2°C is just under 40% and a decrease of 0.5 W/m^2 would improve the likelihood by 8-11 percentage points.

In summary, the likelihood of exceeding 2°C in the next 150 years under a CO_2 emission trajectory that would avoid 2°C at equilibrium is very good. The most significant risk for a transient temperature peak would arise from uncompensated elimination of the cooling sulfate aerosols. In this case, the likelihood of exceeding 2°C would range from 30-40% in 2050-2150 and maximum feasible reductions of short- and medium-lived warming pollutants (0.5 W/m^2) would improve the likelihood of avoiding a 2°C peak in the transient horizon by 8-11 percentage points. The potential likelihood improvement for avoiding a 1.5°C peak in the transient horizon is slightly higher, at 11-14 percentage points (see bottom orange row in Table 13-2).

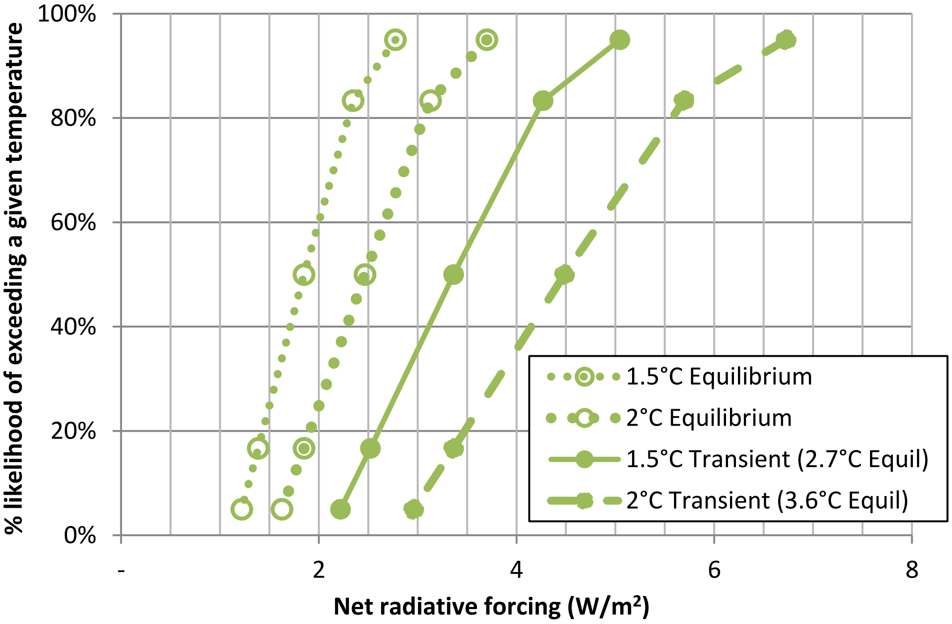

Figure 13-4: Likelihood of Avoiding 1.5-2°C (above pre-industrial) vs. Net RF, Transient and Equilibrium
Net RF on the x axis is the net RF at equilibrium for the equilibrium curves and the net RF during the transient period for the transient curves. Curves are calculated based on the transient climate response (TCR) distribution from the NRC 2011 report [42] and the equivalent equilibrium climate sensitivity (ECS) distribution, using the methods in section 13.1. The legend is calculated, as per Table 13-1, as transient temperature=0.55*equilibrium temperature for the same RF. A replica of this chart for likelihood versus cumulative CO_2 emissions is shown in Appendix L, Figure L-4.

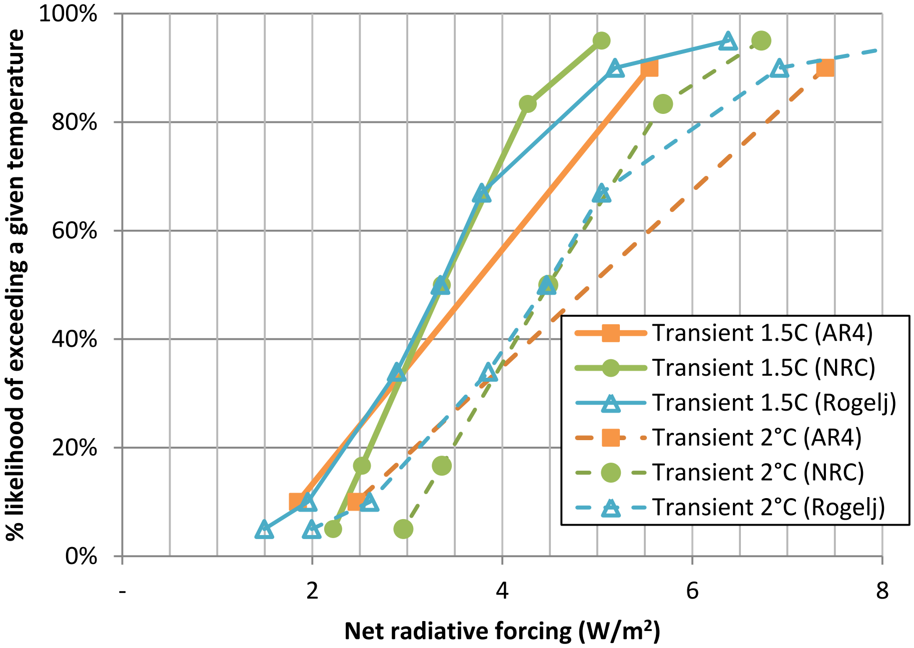

Figure 13-5: Likelihood of Avoiding a Transient Temperature Increase of 1.5-2°C vs. Net RF
These curves are calculated based on the methods in section 13.1 and Eq. 13.1, using the transient climate response (TCR) distributions shown in Figure 13-1 from AR4 [62], NRC 2011 [42], and Rogelj et al. 2012 [37]. The temperature increase being avoided is measured relative to pre-industrial levels.

	Improvement in Likelihood of Avoiding Transient 1.5°C			Improvement in Likelihood of Avoiding Transient 2°C		
RF Reduction	**AR4**	**NRC 2011**	**Rogelj et al. 2012**	**AR4**	**NRC 2011**	**Rogelj et al. 2012**
1.5 to 1.0 W/m^2	n/a	n/a	n/a	n/a	n/a	n/a
2.0 to 1.5 W/m^2	11pp	n/a	6pp	n/a	n/a	n/a
2.5 to 2.0 W/m^2	11pp	10pp	13pp	8pp	n/a	4pp
3.0 to 2.5 W/m^2	11pp	12pp	14pp	8pp	n/a	9pp
3.5 to 3.0 W/m^2	11pp	20pp	18pp	8pp	8pp	9pp
4.0 to 3.5 W/m^2	11pp	18pp	15pp	8pp	9pp	11pp
4.5 to 4.0 W/m^2	11pp	13pp	8pp	8pp	14pp	12pp
5.0 to 4.5 W/m^2	11pp	8pp	8pp	8pp	15pp	17pp
5.5 to 5.0 W/m^2	11pp	n/a	5pp	8pp	13pp	6pp
6.0 to 5.5 W/m^2	11pp	n/a	2pp	8pp	9pp	6pp
6.5 to 6.0 W/m^2	n/a	n/a	n/a	8pp	5pp	6pp
7.0 to 6.5 W/m^2	n/a	n/a	n/a	8pp	n/a	5pp

Table 13-2: Improvement in Likelihood of Avoiding 1.5°C and 2°C for Each 0.5 W/m^2 RF Reduction
Likelihood data are visually interpolated from Figure 13-5 (pp = percentage points). Green highlighted cells reflect 50/50 or better likelihood of avoiding 2°C at equilibrium given the implicit level of CO$_2$ emissions. Orange cells reflect the same for 1.5°C. Highlighting is done based on calculations that will be explained in section 15.1 and shown in Table 15-2.

13.3 Summary

Short- and medium-lived pollutants can only help shave peak warming if there is a peak to shave. If CO_2 emissions are on track to avoid 2°C of equilibrium warming, the cases in which there is a peak to shave are limited and can be visualized in Figure 13-3. A situation that could create a transient temperature peak with a likelihood of 25-40% would be the elimination of cooling sulfate aerosols without an accompanying reduction of other short- and medium-lived pollutants.

The amount by which reductions of short- and medium-lived pollutants can improve the likelihood of avoiding a transient temperature increase of 2°C above pre-industrial levels depends primarily on future CO_2 emissions. The maximum improvement possible would be 8-11 percentage points (11-14 percentage points for 1.5°C), with maximum technically feasible reductions of short- and medium-lived pollutants.

However, CO_2 emissions are currently trending above the level at which reductions of short- and medium-lived pollutants could materially change the likelihood of avoiding 2°C. CO_2 emissions through 2050 would sit above RCP 6.0 based on current pledges (section 2.2.a, Figure 2-10), whereas a trajectory of RCP 3-PD would be consistent with the CO_2 budget discussed above. At the higher CO_2 levels currently pledged, a 0.5 W/m^2 improvement from short- and medium-lived pollutants would do little to avoid 2°C, but would help delay climate outcomes (Box 1) and could make a difference on the steep section of a higher temperature curve – e.g., improving the likelihood of avoiding a transient peak of 3-4°C (Box 3) by a few percentage points.

Chapter 14 Arguments For and Against Box 2 (Avoiding 1.5°C or 2°C)

Avoiding 1.5°C or 2°C (Box 2) requires the most mitigation action of the four boxes, and the mitigation implications of choosing Box 2 were described in Chapter 9 through Chapter 13. Achieving this magnitude of mitigation requires both implementation of the mitigation and the prerequisite enormous effort to build political will and civic interest.

As mentioned in Chapter 1, the choice of box depends not only on the climate outcomes and mitigation implications of the box, but also on the perspectives that a decision-maker applies to evaluating the information. In this chapter, I review some of the prominent arguments for and against Box 2 (avoiding 1.5°C or 2°C). The arguments for Box 2 come primarily in the form of science articles that examine the impacts of 2°C, opinions from those who are concerned about these impacts and critiques of the cost/benefit approach of Box 2 opponents. The arguments against Box 2 (avoiding 1.5-2°C) fall into two categories: Box 2 is inadvisable or Box 2 is impossible or implausible. The arguments that Box 2 is inadvisable come primarily in the form of economic arguments, in short that the benefits of avoiding the impacts of 1.5°C or 2°C are less than the costs. The arguments that Box 2 is implausible relate to politics and societal inertia.

14.1 Arguments for 1.5°C or 2°C

The arguments for Box 2 (avoid 1.5-2°C) revolve around avoiding climate outcomes and are often framed in the "dangerous anthropogenic interference" (DAI) language of Article 2 of 1992 UN Framework Convention on Climate Change [2]. Article 2 of this agreement specifies, "The ultimate objective of this Convention… is to… prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

The most common framing of DAI is the "burning embers" diagram, which was presented in the IPCC's Third Assessment Report [208], recently updated by Smith et al. [209], and translated to US-only by Yohe 2010 [210]. It includes five "reasons for concern" (RFCs), which are intended to reflect "alternative, mutually incompatible worldviews" [211]: 1) risks to unique and threatened systems, 2) risk of extreme weather events, 3) distribution of impacts, 4) aggregate impacts, 5) risks of large scale discontinuities. Bars for each RFC turn from white to yellow to orange to red versus temperature with increasing impacts. The 2009 revision shows the red at lower temperatures than in 2001, reflecting observations and growing climate knowledge. The bars for unique and threatened systems and for extreme weather events now turn red at a global temperature increase of just over 1°C above pre-industrial levels and the bar for distribution of impacts turns red at 2°C above pre-industrial levels (in the early 2000s, global temperature was ~0.8°C above pre-industrial).[206] Schneider and Mastrandrea [212] note that depending which RFC is most important to different stakeholders, they have different opinions on the threshold for DAI.

Other arguments for a 2°C limit include it being a threshold above which risks to ecosystems and non-linear responses increase rapidly [213] and it representing the upper end of fluctuations in the present geological epoch [214].

More broadly, a limit of 1.5°C or 2°C is advocated as a "precautionary" approach [215]. Dietz makes the argument for precaution as follows: "Those who deny the importance of strong and early action should explicitly propose at least one of three arguments: (1) there are no serious risks; (2) we can adapt successfully to whatever comes our way, however big the changes; (3) the future is of little importance. The first is absurd, the second reckless, and the third unethical." [216]

Arguments that even a global temperature increase of 2°C is too high are based on the risks to sea ice and ice sheets (recall Figure 6-2), and are accompanied by calls instead for much tighter limits (1.5°C instead of 2°C, 350 ppm instead of 450 ppm, 1.5 W/m^2 instead of 2.5 W/m^2). [3, 5, 217] Other calls for tighter limits are based on inundation of low-lying island nations and drought in developing nations. [218]

While climate outcomes are the main focus, supporters of a 2°C limit note that avoiding 2°C is technically feasible (as shown in prior chapters) at the cost of a few percent of GDP [179, 219, 220], and note that this amount is comparable to military spending in dozens of nations. [221] Some argue that cost/benefit analyses are optimizing on the wrong variable (GDP) and should instead by optimizing on human well-being and happiness. [215] Others point to the importance of natural capital and the inability of cost-benefit models to account for its irreversible and non-substitutable loss. [222, 223] Many other criticisms of the cost-benefit approach have been made, and it is noted that climate mitigation is more about risk reduction than optimization. [215, 224]

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[206] See footnote 12 for temperature history details.

Finally, the existence of a target is noted to have value in itself, as a “focal point” [225] that makes it “easier for policymakers, environmentalists, and economists to start to work out how to achieve that target” [226].

14.2 Arguments Against 2°C: Inadvisable

Arguments against 2°C range from direct criticism to explicit arguments for higher targets to indirect arguments for higher targets (or none at all).

Direct criticisms of 2°C include: the costs outweigh the benefits, the costs are too high to be “politically acceptable” [227], the basis for 2°C as a threshold for DAI is not sufficiently strong [211], and precautionary approaches are costly [211]. Cost-benefit analyses show an optimal target between 2-4°C and above, depending on different assumptions and value judgments. [228] The most recent publication from prominent economist William Nordhaus puts the optimal target at a peak temperature of ~3°C. [10]

According to the “burning embers” analysis [209], stakeholders who care only about abrupt non-linear global changes would perceive the red danger threshold at 3°C. Schneider and Mastrandrea [212] note that such a stakeholder might be “a midlatitude nation or a nation with high adaptive capacity and little concern for impacts elsewhere in the world.” Yohe [210] considers the case in which the US fits the profile of only caring about its own interests and notes that the US could perceive nothing dangerous below 3.5°C if leaders look only at the aggregate market impacts. He notes, however, that the national security bar that he has added to the US version of the embers diagram turns red at ~1°C.

Finally, there are indirect arguments against targets as an approach rather than against aggressive mitigation, such as the following proposal of a bottom-up approach by Rayner that, “emphasizes the ‘direction of travel’ over targets and timetables. It places an immediate emphasis on adaptation and the development of effective measures to minimize global warming through a diverse range of policy actions, originating from the ‘bottom up’ within nations, based on their own institutional, technological, economic and political capacities.” [19]

There are also those who prefer no action at all. (Box 4)

14.3 Arguments Against 2°C: Impossible or Implausible

In August 2012, former chair of the IPCC Bob Watson was quoted by BBC saying, "I can't be overly optimistic…. [T]he idea of a 2°C target is largely out of the window". [229] This statement captures the views of those discouraged by the difficulty of the task outlined in Chapter 9 and Chapter 10, the short timeline, the societal inertia, and the political impasse. The view is similarly stated by Anderson and Bows 2011 [230]: "There is now little to no chance of maintaining the rise in global mean surface temperature at below 2°C, despite repeated high-level statements to the contrary." They calculate that 3-4°C would be the result of the most aggressive mitigation that most analysts consider feasible – a 2016 peak in Annex I and 2030 peak in non-Annex I, followed by a 3% per year reduction in CO_2 and GHG emissions.

Researchers note that that there is a "disjuncture between the rhetoric and reality of mitigation." [230] Parry 2008 reflects that "a curious optimism – the belief that we can find a way to fully avoid all the serious threats … pervades the political arenas of the G8 summit and UN climate meetings. This is false optimism." [231] Similarly, Risbey 2006 states, " It is dangerous to try and motivate the public on the basis of a patent fiction [that danger can be averted], since that obscures policy-critical ignorance and may ultimately create more brittle political frameworks." [232]

Those who argue that avoiding a global temperature increase of 1.5-2°C is impossible or implausible are making a different case than those in section 14.2. Those represented in section 14.2 consider mitigation on the scale necessary to avoid 1.5-2°C to be inadvisable. In contrast, those represented in this section would consider mitigation to avoid 1.5-2°C to be desirable if it were possible, but consider the goal to be impossible or implausible.

14.4 Summary

Opinions on Box 2 (avoiding 1.5-2°C) come down to perspectives on the desirability of its climate outcome relative to the feasibility and desirability of its mitigation requirements. Proponents of avoiding a 1.5-2°C temperature increase consider any other climate outcome to be dangerous, making Box 2 worthy of strenuous mitigation. Non-supporters of avoiding 1.5-2°C either consider its achievement impossible or implausible, consider the costs of mitigation to be too high relative to the benefits of the reduced climate impacts, or may have other reasons to prefer another box.

In the next section, I turn to the mitigation requirements for the looser temperature limits of Box 3 (avoid 3-4°C).

Section V Mitigation Required to Avoid 3°C or 4°C

Section V completes the analysis of mitigation required to fill in the Climate Boxes Framework (see Table 14-1), focusing on the mitigation required to avoid a global temperature increase of 3°C or 4°C above pre-industrial levels (Box 3). As shown in Chapter 2, temperature increases of 3°C or 4°C would be seen in the second half of the 21st century at earliest, well beyond the 20-40 year near-term time horizon, even for the highest emission scenarios.[207] This places Box 3 squarely in the long-term column of the Climate Boxes Framework.

Chapter 15 describes the CO_2 emission budgets that are compatible with avoiding 3°C or 4°C in both the coming century and at equilibrium, then proposes options for discretizing progress in units of 0.1°C toward these long-term goals (the Point-One approach). This approach is possible because the magnitude and pace of reductions required is more relaxed than for the 1.5-2°C limit of Box 2, as noted in Box 3 in Table 14-1. The chapter also affirms that CO_2 is the dominant driver of avoiding 3-4°C, followed by non-CO_2 medium- and long-lived pollutants (see the "general" row of Table 14-1).

	Most concerned about climate outcomes in the next 20-40 years	**Most concerned about long-term climate outcomes**	**Not concerned**
In general	Reduce all warming pollutants (CO_2 and non-CO_2)	As a first priority, reduce CO_2; Secondarily, reduce other medium- and long-lived pollutants	n/a
Delay or slow down climate change	Box 1: Reduce emissions of all warming pollutants in proportion to the desired delay, and /or Geoengineering (SRM)	n/a	n/a
Avoid 1.5°C or 2°C	Box 2: Limit CO_2 to finite budget: Developed world: immediate CO_2 drop, with 80-100% reduction by 2030-2040 Developing world: immediate CO_2 plateau Reduce non-CO_2 as needed to avoid transient temperature peaks		n/a
Avoid 3°C or 4°C	n/a	Box 3: Limit CO_2 to finite budget (higher than Box 1); Reduce CO_2 emissions at a more relaxed pace than Box 1	n/a
Don't delay or avoid climate change	n/a	n/a	Box 4

Table 14-1: The Climate Boxes Framework, with Mitigation Identified for Boxes 1-3

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[207] Near-term temperatures (by 2050) will likely fall between 1.4°C to 2.8°C across a range of scenarios that modelers consider plausible, including the business-as-usual reference scenarios (see Table 2-6 and Table 2-4).

Chapter 15 The Point-One Approach to Avoiding 3°C or 4°C

In Chapter 9, the concept of a carbon budget was introduced and a CO_2 budget for the 21st century was discussed within the context of avoiding warming of 2°C. In this chapter, I continue to apply the carbon budget approach, this time toward the goal of avoiding a temperature increase of 3°C or 4°C of both transient warming and equilibrium warming.

I will first introduce how CO_2 budgets for longer time periods can be calculated, highlighting the uncertainties that are connected to each step of the calculation. I will present the budgets for transient and equilibrium warming for emissions ranging from negative emissions to the burning of all fossil fuels, and discuss the emission budgets specifically for 3°C or 4°C. I will then introduce what I am calling the Point-One approach, in which the challenge of avoiding 3°C or 4°C is approached in increments of 0.1°C. I will present the emissions that produce a 0.1°C increment of transient warming in the coming century and that produce an increment of 0.1°C at equilibrium, and propose two novel policies based on the increment of 0.1°C. I will close the chapter by considering the role of non-CO_2 pollutants in these policies and in avoiding 3°C or 4°C and by comparing the Point-One approach to Pacala and Socolow's wedges model [233].

To emphasize, the Point-One approach introduced in this section may potentially be effective for Box 3 (avoid 3-4°C), but would not be effective for Box 2 (avoid 1.5-2°C), due to the stringent timeline and reduction requirements of Box 2.

15.1 Methods

The analytical goal in this chapter is to determine the amount of CO_2 emissions that corresponds to a 0.1°C increase in temperature, for a range of temperature levels, for both transient warming and equilibrium warming. To do this, I examine temperature changes in 0.1°C increments from 0.5°C to 10°C and step through conversions from temperature to radiative forcing, to atmospheric CO_2 concentration, to cumulative CO_2 emissions since pre-industrial times, to cumulative CO_2 emissions from 2000 through equilibrium.

Equilibrium is the period that begins after the atmospheric CO_2 equilibrates with the biosphere and ocean, and continues for thousands of years until the processes of chemical reactions with $CaCO_3$ and igneous rocks have been completed. During equilibrium, both atmospheric CO_2 concentrations and global temperatures remain nearly constant on centennial timescales.

The equilibrium time horizon is defined as either the time for atmospheric CO_2 concentrations to equilibrate with the ocean (250 ± 90 years for low levels of emissions and 450 ± 200 years for very high levels of emissions) [29, 68][208] or for temperatures to then equilibrate with the equilibrium level of CO_2 (1000 years for the Northern Hemisphere and 4000 years for the Southern Hemisphere) [116].[209] Because this chapter is focused on calculating CO_2 budgets, I apply the first definition and, to be conservative since real-world emissions are not emitted in the pulses used for these estimates, I assume equilibrium occurs in 500 years. The transient time horizon is roughly defined as decades to a century following pollutant emissions.

I will describe the method for calculating the emissions that correspond to equilibrium warming first and then discuss the method for calculating the emissions that correspond to transient warming.

15.1.a Methods: Translating Equilibrium Temperature into Cumulative CO_2 Emissions

To translate between temperature and radiative forcing (RF), I use the best estimate for climate sensitivity (3°C per 3.7 W/m^2, or 0.8°C per 1 W/m^2) [210] [62] and provide a sensitivity analysis for higher and lower values. There are several uncertainties to highlight in this first step of the calculation. First, climate sensitivity is the standard translation tool between RF and temperature, but it includes only a subset of climate system feedbacks (the "fast" feedbacks). Feedbacks included are water vapor, sea ice, snow, and clouds. Another set of "slow" feedbacks takes place over longer periods of time and is not included in the climate sensitivity value. These additional feedbacks include: carbon cycle feedbacks; other biogeochemical feedbacks (e.g., methane hydrates); ice sheet changes; vegetation changes affecting albedo and the hydrological cycle; changes in atmospheric chemistry; and atmospheric dust loading. [42] Full earth system response is called "earth system sensitivity" (ESS), and Lunt et al. 2010 [234] estimated based on paleoclimate data that these additional feedbacks could make ESS 30-50% higher than the commonly used climate sensitivity value. The confidence interval[211] for climate sensitivity is 2 to 4.5°C; applying a 30-50% increase would make the range for earth system sensitivity 2.6 to 6.75°C. Torn and Harte 2006 [235] estimated from paleoclimate data that the range could be 1.6 to 6°C. To address the range of possible higher long-term temperature

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[208] Per Archer et al. 2007, equilibration time between air and sea is 250 ± 90 years following a 1000 Gt C pulse (3,667 Gt CO_2) and 450 ± 200 years following a 5000 Gt C pulse (18,333 Gt CO_2). The latter amount is roughly equivalent to releasing 500 years of RCP 8.5 emissions (~5,400 Gt C or ~19,700 Gt CO_2, 2000-2500) in an instant.

[209] Stouffer et al. estimate 1000 years for the Northern Hemisphere (longer for the Southern Hemisphere) to reach equilibrium temperature for a stable RF following 70 years of 1% per year increases in CO_2 concentration (1365 Gt C) (see Figure 6-4).

[210] 3.7 W/m^2 corresponds to the forcing from a doubling of CO_2 concentration above pre-industrial level.

[211] 66% confidence interval

responses, I include results in Appendix M for equilibrium climate sensitivity values of 2°C, 4.5°C, and 6°C (in addition to the 3°C results that appear in the main text).

In addition to the uncertainty in the value of the climate sensitivity parameter, there is also uncertainty in the linearity of the relationship between RF and equilibrium temperature, which is implicitly assumed by use of the parameter. A linear relationship between equilibrium temperature and RF is commonly and explicitly assumed (e.g., [37, 42, 236]).[212] However, feedbacks could create non-linearities, especially at the extremes of high forcing (both positive and negative). Hansen and Sato 2012 [237] sketch such a non-linear relationship, proposing that both ECS and ESS are functions of the radiative forcing. If in fact the relationship is non-linear, a given level of cumulative emissions at higher emission levels will produce more temperature change than shown in my results. This means that the higher climate sensitivity charts in Appendix M should be consulted for high emission scenarios.

I translate RF into atmospheric CO_2 concentration (ppm) based on the following formula[213]:

$$RF = 5.35 * \ln\left(\frac{CO_2\ ppm}{preindustrial\ CO_2\ ppm}\right), \text{ or} \qquad \text{Eq. 15.1}$$

$$CO_2\ ppm = preindustrial\ CO_2\ ppm * \ e^{\left(\frac{RF}{5.35}\right)} \qquad \text{Eq. 15.2}$$

This formula, from IPCC 1990 [238], is one of three alternate formulas provided in the third IPCC assessment report [94][214] and the one that the IPCC chose to apply in the most recent assessment report (AR4) [75]. This approach is also consistent with Rogelj et al. 2012 [37][215] and the results in prior chapters. The three alternate formulas produce RF to ppm relationships that are nearly identical at current levels, and begin to diverge as CO_2 concentrations increase (see Figure 15-1). If a different formula were to prove more accurate, my estimates for emissions that are associated with a given forcing level would be overstated. In other words, a given level of cumulative emissions would produce more radiative forcing and hence more temperature change than shown in my results. This bias is in the same direction as the assumption of a linear temperature and radiative forcing relationship. Though both are best practices, results should be interpreted as possibly high estimates of the emissions allowable to

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[212] The NRC 2011 report explicitly assumes a linear relationship between equilibrium temperature and radiative forcing up to 2000 ppm CO_2.

[213] Pre-industrial CO_2 = ~280 ppm

[214] The other two formulas are: $RF = 4.841 * LN(C / C_o) + 0.0906 * (SQRT(C) – SQRT(C_o))$ (Shi 1992) or $RF = 3.35 * LN(1 + 1.2C + 0.005C^2 + 1.4x10^{-6}C^3) – 3.35 * LN(1 + 1.2\ C_o + 0.005\ C_o{}^2 + 1.4x10^{-6}\ C_o{}^3)$ (Hansen et al. 1988), where C = CO_2 ppm, C_o = pre-industrial CO_2 ppm

[215] Rogelj et al. 2012: 1000 ppm = 6.8 W/m^2 with IPCC 1990 (as shown in Figure 13-2). Shi 1992 formula yields 1000 ppm = 7.5 W/m^2 and WMO 1999 produces 1000 ppm = 7.7 W/m^2.

produce a given temperature (or vice versa, as possibly low estimates of the temperature associated with a given level of cumulative emissions).

I translate CO_2 ppm into cumulative CO_2 emissions using the constant buffered carbon framework introduced by Goodwin et al. 2007 [239].[216] They found that for emissions up to 5,000 Gt C (approximately the CO_2 emissions from RCP 8.5 from 2000-2500 [29]), the following equation produces results that lie within 5-6% of those from more complicated models:

$$Total\ cumulative\ CO_2\ emissions\ (Gt\ CO_2) = I_B * \ln\left(\frac{P_{CO_2}}{P_i}\right) \qquad \text{Eq. 15.3}$$

I_B = the steady state, pre-industrial, total buffered carbon inventory =
3,100 Gt C (11,360 Gt CO_2)
P_{CO2} = the equilibrium atmospheric concentration of CO_2, before weathering
P_i = the initial pre-industrial atmospheric concentration of CO_2 = 280 ppm

This method has the advantage not only of being more accurate than competing analytical approaches [239], but also of making the equilibrium airborne fraction (EAF) implicit rather than explicit. Because the EAF varies by double-digit percentages across emission levels, avoiding the need to specify it in the calculation removes a variable from the analysis. I checked the implicit EAF in my results (Table 15-2) against the Archer et al. [68] EAF results (18-27% for 3,665 Gt CO_2 and 35-50% for 18,320 Gt CO_2) and found them to be within the same range.

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[216] Atmospheric CO_2 concentration is proportional to the concentration of charge-neutral carbon species in the ocean (CO_2 and H_2CO_3) and irrespective of the charged carbon species (CO_3^{-2} and HCO_3^-). The buffered carbon inventory equals atmospheric CO_2 plus the portion of ocean CO_2 that does not dissociate into carbonate ions. The ocean portion of the buffered carbon inventory is the total ocean carbon divided by the Revelle factor, so the assumption of a constant buffered carbon inventory assumes that the ocean inventory and Revelle factor rise proportionally. Use of the constant buffered carbon inventory assumption provides a close approximation of atmospheric CO_2 concentration for emissions up to 5000 Gt C (and a better estimate of atmospheric CO_2 than assuming that the Revelle factor remains constant).

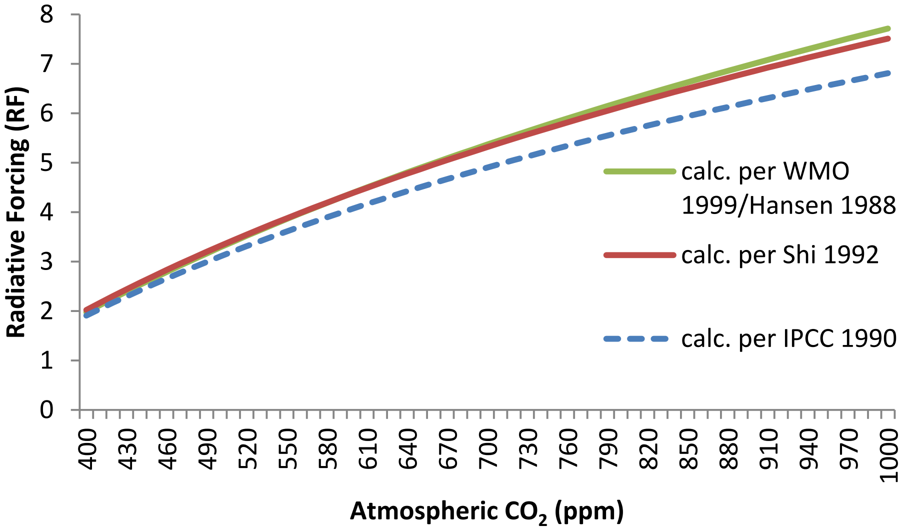

Figure 15-1: Relationship between RF and CO_2 ppm, by 3 formulas

Calculated based on formulas from p.358 of [94]. The IPCC 1990 formula is used in subsequent IPCC assessment reports and in this dissertation.

15.1.b Methods: Translating Transient Warming into Cumulative CO_2 Emissions

In this section, I describe the calculations for transient warming, defined here to be the temperature change that is roughly coincident with emissions (within a couple decades). The descriptions progress again from temperature to emissions per 0.1°C of warming.

For temperature to radiative forcing, I use the transient climate response (TCR), which is approximately 55% of equilibrium climate sensitivity (recall section 13.1). The TCR is estimated to be 1.65°C per 3.7 W/m^2, with a 66% confidence interval of 1.3-2.2°C and a 90% confidence interval of 1.1-2.5°C. [42] Some prominent model results (including some shown in Chapter 2) assume a higher TCR. In Appendix M, I have included TCRs of 2.2°C and 2.5°C, along with a TCR of 3.3°C, which corresponds to 55% of an equilibrium climate sensitivity of 6°C.[217] Higher TCRs could result from either a higher fraction of equilibrium warming being realized in the near-term or from a higher equilibrium climate sensitivity. In either case, higher TCRs would produce smaller transient emission budgets. Results using the best estimate of 1.65°C are presented in the text.

As discussed in section 15.1.a, one possible driver of higher temperatures is the carbon cycle feedback. However, the influence of the carbon cycle on TCR is likely to be modest in this

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[217] 55% is the best estimate of the ratio of TCR/ECS (see Table 13-1).

century. Friedlingstein et al. 2006 [240] found that the carbon cycle could produce 50-200 ppm of additional CO_2 by 2100 in the SRES A2 scenario. Taking the upper estimate, Table 15-1 shows the transient temperature increase that would be attributable to an additional 200 ppm of CO_2, as well as the TCR that would incorporate the additional 200 ppm. The gray row approximates the A2 scenario (recall Table 2-3), and shows a TCR of 1.81°C (per 3.7 W/m^2), which is about 10% higher than the best estimate of 1.65°C (per 3.7 W/m^2) used in the text.

RF w/o C cycle (W/m^2)	CO_2 concen (all-CO_2) (ppm)	CO_2 concen w/extra C (ppm)	Extra RF from C cycle (W/m2)	Total RF w/extra CO_2 (W/m^2)	Temp for RF w/o C cycle (°C)	Temp incl C cycle (°C)	Incre Temp from C cycle (°C)	Implied TCR' (°C per 3.7 W/m^2)
4.5	649	849	1.44	5.94	2.01	2.65	0.64	2.18
5.0	713	913	1.32	6.32	2.23	2.82	0.59	2.09
5.5	783	983	1.22	6.72	2.45	3.00	0.54	2.02
6.0	859	1,059	1.12	7.12	2.68	3.17	0.50	1.96
6.5	944	1,144	1.03	7.53	2.90	3.36	0.46	1.91
7.0	1,036	1,236	0.94	7.94	3.12	3.54	0.42	1.87
7.5	1,138	1,338	0.87	8.37	3.34	3.73	0.39	1.84
8.0	1,249	1,449	0.79	8.79	3.57	3.92	0.35	1.81
8.5	1,371	1,571	0.73	9.23	3.79	4.12	0.32	1.79

Table 15-1: Impact on Transient Climate Response from an Additional 200 ppm of Carbon Cycle Feedback

RF without carbon cycle ranges from RCP 4.5 to RCP 8.5. The CO_2 concentration assumes all RF is attributable to CO_2 and is calculated from Eq. 15.2. The CO_2 concentration with extra carbon adds 200 ppm to the previous column. Total RF with extra CO_2 is calculated from the CO_2 concentration with extra carbon, using Eq. 15.1. Extra RF from the C cycle is calculated by subtracting RF without (w/o) the C cycle from Total RF with (w/) extra CO_2. Temperatures are calculated from RF using the best estimate of TCR (1.65 °C per 3.7 W/m^2). Incremental temperature from the C cycle is calculated by subtraction. Implied TCR is calculated by dividing Temperature including the C cycle by RF without C cycle. The gray row corresponds most closely with the SRES A2 scenario, for which the 50-200 ppm CO_2 feedback was computed by Friedlingstein et al. 2006 [240].

The translation of RF to atmospheric CO_2 concentration is the same as previously described, with the call-out that both RF and ppm in this case refer to their transient values after all CO_2 has been emitted, not their equilibrium values after the air, sea, and biosphere have equilibrated.

The translation of ppm into cumulative emissions in the transient case is done using the current cumulative airborne fraction (AF) of 46%. This fraction varied in a narrow range from 44-46% over 1960-2005. The fraction through 2100 is expected to remain within ± 1-4 percentage points of the current level for emissions in the range of RCP 4.5 or RCP 6.0, to rise for high emissions (e.g., A2 or RCP 8.5), and to decline for low emissions (e.g., RCP3-PD). Estimates of the magnitude of the AF changes for low and high emissions vary widely. For a more detailed discussion of the airborne fraction trends, see Appendix J. Tables are provided in Appendix M for transient cumulative airborne fractions of 56% (mid-range of AR4 models for SRES A2) and 72% (upper end of AR4 models for SRES A2); the results in the main text are calculated using the 46% airborne fraction. Appendix M tables should be consulted for high emission scenarios.

Temperature and emission relationships in the decadal horizon in this and other studies should be interpreted with awareness that different transient airborne fraction assumptions and different transient climate response assumptions can change decadal projections materially. Equilibrium climate sensitivity assumptions can similarly change equilibrium projections considerably. Since the main text presents results using central estimates of the key parameters, results can be interpreted as providing 50/50 odds of avoiding a given temperature.

15.1.c Which Constraint is Tighter? Equilibrium Budget or Transient Budget?

Over half of the temperature response to RF occurs within decades, with the remainder taking hundreds of years of ocean warming to realize (recall section 6.2.b.ii.i, Figure 6-4 and Figure 6-5, and section 15.1). Thus, transient warming is lower than equilibrium warming for the same RF. However, because it takes several centuries for the concentrations of CO_2 in the air, biosphere, and ocean to reach equilibrium, the airborne fraction today is higher than it will be at equilibrium for all but the most extreme levels of cumulative emissions. This means that for a given level of cumulative emissions, the transient RF is higher than the equilibrium RF. The relationship between these two opposing dynamics determines whether the equilibrium CO_2 budget is bigger or smaller than the transient CO_2 budget, and hence which budget creates the tighter constraint on avoiding a given temperature increase.

On balance, assuming the best estimate for transient climate response (55% of ECS) and the current airborne fraction (46%), the equilibrium budget is smaller (a tighter constraint) than the transient budget for all temperature increases above ~1°C (see “Equil Budget vs. Transient Budget” column in Table 15-2). Said another way, equilibrium warming is higher than transient warming for all but the lowest emission budgets.

Figure 15-2 tests the robustness of this finding. The red line of squares shows that the finding is robust for the current airborne fraction across all temperatures discussed in this dissertation (1.5C, 2°C, 3°C, 4°C) for a 55% TCR/ECS ratio (the 55% line lies below the red line). For 3°C and

4°C (the focus of this chapter), the finding is robust across all airborne fractions for a 55% TCR/ECS ratio (the 55% line lies below all of the AF lines).

If, however, the TCR/ECS ratio is higher than 55%, the finding becomes less robust. At a 65% ratio, the equilibrium budget is still tighter (smaller) than the transient budget for the current airborne fraction, but not for the higher airborne fraction under the 3°C limit. At a 75% ratio, the transient budget is tighter (smaller) than the equilibrium budget for all airborne fractions for 1.5°C and 2°C, for all except the lowest airborne fraction for 3°C, and all except the current and lowest airborne fractions for 4°C.

This chapter focuses primarily on temperature at two points in time: the transient temperature coincident with emissions (within a couple decades) and the temperature at equilibrium. Between these two points, the transient fraction of equilibrium warming will gradually progress up Figure 15-2 from its coincident fraction (assumed here to be 55%) up to 100%. The airborne fraction will also gradually decline from its transient level down to its equilibrium level, effectively also progressing up the chart.[218] If the transient warming fraction line stays below the airborne fraction line as each line progresses up the chart over time, then the equilibrium budget will always be tighter (smaller) than the transient budget. If, however, the transient warming fraction line overtakes the airborne fraction line, the transient budget could temporarily be tighter (smaller) than the equilibrium budget – i.e., transient warming could exceed equilibrium warming even if emissions were consistent with the equilibrium budget. This would create the type of transient temperature peak discussed in section 13.2.a.

The relative constraints of the transient budget and equilibrium budget are important not only for setting the overall budget, but also for determining the mitigation particulars. If the transient budget is a tighter constraint than the equilibrium budget (i.e., there is a potential for transient temperature peaks), then reducing emissions from anthropogenic forest fires could play an important role in avoiding a given temperature increase (both by reducing emissions and by maintaining part of the carbon sink that reduces the airborne fraction). Similarly, emissions from short- and medium-lived pollutants could play an important role in avoiding a given transient temperature peak (section 13.2). If the equilibrium budget is the tighter constraint, then these emission sources play a lesser role in avoiding a given temperature increase, since over the course of hundreds of years, a fraction of the fire emissions will be offset by re-growth and the short- and medium-lived pollutants from the present century will be gone from the atmosphere.

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[218] On the approach to equilibrium, the airborne fraction declines, from today's fairly constant 46% level to 22-36% for emissions ranging from RCP 3-PD to RCP 6.0, with higher equilibrium airborne fractions for higher cumulative CO_2 emissions (see "implicit airborne fraction" column in Table 15-2).

Characterizing the potential for a transient temperature peak will require more research to constrain the climate response function (the transient warming fraction over time, shown in Figure 6-5) and the trajectory of the airborne fraction (see Appendix J). As shown in this section, there are cases in which the transient budget could be tighter (smaller) than the equilibrium budget given the range of uncertainty in current knowledge. However, the equilibrium budget is tighter (smaller) than the transient budget for the central assumptions used in this chapter (55% TCR/ECS ratio and 46% airborne fraction) and the remainder of the chapter will assume that the equilibrium budget is tighter (smaller) than the transient budget.

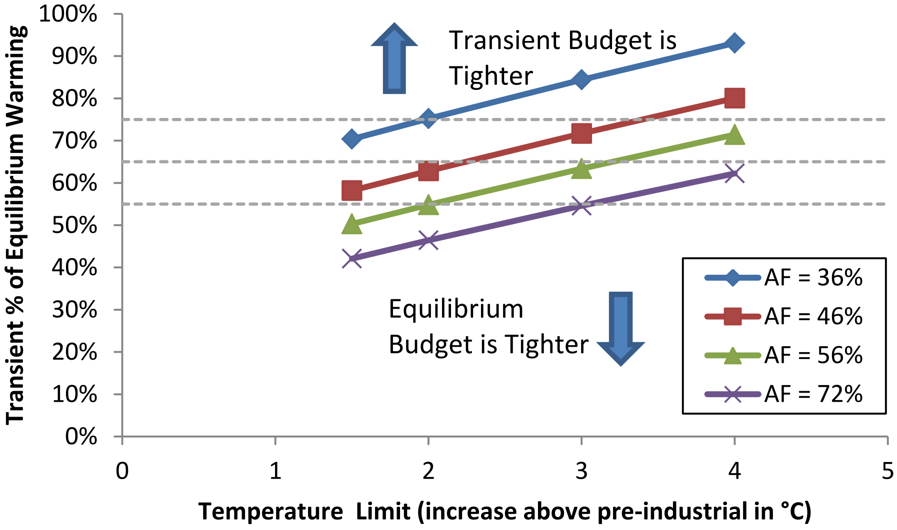

Figure 15-2: Relationship between Transient CO_2 Budget and Equilibrium CO_2 Budget

Each solid line identifies the transient percentage of equilibrium warming at which the transient budget is equal to the equilibrium budget. For a given temperature limit, if the transient percentage of equilibrium warming lies above a given airborne fraction (AF) line, the transient budget is smaller than the equilibrium budget and thus provides a tighter constraint on emissions. Vice versa, if the intersection point of the temperature limit and the transient percentage of equilibrium warming lies below a given AF line, the transient budget is larger than the equilibrium budget and the equilibrium budget provides a tighter constraint. AF = airborne fraction of cumulative emitted CO_2. Values chosen for AF reflect the upper end of the AR 4 models for SRES A2 (72%), the mid-range of AR4 models for SRES A2 (56%), the current AF (46%), and an arbitrarily chosen value ten percentage points lower (36%) that is still above the equilibrium AF (23-32%; see Table 15-2). The calculation is done based on the following equation: $\%\text{ of equilibrium warming } = \frac{T}{\left(5.35*ECS*\ln\left(\frac{equilibrium\ budget*\left({}^{AF}/_{7.92}\right)+280}{280}\right)\right)}$, where ECS is the equilibrium climate sensitivity (assumed here at the best estimate of 3°C per 3.7 W/m^2), the equilibrium budget is calculated by the methods in section 15.1.a and shown in Table 15-2, 280 is the pre-industrial CO_2 concentration (ppm), 7.92 is the Gt airborne CO_2 per ppm, and 5.35 is a constant from Eq. 15.2. Dashed gray lines represent the best estimate of the TCR/ECS ratio (55%), a higher ratio suggested by Hansen et al. 2011 (75%), and an intermediate ratio.

15.2 Emissions that Avoid a Range of Temperature Increases

In this section, I examine the relationship between temperature and cumulative emissions for the full range of possible future emissions, from below-zero emissions to the burning of all fossil fuels. The task of avoiding 3-4°C is then discussed within this context.

Table 15-2 forms the centerpiece for discussion in the rest of the chapter, and in it, I examine warming from the angles of both transient warming and equilibrium warming. For both cases, Table 15-2 provides the radiative forcing, atmospheric concentration of CO_2, and cumulative CO_2 emissions that are correlated with a given temperature, assuming the central estimate for climate sensitivity. Analogous charts are shown in Appendix M, with different assumptions for transient climate response, transient airborne fraction, and equilibrium climate sensitivity.

Note that Table 15-2 shows the CO_2 emissions that correspond to a given temperature and radiative forcing level, if RF from non-CO_2 were zero. While today's non-CO_2 RF is approximately zero due to cooling pollutants offsetting warming pollutants [75],[219] the cooling pollutants are short-lived and today's cooling pollutants will be absent at equilibrium. Therefore, an adjustment for non-CO_2 is needed. For calculating the actual CO_2 emissions that would be possible under different temperature limits, I estimate that ~80% of the equilibrium radiative forcing will be attributable to CO_2 and the remaining ~20% will be attributable to non-CO_2, the assumption made in the RCP scenarios.[220] [26, 29, 75, 94] This adjustment is not shown in Table 15-2, rather is discussed in the results section.

The RCP scenarios are identified in Table 15-2 as points of reference. For transient warming, they are aligned with their prescribed radiative forcing level in 2100 (2.6, 4.5, 6.0, and 8.5 W/m^2). For equilibrium warming, they are aligned with either their prescribed RF levels in 2500 (RCP 4.5 and RCP 6.0 at 4.5 W/m^2 and 6.0 W/m^2, respectively) or with their projected Kyoto-gas concentrations (RCP 8.5 and RCP 3-PD, at 2865 ppm and 369 ppm, respectively). Note that in year 2500, RCP 8.5 would be at ~12.5 W/m^2 (significantly above its year 2100 level of 8.5 W/m^2) and RCP 3-PD would be at ~1.5 W/m^2 (significantly below its year 2100 level of 2.6 W/m^2).

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[219] Total anthropogenic RF is 1.6 W/m^2 (90% confidence interval: 0.6-2.4 W/m^2). CO_2 RF is 1.7 W/m^2 (90% confidence interval: 1.5-1.8 W/m^2), thus other pollutants roughly cancel, at present.

[220] I calculated the year 2500 RF for each gas from the RCP database of projected concentrations, the TAR formulas for radiative forcing for CO_2, CH_4, and N_2O, and the AR4 radiative efficiencies for other pollutants. In year 2500, 21% of the RF in RCP 4.5 and 16% of the RF in RCP 6.0 and RCP 8.5 were attributable to non-CO_2 pollutants. To be conservative in the CO_2 budget, I am using the high end of this range and approximating non-CO_2 RF to be 20%.

	Emissions for Transient Warming								
Transient Temp (°C) (above pre-indus)	W/m^2	CO_2 ppm	CO_2 ppm per 0.1°C	Cumu CO_2 (Gt), all time (transient AF)	Cumu. CO_2 (Gt), yr 2000 -> (transient AF)	# years at constant 2008 CO_2 emissions	Cumu. CO_2 (Gt), per 0.1°C (transient AF)	# years at constant 2008 emissions, per 0.1°C	
10.1	22.6	19,306	826	328,792	327,254	8,872	14,281	387	
10.0	22.4	18,513	792	315,097	313,560	8,501	13,695	371	
9.0	20.2	12,174	521	205,554	204,017	5,531	9,006	244	
8.0	17.9	8,006	343	133,517	131,980	3,578	5,922	161	
7.0	15.7	5,265	225	86,145	84,608	2,294	3,895	106	
6.0	13.5	3,462	148	54,993	53,456	1,449	2,561	69	
5.5	12.3	2,808	120	43,681	42,144	1,143	2,077	56	all FF
5.0	11.2	2,277	97	34,507	32,970	894	1,684	46	
4.9	11.0	2,183	93	32,892	31,355	850	1,615	44	
4.0	**9.0**	**1,497**	**64**	**21,035**	**19,498**	**529**	**1,108**	**30**	
3.8	8.5	1,377	59	18,955	17,418	472	1,018	28	RCP 8.5 (2100)
3.6	8.1	1,266	54	17,042	15,505	420	937	25	
3.5	7.8	1,214	52	16,143	14,606	396	898	24	
3.0	**6.7**	**985**	**42**	**12,176**	**10,639**	**288**	**728**	**20**	
2.7	6.1	868	37	10,166	8,629	234	642	17	RCP 6.0
2.5	5.6	798	34	8,959	7,422	201	591	16	
2.0	4.5	647	28	6,351	4,813	131	479	13	RCP 4.5
1.7	3.8	571	24	5,028	3,491	95	422	11	doubling CO_2
1.5	3.4	525	22	4,235	2,698	73	388	11	
1.2	2.7	463	20	3,163	1,626	44	343	9	
1.1	2.5	444	19	2,834	1,297	35	328	9	RCP 3-PD (2100)
1.0	2.2	426	18	2,519	982	27	315	9	
0.8	1.8	392	17	1,928	391	11	290	8	yr 2012 actual ppm
0.5	1.1	345	15	1,128	(409)	(11)	255	7	
Average, 7°C to 3°C			**107**				**1,849**		
Total, 7°C to 3°C			**4,280**				**73,969**		
Average, 5°C to 2°C			**54**				**939**		
Total, 5°C to 2°C			**1,629**				**28,157**		

	Emissions for Equilibrium Warming									
Equil Temp (°C) (above pre-indus)	W/m2	CO_2 ppm	CO_2 ppm per 0.1°C	Cumu CO_2 (Gt), all time	Implicit equil. airborne fraction	Equil Budget vs. Transient Budget	Cumu CO_2 (Gt), 2000->	# years at constant 2008 CO_2 emissions	Cumu. CO_2 (Gt), per 0.1°C	
10.1	12.5	2,873	67	26,448	78%	-92%	24,911	675	262	RCP 8.5 (yr 2500)
10.0	12.3	2,808	65	26,186	76%	-92%	24,649	668	262	
9.0	11.1	2,230	52	23,567	66%	-89%	22,030	597	262	
8.0	9.9	1,771	41	20,949	56%	-84%	19,412	526	262	
7.0	8.6	1,406	33	18,330	49%	-79%	16,793	455	262	
6.0	7.4	1,117	26	15,712	42%	-71%	14,174	384	262	
5.5	6.8	995	23	14,402	39%	-67%	12,865	349	262	
5.0	6.2	887	21	13,093	37%	-62%	11,556	313	262	
4.9	6.0	866	20	12,831	36%	-61%	11,294	306	262	RCP 6.0
4.0	**4.9**	**704**	**16**	**10,474**	**32%**	**-50%**	**8,937**	**242**	**262**	
3.8	4.7	672	16	9,951	31%	-48%	8,414	228	262	
3.6	4.4	642	15	9,427	30%	-45%	7,890	214	262	RCP 4.5
3.5	4.3	627	15	9,165	30%	-43%	7,628	207	262	
3.0	**3.7**	**559**	**13**	**7,856**	**28%**	**-35%**	**6,319**	**171**	**262**	doubling CO_2
2.7	3.3	522	12	7,070	27%	-30%	5,533	150	262	
2.5	3.1	498	12	6,546	26%	-27%	5,009	136	262	
2.0	2.5	444	10	5,237	25%	-18%	3,700	100	262	
1.7	2.1	414	10	4,452	24%	-11%	2,915	79	262	
1.5	1.9	396	9	3,928	23%	-7%	2,391	65	262	
1.2	1.5	369	9	3,142	22%	-1%	1,605	44	262	RCP 3-PD (yr 2500)
1.1	1.4	361	8	2,880	22%	2%	1,343	36	262	
1.0	1.2	353	8	2,619	22%	4%	1,081	29	262	
0.8	1.0	337	8	2,095	21%	9%	558	15	262	all CO_2 emissions to-date
0.5	0.6	314	7	1,309	21%	16%	(228)	(6)	262	fossil-only emissions to-date
Average, 7°C to 3°C			**21**						**262**	
Total, 7°C to 3°C			**847**						**10,474**	
Average, 5°C to 2°C			**15**						**262**	
Total, 5°C to 2°C			**443**						**7,856**	

Table 15-2: CO_2 Emissions per 0.1°C of Temperature Change (Best Estimate; 50/50 Odds)

The relationship between temperature and radiative forcing is approximated as 0.45°C per 1 W/m^2 for transient warming and 0.8°C per 1 W/m^2 for equilibrium warming. This is consistent with the best estimates for transient climate response and equilibrium climate sensitivity. The atmospheric concentration of CO_2 (ppm) for a given radiative forcing (RF) is calculated via the IPCC 1990 formula (CO_2 ppm = 280 * e^(RF/5.35) [94], as discussed in section 15.1. In the transient warming calculation, cumulative CO_2 emissions for all time are calculated assuming a constant airborne fraction of 46% (1960-2005 average): (ppm-280)*7.92 Gt airborne CO_2 per ppm / .46. In the equilibrium warming calculation, cumulative CO_2 emissions are calculated from year 2000 until equilibrium – i.e., until atmospheric CO_2 equilibrates with the biosphere and ocean, but before the millennial processes of chemical reactions with $CaCO_3$ and igneous rocks occur. Cumulative CO_2 emissions for all time are calculated by the formula discussed in section 15.1: Gt CO_2 = 3100*LN(ppm/280). This result minus emissions from pre-industrial through 1999 (1537 Gt CO_2, per RCP database [29]) equals cumulative emissions for year 2000 through equilibrium. Emissions from 2000 through equilibrium, divided by year 2008 emissions (37 Gt CO_2) equals number of years. Cumulative Gt per 1°C is calculated via simple subtraction between rows. The implicit equilibrium airborne fraction (EAF) is calculated by the formula: EAF = (ppm-280)*7.92 Gt airborne CO_2 per ppm / cumulative CO_2 emissions. Gray rows denote RCP stabilization scenarios. Emissions from burning all fossil fuels (FF) (44,500 Gt CO_2; see Table 2-7) and doubling CO_2 from the pre-industrial concentration (280 ppm) are also noted. The 3-4°C range highlighted in this chapter is outlined in bold. Green rows denote targets below 2°C that were discussed in previous chapters.

Cells in dark grey sit above the level of emissions for which the equilibrium emission budget calculation is robust (~18,333 Gt CO_2) [239] and above the level of emissions that would result from burning all fossil fuels (44,500 Gt CO_2; see Table 2-7). Note, this table assumes that all other positive and negative forcing agents (aside from CO_2) cancel each other out. This is unlikely to be the case at equilibrium (since short-lived cooling pollutants will likely no longer be emitted), so the radiative forcing and temperature that accompanies a given CO_2 ppm is likely to be higher. The RCP database [29] assumes that ~80-85% of the radiative forcing in year 2500 will be attributable to CO_2 and the remaining ~15-20% will be attributable to non-CO_2; throughout this chapter, I assume non-CO_2 accounts for 20% of RF. Adding non-CO_2 forcing could thus increase temperature by 25% (=20%/80%), a reminder of the importance of non-CO_2 pollutants in improving the likelihood of avoiding a given temperature (see section 15.4.)

15.2.a Findings Regarding CO_2 Emissions

A number of points stand out in Table 15-2.

First, the row labeled "year 2012 actual ppm" provides a starting point within the table. This row is based on emissions to-date of approximately 1,980 Gt CO_2 through 2012 (1,723 Gt CO_2 for 1750-2005 [26, 29] plus an average of 37 Gt CO_2/year for 2005-2012 [46][221]). This corresponds in to transient warming of 0.8°C and 392 ppm, approximately today's levels. At equilibrium, 1,980 Gt CO_2 corresponds approximately to the 0.8°C row with 337 ppm, which is the same warming and a lower atmospheric concentration (the lower equilibrium airborne fraction is almost exactly offset by the higher equilibrium climate sensitivity at this emission level). This means that the long-term warming that is irrevocably committed (unless there are net negative CO_2 emissions) is 0.8°C. This is consistent with the estimates for committed warming under zero CO_2 emissions shown earlier in Figure 2-13. Also note that it is not physically possible to reduce the equilibrium atmospheric CO_2 concentration below 337 ppm without net negative CO_2 emissions (e.g., pulling CO_2 from the atmosphere and sequestering it) that would reduce the cumulative emissions below the total to-date.

There is one caveat to this finding. Of the 1,980 Gt CO_2 emitted to-date, approximately 560 Gt CO_2 [29, 46] has been from non-fossil sources, primarily from anthropogenic forest fires. The equilibrium airborne fraction is defined by the relationship between the atmosphere and the ocean, assuming a constant carbon inventory in the biosphere (Eq. 15.3). If the biosphere re-equilibrates to a level near its pre-industrial level of carbon, the non-fossil CO_2 may be taken up again by re-vegetated land. Whether this re-equilibration would happen and to what extent it would happen under different climatic conditions is not well defined. If 100% of non-fossil CO_2 were re-absorbed by vegetation, then a bit less would be taken up by the ocean and the equilibrium atmospheric concentration attributable to emissions to-date would lie between 317-337 ppm and the equilibrium warming would be 0.5-0.8°C (see Table 15-2).

Second, there is a finite emission budget, from pre-industrial time to equilibrium, for every temperature level.[222] For equilibrium temperature, this budget is tightly specified once a climate sensitivity assumption is made, because the equilibrium airborne fraction is defined by the limits of ocean chemistry. For transient warming temperature, the emission budget is tightly specified once both a transient climate response assumption and an airborne fraction

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[221] This calculation approximates the 2005-2012 average to equal the 2008 CO_2 emissions from the EDGAR 4.2 database.

[222] Note that the 2000-2049 carbon budget discussed in Chapter 9 is a subset of this budget.

assumption are made, but the transient behavior of both parameters is quite uncertain (section 15.1).

Third, the size of the finite budget differs materially between the goals of avoiding transient warming and avoiding equilibrium warming, and the equilibrium budget is *smaller* than the transient budget for all but the lowest temperatures (see caveat in section 15.1.c). This difference exists because the equilibrium climate sensitivity is significantly higher than the transient climate sensitivity (1/.55 = 1.8x) (see section 13.1, Table 13-1). The difference is offset at low temperatures by the lower airborne fraction, but the offset diminishes as the equilibrium airborne fraction increases at higher temperatures.

This means that the ratio between the transient budget and the equilibrium budget increases for higher temperatures (see "Equil. Budget vs. Transient Budget" column in Table 15-2). E.g., for a temperature increase of 1.5°C, the equilibrium budget is smaller than the transient budget by only 7%. For 4°C, the equilibrium budget is 50% smaller than the transient budget. And at 6°C, the equilibrium budget is 71% smaller than the transient budget. Knowing whether the goal is to avoid transient warming or equilibrium warming is particularly important when considering higher temperature limits such as 3-4°C, because the emissions budgets are significantly different. If, for example, we were to emit the transient budget for 3°C (10,639 Gt CO_2) over the coming century, the result would be transient warming of 3°C, followed by equilibrium warming to over 4.5°C. This level of warming might also trigger some of the non-linearities discussed in methods section 15.1; at high or very high climate sensitivity, this level of emissions could result in 7-9.5°C of warming at equilibrium (see Appendix M, Table M-5 and Table M-6).

Fourth, the level of constraint posed by the finite budget depends highly on the temperature to be avoided. In this chapter, we are focusing on avoiding 3°C or 4°C of warming. The available budget remaining for 3°C and 4°C of equilibrium warming is 171 years and 242 years, respectively, of constant 2008 CO_2 emissions. If we adjust the budget down by 20% to account for other greenhouse gases, we get an available budget of 129 years for 3°C and 186 years for 4°C.[223] Applying the approximation that the equilibrium budget is for 500 years [68], then we get average reductions of 73% for 3°C and 61% for 4°C.

Fifth, while the budget constraints are tighter for equilibrium warming and attention should be focused there, it is worth noting that there are limited combinations of assumptions that

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[223] Note, 20% of the total CO_2 budget (since pre-industrial) is excluded in this calculation. The reduction in number of years is greater than 20% because the number of years is based on only the CO_2 emissions after year 2000.

produce more than 4°C of transient warming (e.g., in this century). Table 15-3 shows that RCP 8.5 is below 4°C with the best estimate transient climate response (TCR); RCP 6.0 is below 4°C for all but the highest assumption for TCR; and RCP 4.5 is below 4°C for all TCR assumptions. For 3°C of transient warming, RCP 8.5 exceeds it with the best estimate of TCR; RCP 6.0 stays below 3°C with the best estimate of TCR and otherwise exceeds it; and RCP 4.5 stays below or near 3°C for all but the highest TCR assumption. In other words, staying below 4°C of transient warming is unlikely to be a challenge; the challenge lies in staying below 3-4°C of equilibrium warming.

Lastly, for the sake of a bounding estimate, we see that emitting the carbon from all fossil fuels would produce a transient temperature increase of at least 5.5°C and an equilibrium temperature increase well above 10°C. Temperature estimates at emission levels this high are almost certain to be under-estimates, as discussed in the methods section 15.1.

	Transient Warming under Different Transient Climate Response (TCR) Assumptions			
	TCR =1.65°C (best estimate)	TCR = 2.2°C (high end of 66% confidence interval)	TCR = 2.5°C (high end of 90% confidence interval)	TCR = 3.3°C (above 90% confidence interval)
RCP 8.5	3.8°C	5.1°C	5.8°C	7.6°C
RCP 6.0	2.7°C	3.6°C	4.0°C	5.4°C
RCP 4.5	2.0°C	2.7°C	3.1°C	4.0°C

Table 15-3: Transient Warming from the RCP Scenarios under Different TCR Assumptions
Data in this chart are interpolated from Table 15-2, Table M-1, Table M-2, and Table M-3. Transient climate response (TCR) estimates are from NRC 2011 [42], as shown in Table 13-1.

15.2.b Findings Regarding CO_2 Emissions per 0.1°C

In this section, I review the characteristics of a 0.1°C increment of transient and equilibrium warming, to establish the information that one would need to apply such an increment in climate mitigation policy.

First, we observe in Table 15-2 that avoiding 0.1°C at higher atmospheric concentrations involves a larger reduction in atmospheric concentration than at lower levels. For example, the "CO_2 ppm per 0.1°C" column under equilibrium warming shows a reduction of 33 ppm from 7.1°C to 7.0°C and 13 ppm from 3.1°C to 3.1°C, with an average of 21 ppm per 0.1°C. Because the radiative efficiency of CO_2 is lower at higher concentrations, a larger change in ppm is required to achieve the same RF change at higher concentrations than lower concentrations.

Next, we observe that the same pattern holds for the CO_2 emission budget for transient warming (see "Cumu. CO_2 per 0.1°C" column of Table 15-2). For example, avoiding 0.1°C of transient warming involves a reduction of 728 Gt CO_2 from 3.1°C to 3.0°C and only 479 Gt CO_2 from 2.1°C to 2.0°C. This pattern persists for transient warming because we are assuming a constant airborne fraction over the coming decades, so the atmospheric concentration is being multiplied by a constant.

Next, we observe in the "Cumu. CO_2 per 0.1°C" column for equilibrium warming that the number is a constant: 262 Gt CO_2 per 0.1°C, regardless of the temperature. This number is a constant because the increase in the equilibrium airborne fraction with higher temperatures exactly offsets the decrease in radiative efficiency (the formula for cumulative emissions through equilibrium involves a natural log of an exponential, which simplifies to 2,619 times temperature). Note that this number would be different if climate sensitivity differed from the central estimate, and would range from 131-393 Gt CO_2 per 0.1°C (see Appendix M).

Putting 262 Gt CO_2 per 0.1°C in perspective, total CO_2 emissions in year 2008 were 37 Gt CO_2/year [46]. If emissions were to continue to a constant level, 262 Gt CO_2 would be emitted and 0.1°C of equilibrium warming would be committed every 7 years. Total emissions through year 1999 from all anthropogenic sources were 1,535 Gt CO_2. [26, 29] If we divide 1535 by 262, we get 0.6°C of equilibrium warming committed through 1999, which is generally consistent with the zero CO_2 emission scenario shown in Figure 2-13.

We can use the 262 Gt CO_2 figure to extend Friedlingstein and Solomon 2005's [58] concept of a generational warming commitment. In their analysis, they considered warming through 2100 and defined a generation as 25 years. If we consider equilibrium warming instead, we find that each generation that emits for 25 years at constant 2008 emission levels would commit the planet to equilibrium warming of an additional 0.35°C.

Finally, we observe that at the 2008 CO_2 emission rate, we are contributing an additional 0.1°C of transient warming every 8 years. This is shown in the column "years per 0.1°C", in the row labeled "year 2012 actual ppm", which corresponds approximately to total emissions through 2012 (~1,980 Gt CO_2).

The next section considers the choice of which CO_2 per 0.1°C value (transient warming or equilibrium warming) is the better choice for policy.

15.3 The Point-One Approach: CO_2 Reductions and 0.1°C

The conventional way to examine what is required to avoid a given temperature increase is by identifying emission scenarios that achieve the outcome, as done in Chapter 9. This approach is particularly useful for low-temperature limits for which the time available is on the order of years and the amount of reductions required is large, hence the options can be described in a finite way as shown in Figure 9-3.

While a similar targeting approach can also be applied to higher temperature limits, alternatives are also possible. In this section, I consider the option of setting targets based on increments of 0.1°C temperature increase. At the 2008 CO_2 emission rate, we saw in section 15.2.b that we are adding an increment of 0.1°C of equilibrium temperature increase every seven years. We can also use the 0.1°C increment concept to count down avoided emissions and avoided temperature increases.

If we are going to count in 0.1°C increments, the central counting question is whether to use the emissions that produce transient warming or the emissions that produce equilibrium warming. The constant 262 Gt CO_2 per 0.1°C of equilibrium warming has clear appeal for purposes of simplicity, but the variable number for transient warming is more directly applicable to the present century. The numbers are current similar (262 Gt CO_2 for 0.1°C of equilibrium warming and 290 Gt CO_2 for 0.1°C of transient warming), but the transient number will increase with temperature.

To answer this question, we must first consider how the concept of 0.1°C increments might be used in policy. If increments of warming were counting up, you could imagine a global carbon tax that was re-set each time the emissions equivalent to 0.1°C of warming were emitted and was set to total the level of damages expected from the next 0.1°C increment of warming. If increments were counting down, you could imagine a global celebration marking each 0.1°C milestone at which investments were made that avoided CO_2 emissions equivalent to 0.1°C of warming.

In the case of a global carbon tax that was set to total the damages expected from the next 0.1°C of warming, there would be good reasons to use the transient warming emission increment. The damages being discussed are decadal because they are associated with the next 0.1°C increment and that warming relates to transient warming, not to eventual equilibrium warming. Additionally, the damages calculation would be quite complex, so adding the complexity of a different emission number for each 0.1°C increment would be a negligible calculation burden. At current rates of emissions, the calculation would be done and the tax would be re-set every 7-8 years (time for temperature to rise by 0.1°C), which seems like a reasonable amount of time considering the need to incorporate rapidly growing knowledge regarding climate impacts.

In the case of celebrating packages of investments that avoid 0.1°C, there would be clear reasons to use the 262 Gt CO_2 constant that produces equilibrium warming of 0.1°C. It provides a clear, unambiguous target. If adopted in conjunction with the carbon tax, it would acknowledge the need to avoid equilibrium warming, as well as transient warming. Additionally, because temperatures will continue to rise from the emissions that are not avoided by the investment package, it would be unclear which row of the transient warming table would provide the most appropriate emission number, so a transient warming approach to the countdown would be difficult to technically justify, making the equilibrium warming approach the more technically sound choice.

So, the incremental emissions associated with 0.1°C of warming could be taken from either the transient warming calculations or the equilibrium warming calculations, with the choice determined by the purpose of the policy.

In the next section, I will look briefly at how each of these complementary policies might work.

15.3.a Crowd-Sourcing Computation of a 0.1°C Global Carbon Tax

As discussed earlier, the current rate of CO_2 emissions contributes 0.1°C of transient warming every 7-8 years. This warming will gradually occur over the decades following the emissions.

One approach to a global carbon tax would be to assess the damages expected for the next 0.1°C of peak warming and to set the global carbon tax equal to that amount divided by the emissions that will produce the next 0.1°C. For example, the damages for the increment from 0.9°C to 1.0° of transient warming would be divided by the 302 Gt CO_2 emissions that will produce that warming to calculate a tax on each Gt of emitted CO_2. Non-binding estimates of the tax level for the next several increments could be published so that investors had insights into costs for long-term planning. Re-setting the tax every 7-8 years has the advantage of incorporating new knowledge about climate impacts and damages and incorporating learning about the impact of the tax on emissions. It also has the advantage of reminding world leaders and citizens each time emissions have added up to another 0.1°C of peak warming.

As a twist on the usual way of forecasting damages, I think it would be worth considering a crowd-sourcing approach in which those who expect to have damages submit their forecasted damages to a central international group that is charged with totaling up the damages to compute the global carbon tax. This would be particularly effective if the tax proceeds were used to compensate for damages, and if those who made the effort to submit estimates were first in line for compensation in the future. While logistically challenging[224], a crowd-sourced approach would have the benefit of engaging the world's leaders and their constituents in a discussion about climate damages every 7-8 years, and could potentially create a groundswell of interest in the initiation and continuation of a carbon tax.

15.3.b Celebrating Investments that Avoid 0.1°C

Celebrations of investments that avoid 0.1°C of equilibrium warming could be a powerful complement to a global carbon tax, in providing motivation and positive recognition. Breaking the challenge into discrete pieces (0.1°C) would set a massive but doable goal, and provide opportunity for frequent successes.

Determining the rules for counting the investments that avoid 0.1°C of equilibrium warming would be a non-trivial task. For example, since 262 Gt CO_2 is the total from now through equilibrium, should this number be divided by 500 years, so that permanent avoidance of ~0.5 Gt CO_2/year is considered equal to avoiding 0.1°C? I consider this to be a reasonable approach for permanent investments such as renewable energy and associated transmission lines that are unlikely to be replaced by fossil fuel emissions in the future. Each category of investment would need to be considered separately to determine the best way of counting.

Regardless of counting method, avoiding 0.1°C worth of carbon emissions, 262 Gt CO_2, would be a non-trivial task. Consider the current power generation sector. In 2009, global power generation produced 11.7 Gt CO_2 and 33% of power was produced from non-fossil fuel sources (19.5% renewables and 13.5% nuclear). [33] A 9% increase in non-fossil fuel generation would be required to save 0.5 Gt CO_2/year.[225] Without nuclear additions, a 15% increase renewable power generation would be required to avoid 0.5 Gt CO_2/year.[226]

The fact that so much effort is required to avoid a single 0.1°C piece of equilibrium warming is a somber but important reminder of the magnitude of the climate change mitigation task.

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[224] Logistically, the process could designate some minimum size to the group submitting the damage estimates and involve a standard form to minimize processing time. The costs of rolling up the damage estimates could be rolled into the tax.

[225] Calculation: (0.5 Gt CO_2 / 11.7 Gt CO_2)*.67/.33 = 9%.

[226] Calculation: (0.5 Gt CO_2 / 11.7 Gt CO_2)*.67/.195 = 15%.

15.3.c Comparison to the Wedges Concept

The Point-One approach of discretizing mitigation into 0.1°C increments, as just described, has similarities to Pacala and Sololow's "wedges" model [233], which discretized mitigation into 1 Gt CO_2/year technology wedges. Pacala and Sokolow proposed eliminating a projected gap of 7 Gt CO_2 in 2054 between the business-as-usual and constant emission trajectories via 7 mitigation "wedges" that would grow linearly from zero in 2004 to 1 Gt CO_2/year in 2054. They also identified a list of mitigation options that would each be large enough to constitute a wedge (e.g., 2 million 1 MW wind turbines).

There are some significant differences between the Point-One approach introduced in this dissertation and the "wedges" model from Pacala and Socolow. First, the Point-One approach is denominated in units of temperature (0.1°C) versus units of emissions (1 Gt CO_2/year in 2054 for wedges). I consider the direct discussion of temperature to be important to climate mitigation policy because temperature is the primary metric that climate policy is intended to address. Second, the Point-One approach includes no prescription for either the emissions trajectory or the target temperature, whereas the wedges model is built around the specific prescription of flat emissions from 2004-2054, then a 66% linear decline to 2100.[227] In the context of avoiding a higher temperature such as 3-4°C, I think a non-prescriptive approach can be effective and could eliminate years of debate over the optimal target. Third, the Point-One approach measures actions over a time period on the order of 7-8 years – the time it takes to either make investments that avoid 0.1°C or emit enough to produce future warming of an additional 0.1°C. The wedges approach focuses attention on action over a 50 year period. Fourth, the Point-One approach focuses attention on a single increment of 0.1°C at a time, whereas the wedges are all intended to be done in parallel. Sixth, each increment of 0.1°C in the Point-One approach could involve a wide variety of mitigation approaches, whereas each wedge of 1 Gt CO_2/yr is intended to represent one mitigation technology or approach. Seventh, the increment of 0.1°C is reached in a cumulative fashion, in contrast to the annual metric of 1 Gt CO_2/year for a 2054 wedge.

Finally, and probably most importantly, the Point-One approach is designed to be directly applicable to policy and implementation. The wedges model is conceptually important because it identified the need for a portfolio approach, provided a sense of the scale of mitigation required to avoid growth in emissions, and showed evidence that such mitigation is within the

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[227] The "wedges" paper by Pacala and Socolow models constant emissions for 50 years, followed by "a linear decline of about 2/3 in the following 50 years, and a very slow decline thereafter that matches the declining ocean sink." This produces ~500 ppm and as we can see in Table 15-2, would result in a temperature increase of ~2.5°C at equilibrium and 1.4°C at 2100.

realm of what is technically feasible with existing technology. It does not, however, translate directly to policy.

The Point-One approach provides at least two complementary paths that bring increments of 0.1°C directly into the policy discussion: a global carbon tax set on the emissions corresponding to each increment of 0.1°C of transient warming and a global celebration for each increment of 0.1°C of equilibrium warming avoided.

15.4 Role of Non-CO_2 Pollutants in Avoiding 3-4°C

Thus far, I have focused on CO_2 in this chapter, because it plays the largest role in producing large long-term temperature increases. Recall from section 15.2 that approximately 80% of the radiative forcing in year 2500 across the RCP scenarios is expected to be from CO_2. In this section, I explore the role that non-CO_2 pollutants play in avoiding a global temperature increase of 3-4°C.

The CO_2 emissions budget that corresponds to 3°C of equilibrium warming corresponds to ~2.3C of transient warming (see Table 15-2). This means that actions to improve the likelihood of avoiding 3°C must influence the radiative forcing at equilibrium and the same holds true for 4°C. Because most short-lived warming pollutants (black carbon, ozone precursors) are co-emitted with fossil fuels in the near-term and nearly all of their residual temperature effect disappears from the climate system within decades [241],[228] changes in their emissions will not influence equilibrium warming. So, while short-lived pollutants can be important levers for delaying climate change (as discussed in Chapter 5) and for avoiding near-term warming of 1.5 or 2°C in very limited cases (as discussed in Chapter 13), they are unlikely to influence the likelihood of avoiding 3-4°C.

For equilibrium warming, the most prominent non-CO_2 pollutants in the atmosphere in year 2500 are projected in the RCP scenarios to be methane (CH_4) and nitrous oxide (N_2O), at 6-9% and 6-8% of total forcing, respectively.[229] Other pollutants (HFCs, CFCs, etc.) are projected to

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[228] Solomon et al. 2010 demonstrated that, for a pollutant with a lifetime of 1.4 years and a modeling experiment with 100 years of steadily increasing forcing from the pollutant followed by zero emissions, ~20% of the temperature response persisted for a few decades after emissions stopped and ~5% of the temperature response persisted 100 years after emissions stopped.

[229] Range is across RCP 4.5, RCP 6.0, and RCP 8.5; it excludes RCP 3-PD, which has a much higher percentage of non-CO_2 (45%).

account for an additional 2-4%.[230] [26, 29, 75, 94] In total, non-CO_2 pollutants are projected to account for 16-21% of the forcing in year 2500, which means that they would also be accountable for that percentage of equilibrium warming.

However, only a very small fraction of the warming from CH_4, N_2O, and the HFCs would be attributable to emissions from the present century, since CH_4 has a lifetime of ~12 years, N_2O has a lifetime of ~114 years, and the HFCs have lifetimes of 14-52 years. [75][231] Agricultural practices that produce a significant fraction of today's CH_4 and N_2O emissions are expected to continue and would account for a large fraction of the warming attributable to CH_4 and N_2O at equilibrium. The CH_4 that accompanies fossil fuel extraction and distribution would no longer be emitted if those fuels were not being used. The other sources of CH_4 emissions are wastewater and landfills; those emissions are avoidable and permanent changes should be encouraged by policy.

Approximately 1% of equilibrium warming would be attributable to emissions from very long-lived pollutants, most prominently SF_6 (3,200 years) and CF_4 (50,000 years). Of the concentrations of these pollutants projected for year 2500 in the RCP scenarios, only ⅙ to ½ have been emitted to-date. These very long-lived pollutants are produced by industrial processes and avoidance of these emissions should be encouraged by policy.

15.5 Summary

In the context of a goal to avoid 3-4°C (Box 3), both transient warming and equilibrium warming should be considered. The emissions budget for a given level of equilibrium warming is smaller than the budget for the same level of transient warming for all but the lowest temperature targets (with the caveats provided in section 15.1.c). The budgets differ because both the airborne fraction and the temperature response to radiative forcing differ between transient and equilibrium timescales.

The Point-One approach presented in this chapter discretizes mitigation efforts in units of 0.1°C. Two of the possible applications of the Point-One approach would be a global carbon tax that was re-set each time emissions added up to an additional 0.1°C of peak warming (every 7-8 years at current emission rates) and a global celebration each time 0.1°C of equilibrium warming was avoided by deployment of zero-emission technologies. Both of these applications would ideally involve as much public involvement as possible, with a possibility of crowd-

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[230] I calculated the year 2500 RF for each gas from the RCP database of projected concentrations, the TAR formulas for radiative forcing for CO_2, CH_4, and N_2O, and the AR4 radiative efficiencies for other pollutants.

[231] HFCs projected in the RCP database to be present in year 2500 are HFC134a, HFC125, and HFC143a.

sourced estimations of damages providing input for the tax rate calculation and public participation in the celebrations of zero-emission milestones.

The Point-One approach is most appropriate for the higher temperature limits of Box 3 (avoid 3-4°C). While it has many advantages, it would be insufficient to the task of achieving Box 2 (avoid 1.5-2°C) or Box 1 (delay) due to the tight timelines and limited mitigation options associated with those boxes.

The next and final chapter will summarize the options and implications of the three boxes discussed so far (delaying, avoiding 1.5-2°C, and avoiding 3-4°C) and the fourth box (no action).

Section VI Conclusions

Chapter 16 Applying the Climate Boxes Framework to Decision-Making

Over the course of the dissertation, I have presented the Climate Boxes Framework for making decisions about climate change mitigation, populated the framework with the mitigation required for each box, and provided context for the choice of each box. The final boxes framework, populated with required mitigation actions appears in Table 16-1.

In the best case, the Climate Boxes Framework can provide a structure for conversation, for understanding different points of view about climate change mitigation, and for refining the questions that each person would like to have answered about mitigation options. The concluding sections summarize the common themes of the dissertation and their implications for policy choices. In closing, I would like to challenge the reader to identify the box that most closely matches the action and outcome that they would most like to see and to compare perspectives with friends and colleagues.

	Most concerned about climate outcomes in the next 20-40 years	**Most concerned about long-term climate outcomes**	**Not concerned**
In general	Reduce all warming pollutants (CO_2 and non-CO_2)	As a first priority, reduce CO_2; Secondarily, reduce other medium- and long-lived pollutants	n/a
Delay or slow down climate change	Box 1: Reduce emissions of all warming pollutants in proportion to the desired delay, and /or Geoengineering (SRM)	n/a	n/a
Avoid 1.5°C or 2°C	Box 2: Limit CO_2 to finite budget: Developed world: immediate CO_2 drop, with 80-100% reduction by 2030-2040 Developing world: immediate CO_2 plateau Reduce non-CO_2 as needed to avoid transient temperature peaks		n/a
Avoid 3°C or 4°C	n/a	Box 3: Limit CO_2 to finite budget (higher than Box 1); Reduce CO_2 emissions at a more relaxed pace than Box 1	n/a
Don't delay or avoid climate change	n/a	n/a	Box 4: No action required

Table 16-1: The Climate Boxes Framework, populated with Mitigation Requirements

16.1 Common Themes of the Dissertation

The main theme of the dissertation is that mitigation requirements differ significantly depending on the mitigation goal, as reflected in the four boxes of the Climate Boxes Framework. Two main sub-themes cut across the boxes: 1) the widely varying roles of short- and medium-lived pollutants in mitigation across Box 1, Box 2, and Box 3, and 2) the centrality of finite CO_2 budgets for Box 2 and Box 3. These two sub-themes, along with a handful of smaller ones, are summarized in the sections below.

16.1.a Different Roles for Short- and Medium-Lived Pollutants in Box, Box 2, and Box 3

Short- and medium-lived pollutants are those with atmospheric lifetimes ranging from days to a decade (e.g., black carbon, methane) (section 4.1). Short- and medium-lived pollutants emitted during the current century will be absent from the atmosphere when it reaches equilibrium, many centuries to millennia hence (section 6.2.b.ii.i). This means that short- and medium-lived pollutants are useful for climate mitigation to reduce transient warming, not equilibrium warming.

Box 1 (Delay) offers the largest role for short- and medium-lived pollutants. Because these pollutants disappear from the atmosphere quickly, reducing their emissions results in an immediate drop in radiative forcing (RF) and a near-immediate drop in the associated transient temperature response.

The maximum impact of reducing these emissions is constrained by their maximum technically feasible reductions (MTFR). MTFR would reduce RF by 0.1-0.3 W/m^2 for methane (CH_4) and 0.2-0.4 W/m^2 for non-SO_2 short-lived pollutants, for a total of 0.3-0.7 W/m^2 for short- and medium-lived warming pollutants (section 4.4). If there were no constraints on the technical feasibility and 100% of these pollutants were able to be eliminated, the RF change would be 0.8 W/m^2 for methane emissions and 0.45 W/m^2 for non-SO_2 short-lived pollutants, for a total of 1.25 W/m^2, with narrow uncertainty on methane and wide uncertainty on the non-SO_2 short-lived pollutants (section 4.5).

What this means for delay depends on how quickly total RF is growing (the steepness of the RF versus time curve in Figure 5-1). MTFR of short- and medium-lived pollutants (~0.5 W/m^2) could delay the time to reach a given temperature by 5-35 years, depending on the underlying RF growth rate from all radiatively active pollutants, with longer delays associated with less steep RF curves and lower CO_2 emission levels (section 5.2). At the current RF growth rate, the delay from MTFR of short- and medium-lived pollutants would be approximately 15 years.[232]

Box 2 (Avoid 1.5-2°C) may or may not involve a role for short- and medium-lived pollutants. A role for these pollutants depends on two conditions: 1) that emissions of CO_2 and other long-lived pollutants be on track to avoid 1.5°C or 2°C at equilibrium, and 2) that there be a transient temperature peak in excess of 1.5°C or 2°C. The CO_2 condition is summarized in section 16.1.b below. The possibility of a transient temperature peak arises primarily from the risk of elimination of the cooling sulfate aerosols without a compensating elimination of warming pollutants. Complete (100%) elimination of only these aerosols would produce ~0.3-0.5°C of transient warming, with wide uncertainty on the indirect forcing from sulfates and the strength of the transient climate response (section 4.5).

The likelihood of exceeding 2°C in a transient temperature peak is determined by the distribution of possible transient climate response to a given level of RF (Figure 13-1). If CO_2 is on track to avoid a 2°C temperature increase at equilibrium, the likelihood of temporarily exceeding 2°C in the transient period due to the elimination of sulfate emissions is 25-30% in 2050 and ~40% in 2150. The likelihood can be improved by 8-11 percentage points by maximum feasible reductions of short- and medium-lived warming pollutants (0.5 W/m^2) (section 13.2.b). The equivalent number for avoiding a transient 1.5°C increase is 11-14 percentage points. This suggests that, for purposes of a goal to avoid 1.5-2°C, reductions of short- and medium-lived pollutants are less urgent than getting the CO_2 emissions on track to meet the finite CO_2 budget.

Box 3 (Avoid 3-4°C) has no role for short- and medium-lived pollutant reduction in the next few decades. Even in the highest emission scenarios, 3°C is projected to be reached at 2060 at the earliest (Table 2-5). Avoiding 3-4°C would be consistent with an emission scenario in the vicinity of RCP 4.5 (somewhat lower for 3°C; somewhat higher for 4°C; see Table 15-2; in RCP 4.5, 3°C would be reached after 2300 (Table 2-5). In short, a transient temperature peak of 3°C or 4°C is not a near-term problem and does not require near-term mitigation of short- and medium-lived pollutants.

A few centuries hence, as temperature approaches its equilibrium level (see Figure 6-4), it will be necessary that emissions of short-lived pollutants and methane are minimized. This applies to both Box 2 and Box 3. Many of these pollutants are co-emitted with CO_2 and will be

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[232] RF of CO_2 grew by 0.027 W/m^2 per year in 1996-2005, per the RCP database; applying the delay formula derived in section 5.2, years of delay from 0.5 W/m^2 of reduction would be: 0.5/0.027 = 18.5 years.

eliminated as the CO_2 emission sources are eliminated. For any short- and medium-lived sources that are not also CO_2 sources, gradual reduction efforts over many decades would suit the task.

16.1.b Finite CO_2 Budgets for Box 2 and Box 3

Over a longer-term horizon, continued CO_2 emissions result in continued build-up of CO_2 in the atmosphere due to CO_2's long lifetime. A finite fraction of CO_2 will remain airborne at equilibrium (the equilibrium airborne fraction), which means that there is a finite budget for cumulative CO_2 emissions, summed from pre-industrial to equilibrium (section 15.1.a). This budget concept applies to any global temperature ceiling, including both Box 2 (avoid 1.5-2°C) and Box 3 (avoid 3-4°C).

The CO_2 budget provides insight into the relative urgency of CO_2 emission reduction across the boxes. The urgency of CO_2 emission reduction depends on both the mitigation goal and the level of acceptable risk. Table 16-2 summarizes the finite CO_2 budgets for Box 2 (avoid 1.5-2°C) and Box 3 (avoid 3-4°C), for different levels of likelihood of avoiding the temperature ceiling. The CO_2 budget is shown in both Gt CO_2 and also in the equivalent number of years of constant year 2008 emissions.

A few highlights from Table 16-2 clarify the importance of identifying both a mitigation goal and acceptable level of risk of exceeding the temperature limit. First, if the goal is to avoid 1.5C with a very high likelihood, it is too late by 11 years (unless technologies are deployed remove CO_2 from the air and permanently sequester it at very large scale). If the goal is to avoid 2°C with 50/50 odds, there are 60 years of constant CO_2 emissions remaining in the budget to be allocated over the next ~500 years (section 15.1). If the goal is to avoid 4°C with very high likelihood, the task is the same as for 2°C with 50/50 odds and the same as for 3°C with high likelihood: 60 years of constant CO_2 emissions remaining in the budget to be allocated over the next ~500 years. Note that box preferences can overlap due to different risk tolerances for different outcomes; 50/50 odds may be acceptable to someone for a lower temperature but risk aversion may rise with increasingly undesirable outcomes. Finally, if the goal is to avoid 3-4°C with 50/50 odds, there is less urgency, but still a need for reductions: 117-173 years of constant CO_2 emissions remaining in the budget to be allocated over the next ~500 years.

Finite CO_2 budgets of any size have policy implications. For example, there are presently certain CO_2 emission sources for which there are no technically available substitutes or for which the substitutes are extremely expensive or inferior on some dimension. [201][233] An inventory of these non-substitutable emissions, with their estimated minimum requirements over 500 years, would constrain the budget that remains for all other sources below the levels listed in Table 16-2. I have listed this suggestion under future research needs.

Equilibrium CO_2 Budget, Yr 2013 to Equil (Gt CO_2)

		Likelihood of Avoiding Temperature Ceiling			
	Equil T	**Low**	**50/50**	**High**	**Very High**
Box 2	**1.5°C**	2,732	1,161	114	(410)
	2°C	4,304	2,209	812	114
Box 3	**3°C**	7,446	4,304	2,209	1,161
	4°C	10,588	6,398	3,605	2,209

Yrs of Constant Yr 2008 CO_2 Emissions Remaining

		Likelihood of Avoiding Temperature Ceiling			
	Equil T	**Low**	**50/50**	**High**	**Very High**
Box 2	**1.5°C**	74	31	3	(11)
	2°C	117	60	22	3
Box 3	**3°C**	202	117	60	31
	4°C	287	173	98	60

Table 16-2: CO_2 Budget Remaining (in Gt CO_2 and in Years of Constant Emissions), for Box 2 and Box 3
This chart is compiled from the data in Table 15-2 and the tables in Appendix M. The low and high likelihood estimates correspond to the ends of the 66% likely range for equilibrium climate sensitivity, and the 50/50 likelihood estimate corresponds to the best estimate of equilibrium climate sensitivity. The very high estimate does not have a percentage likelihood assigned to it, but is considered possible. (See discussion in section 15.1.a.) All emission amounts listed are less than the emissions equivalent to burning all fossil fuel resources (~44,500 Gt CO_2) (see Table 2-7). Calculations assume that non-CO_2 accounts for 20% of equilibrium RF (numbers are adjusted down from the all-CO_2 source tables) (see section 15.2).

16.1.c Other Common Themes

Other common themes in the dissertation have included: near-term versus long-term considerations, technical and physical limits, and sensitivity analysis and likelihood assessment. I will discuss each briefly in turn.

Near-term and long-term perspectives intersect throughout the dissertation. They define the columns of box choice, and the relative importance of near-term climate change is a particularly prominent factor in assessing the desirability of delay (Box 1). Near-term versus long-term arises again in Chapter 9 and Chapter 10 in the discussion of global targets, where peaking early (which requires more effort in the near-term) reduces the stringency of later mitigation requirements for Box 2 (Avoid 1.5-2°C). And near-term and long-term arise prominently again in Chapter 15, in the discussion of the significantly different transient and equilibrium temperatures associated with a given quantity of cumulative CO_2 emissions for Box 2 (Avoid 1.5-2°C) or Box 3 (Avoid 3-4°C). As shown in section 15.2.a, emitting a level of CO_2 commensurate with a certain temperature ceiling for the transient time horizon would result in

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[233] The 2011 California Energy Futures Report took a similar approach for liquid fuels, identifying end uses with no practical substitutes to liquid fuel (e.g., aviation, heavy trucks) and assigning those uses first priority in a scenario with constrained liquid fuel supplies.

dramatically exceeding that temperature ceiling over several centuries due to lags in the climate system (section 6.2.b.ii.i).

Technical and physical limits have also featured prominently in the dissertation, and I find them particularly helpful for bounding big questions. I started off in Chapter 2 by exploring the six definitions that have been used for committed warming (Table 2-8), some of which reflect true physical limits and some of which reflect societal inertia. The potential mitigation benefit of different pollutants was captured from the perspective of both technical limits (maximum technical feasible reductions) and physical limits (100% reductions) in sections 4.4, 4.5, and 5.2. The mitigation requirements of both Box 2 (Avoid 1.5-2°C) and Box 3 (Avoid 3-4°C) are calculated based on the physical limit of the equilibrium airborne fraction and the resulting finite CO_2 budgets (section 15.1, Table 16-2).

Due to the wide uncertainties in aerosol forcing, transient climate response, and equilibrium climate sensitivity, sensitivity and likelihood analysis features prominently in the dissertation. Narrowing those uncertainties also features prominently in needs for future research (section 16.3). Sensitivity analysis is particularly important for the potential RF improvements resulting from reductions in short-lived warming pollutants (section 4.4.b and section 4.5), the potential for delay from reducing the slope of the RF curve (section 5.3), the potential for a transient temperature peak in excess of equilibrium temperature due to elimination of cooling sulfates (section 13.2.a), the improvement in likelihood of avoiding such a peak via reductions of short- and medium-lived pollutants (section 13.2.b), and the CO_2 budgets that will stay below a certain temperature ceiling (Table 16-2).

16.2 Summary of Policy Implications

Throughout the dissertation, I have demonstrated that whether policies are consistent with “addressing climate change” depends materially on *which* mitigation goal is being pursued; this applies particularly to policies related to CO_2 targets, short- and medium-lived pollutants, offsets, geo-engineering, fossil fuel expansion, and developing world infrastructure.

While some policies can achieve the goals of any of Box 1 (delay), Box 2 (avoid 1.5-2°C), or Box 3 (avoid 3-4°C), most policies satisfy only a subset of the boxes. Table 1 provides a list of commonly discussed targets and policies and identifies which boxes are consistent with each of them (with a 50% or higher likelihood of achieving the box goal). This figure can be used two ways. First, an organization can choose policies to support from this list that align with their chosen box. Second, and less intuitively, an organization that already supports a certain set of policies can work backwards to infer the climate outcome and box choice that they are implicitly supporting. In either case, organizations may find incongruities between the policies they want to support and their preferred box choice and need to iterate through box choice and policy choice until consistency is achieved.

In the sections below, I will discuss the pollutant targets, energy and technology policies, and climate policies outlined in Table 1 and describe their alignment within the four boxes.

Support of this…	**Is consistent with this box (50/50 odds)…**	**As discussed in…**
Climate Outcome Targets		
1.5°C or 2°C temperature increase ceiling	Box 2	By definition
3°C or 4°C temperature increase ceiling	Box 3	By definition
Pollutant Targets		
350 ppm CO_2 concentration in atmosphere	More stringent than 50/50 odds of Box 2	Section 15.2
Reduction of short- and medium-lived pollutants	Box 1 (in all cases) or Box 2 (in some cases)	Chapter 3, Section 5.2, Chapter 13, Section 15.4
Finite CO_2 budgets, now through equilibrium	Box 2, Box 3	Chapter 15
80-100% reduction in developed world CO_2 emissions	Box 2	Chapter 10
Halt of growth in developing world CO_2 emissions	Box 2	Chapter 10
Growth of emissions in developing world	Box 3 or Box 4 (depending on scale)	Chapter 10
Energy and Technology Approaches		
Renewable energy (solar, wind, hydro, etc.)	Box 1, Box 2, or Box 3 (depending on scale)	Section 16.2.b
Nuclear power	Box 1, Box 2, or Box 3 (depending on scale)	Section 16.2.b
Energy efficiency and conservation	Box 1 (alone), Box 2 or Box 3 (in combination)	Section 16.2.b
Carbon capture and sequestration (CCS)	Box 3	Section 16.2.b
Avoiding deforestation	Box 1, Box 2 (transient peaks), Box 3 (transient peaks)	Sections 5.3.a and 15.1.c
Geo-engineering via increased CO_2 removal	Box 1, Box 2 (in combination), or Box 3 (depending on scale)	Section 16.2.b
Geo-engineering via solar radiation management	Box 1 (at a future date)	Sections 5.4 and 7.3
Natural gas expansion	Box 3	Chapter 11
Oil expansion	Box 4	Section 16.2.b
Coal expansion	Box 4	Section 16.2.b

Climate and Energy Policy		
Cap and trade	Box 1, Box 2, Box 3, or Box 4 (depending on structure)	Section 16.2.c
Offsets	Box 2, Box 3, or Box 4 (depending on structure)	Section 10.4
GWP100 trading metric (w/6 Kyoto GHGs)	None	Section 16.2.c
GWP20 trading metric	Box 1	Section 16.2.c
GWP100 trading metric w/only 100+ yr lifetime pollutants (CO_2, N_2O, SF_6, PFCs, HFC-23, HFC-236fa)[234]	Box 2 or Box 3	Section 16.2.c
Carbon tax	Box 2, Box 3, or Box 4 (depending on structure)	Section 16.2.c
"Point One" approach (0.1°C tax rate and celebrations)	Box 3	Section 15.3.a
Energy policies (regulations, codes and standards, subsidies, tax incentives, etc.)	Box 1, Box 2, or Box 3 (depending on specifics)	Section 16.2.c
Related policies (technology R&D funding, science funding, reporting and disclosure rules)	Box 1, Box 2, and Box 3	Section 16.2.c

Table 16-3: Targets and Policies Consistent with Achieving Box Goals with 50% or Higher Likelihood
Box 1 = delay; Box 2 = avoid 1.5-2°C; Box 3 = avoid 3-4°C; Box 4 = neither delay nor avoid climate change

16.2.a Pollutant Targets

Climate goals advocated in the public sphere most prominently have been avoiding 1.5-2°C (2009 Copenhagen Accord [3]) and returning to 350 ppm (350.org and James Hansen [5]). The first goal has been discussed at length in the dissertation and is labeled as Box 2. The second goal (350 ppm) is consistent with a very high likelihood of achieving Box 2; the equilibrium climate sensitivity (ECS) that would produce 2°C from an equilibrium concentration of 350 ppm is twice the ECS best estimate (Table M-6). Box 2, with 50/50 odds, has a more generous limit of 395 ppm for 1.5°C and 445 ppm for 2°C at equilibrium (see Table 15-2).[235] Because the current airborne fraction is higher than the long-term airborne fraction, the same CO_2 budget that produces 395 ppm at equilibrium produces 507 ppm in the transient period. In short, 350 ppm at equilibrium would be somewhat more aggressive than Box 2 with 50/50 odds (would

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[234] Kyoto pollutants with lifetimes under 100 years include: CH_4 (12 yrs) and most HFCs (1-52 yrs, except those listed in Table 16-3).

[235] If high climate sensitivity is used (Table M-5), then the equilibrium limits are 353 ppm for 1.5°C and 381 ppm for 2°C.

produce 1.0°C with 50/50 odds) and 350 ppm in the transient period would be significantly more aggressive than Box 2.

The near-term mitigation requirements for Box 2 (Avoid 1.5-2°C) are particularly stringent, due to the small number of years of emissions remaining in the CO_2 budget (Table 16-2). In Figure 9-3, I identified the full range of possible combinations of peak year, target year, and magnitude of reduction through 2050 that could retain the possibility of achieving Box 2. Then in Chapter 10, I considered which of these options could be achieved with the least demanding requirements for developing countries, in line with the UNFCCC Article 3 principle that "developed country Parties should take the lead". [2] The least demanding option that retains 50/50 odds of avoiding a temperature increase of 2°C requires 80% reductions by 2030 in Annex I nations and emissions in developing nations that are flat to 2008 in 2030. Further reductions are required in the second half century and beyond (Figure 9-5 and section 10.3). The requirement that developing nations hold emissions flat faces infrastructure timing issues, with front-loaded demand growth and likely back-loaded roll-out of non-emitting infrastructure (section 10.2).

16.2.b Energy and Technology Policy

Energy and technology choices have consequences beyond climate, including environmental impacts, public health, distribution of wealth, relative power among nations, national security, and costs of common goods and services. In this section, I consider only the climate consequences of these choices.

Renewable energy (solar, wind, hydro, etc.) and nuclear power are the only energy technology choices that do not require a choice among boxes, since they are zero-CO_2-emitting sources and are scalable.[236] Energy efficiency and conservation are also zero-CO_2-emitting,[237] and can play a slightly different role in each box. In Box 1 (Delay), energy efficiency and conservation can delay emissions to future periods, effectively delaying climate change. In Box 2 (Avoid 1.5-2°C), energy efficiency and conservation can reduce near-term demand so that the roll-out of non-emitting infrastructure can keep pace with demand and so that early obsolescence of additional fossil fuel infrastructure can be avoided (section 10.2). In Box 3 (Avoid 3-4°C) energy efficiency

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[236] Construction of these facilities currently involves CO_2 emissions, but in Box 2 and Box 3, those emissions will cease as the transition to non-fossil-fuel sources occurs for nearly all uses, including construction, manufacturing, and distribution.

[237] Production of energy efficient technologies also currently involves CO_2 emissions. As with renewable energy, in Box 2 and Box 3, those emissions will cease as the transition to non-fossil-fuel sources occurs for nearly all uses, including manufacturing, and distribution.

and conservation can again reduce near-term demand, saving a portion of the CO_2 budget for later periods.

Carbon capture and sequestration (CCS) is an emerging technology that would capture CO_2 during power production and sequester it deep underground. This technology would potentially allow continued fossil fuel burning with near-zero emissions or enable biomass burning with net negative emissions (since CO_2 is removed from the air as the plants grow). Limitations on sequestration exist based on the size, location, and physical characteristics of available sequestration areas. [242] Limitations on bioenergy with CCS exist based on land area, nutrient, and water constraints. [243] CCS is still largely in the development and demonstration phase and plans for near-term deployment are modest,[238] in part due to high costs and in part due to technological and regulatory uncertainties. [242] Mitigation for Box 1 and Box 2 would require near-immediate deployment, so I consider CCS to be a Box 3 technology.

Avoiding deforestation prominently includes avoiding the CO_2 emissions that accompany anthropogenic forest fires and post-burn decay. Forest fire emissions are different from fossil fuel emissions because they have a built-in mechanism for partial re-capture of the CO_2 via re-vegetation of the land (though not necessarily with forest) over many decades and centuries, to an extent that will vary with different climate conditions. This means that less than 100% of these emissions may directly affect equilibrium temperature, but the full emissions affect transient temperature. Forest fires also affect biodiversity, hydrology, and other dimensions of ecosystem health that may contribute to feedbacks and regional climate changes. Emissions from anthropogenic forest fires and post-burn decay currently account for 14% of total CO_2 emissions. Eliminating these emissions would delay 2°C by 20 years (section 5.3.a) (Box 1) and could reduce the likelihood of transient temperature peaks for Box 2 (Avoid 1.5-2°C) or Box 3 (Avoid 3-4°C) (section 15.1.c).

Geo-engineering via increased carbon dioxide removal (CDR) is an umbrella term for a set of existing and prospective techologies that remove CO_2 from the air and sequester it. Removal methods include chemical air capture, enhanced plant growth (e.g., afforestation, biochar, ocean fertilization), and increased chemical reaction rates (e.g., altering ocean alkalinity). Sequestration methods include physical burial on land, physical sinking to the deep ocean, or increased dissolution in ocean waters. [96] Many of these techniques have physical limits on their potential scale. There are also environmental side effects. [96] Techniques that are

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[238] Five commercial-scale CCS projects were operational in 2010 and fifteen commercial-scale projects are expected to be operational in 2015.

available now could potentially be used for Box 1 (Delay) or in combination with other mitigation actions for either Box 2 (Avoid 1.5-2°C) or Box 3 (Avoid 3-4°C).

Geo-engineering via solar radiation management (SRM) includes techniques that would reflect more than the usual amount of sunlight, such as regular injections of reflective particles (e.g., sulfates) into the stratosphere, regular seeding of clouds over oceans (more reflective than water), or the placement of mirrors in space. These techniques do not change CO_2 concentration or the CO_2 budget, and instead reduce warming temporarily by increasing planetary reflection. Preliminary research suggests that precipitation patterns and regional climate patterns would be altered, ocean acidification would continue to increase, and there would be numerous adverse side effects (e.g., difficulty in doing astronomy) (see sections 5.4 and 7.3). These techniques are in the early stages of research and not ready for near-term deployment. At a future date, they could potentially be used for Box 1 (Delay). The effects of SRM are temporary, requiring consistent maintenance, so mitigation via other measures would be required to permanently accomplish Box 2 (Avoid 1.5-2°C) or Box 3 (Avoid 3-4°C).

Natural gas is a fossil fuel used for a wide variety of purposes including electricity production, heating, cooking, and industrial use. It emits about half as much CO_2 as coal per unit of energy, and has been promoted as a bridge fuel (section 11.1). However, in displacing coal, it also eliminates the cooling sulfate emissions from coal and the net effect in the near-term is warming, so it is not a good solution for Box 1 (Delay) (section 11.1). The CO_2 budget for Box 2 (Avoid 1.5-2°C) would require significant reductions of natural gas usage in the developed world to enable 80% CO_2 reductions in Annex I nations by 2030, though minimal expansion in the developing world to replace existing coal plants might be possible within the budget (section 11.2).

A possible role for natural gas lies in Box 3 (Avoid 3-4°C). Natural gas as a substitute for coal has two primary advantages over the long-term. First, it emits about half as much CO_2 as coal per unit of energy. Second, the natural gas reserves and resources (conventional and unconventional) are much smaller (about ⅕) than the coal reserves and resources (see Table 2-7). This suggests an opportunity for natural gas technology to lock out coal technology, so that the tens of thousands of possible Gt of CO_2 from coal are not emitted. However, burning all natural gas (7,000 Gt CO_2) would still exceed the CO_2 budgets in Table 16-2 for 50/50 odds of avoiding 3-4°C (Box 3). While all conventional natural gas (700 Gt CO_2) could be burned in a Box 3 scenario where coal was locked out, most of the unconventional natural gas (6,300 Gt CO_2) would need to remain in the ground to avoid 3-4°C (Box 3). Carbon capture and sequestration could extend the use of unconventional natural gas. In short, natural gas is a possible Box 3 technology (Avoid 3-4°C).

Oil and coal are fossil fuels that are used for 60% of world energy needs. [33] They account for 64% of 2008 world CO_2 emissions [33, 46],[239] and burning all resources would greatly exceed the CO_2 budgets shown in Table 16-2 (see Table 2-7). Reducing their usage would assist in Box 1 (Delay), rapidly reducing their usage is required for Box 2 (Avoid 1.5-2°C), and more gradually reducing their emissions is required for Box 3 (Avoid 3-4°C). Carbon capture and sequestration (CCS) could extend the use of coal as a Box 3 solution (Avoid 3-4°C), though eventually limits on storage capacity would be reached since CCS reservoirs are smaller than the volume of the CO_2 that would be emitted by the full coal resource. [242][240] Only Box 4 (Don't delay or avoid climate change) would be served by the continued or expanded use of oil and coal without CCS.

16.2.c Climate Policy

A variety of policy instruments have been tried or proposed to mitigate climate change, including the ones listed in Table 16-3. Cap and trade is one of the most prominent approaches, with active markets in place in Europe, the Northeastern US, and most recently, California and some Chinese provinces. The basic concept of cap and trade is that emissions for future periods are capped at a certain level that declines over time and a certain number of emission permits is issued for each year that corresponds to the emission cap. Participating emitters who reduce emissions can sell their extra permits to other participating emitters. Some programs allow offsets (section 10.4), in which emission reductions by emitters outside the cap and trade program can be counted toward the reductions of a participating emitter.

Cap and trade may be consistent with any of Box 1 (Delay), Box 2 (Avoid 1.5-2°C), Box 3 (Avoid 3-4°C), or even Box 4 (Don't delay or avoid climate change), depending on the structure of the program. A cap and trade program that was specific to methane could fit in Box 1 (Delay), and could be applied at any scale (state/province, nation, world) since methane is a well-mixed global pollutant, though the fragmentation of sources could pose problems with administration. A cap and trade program could also be applied locally in a city or small region for short-lived pollutants such as black carbon.[241]

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[239] Coal and oil account for 80% of world CO_2 emissions from energy; natural gas accounts for the remaining 20%. Energy-related emissions account for 79% of total world CO_2 emissions.

[240] Per GEA 2012, the estimated global storage capacity in saline formations, depleted oil and gas reservoirs, and coal seams is 5,000-24,000 Gt CO_2. The coal reserve and resource is 29,000-42,000 Gt CO_2 (Table 2-7). Note, this is a long-term constraint; total fossil fuel emissions through 2005 were ~1,200 Gt CO_2 (Table 2-7).

[241] A cap and trade program could backfire for ozone precursors due to their complicated local effects (discussed in 7.1).

For CO_2 and other long-lived pollutants, whether cap and trade addresses Box 2 (Avoid 1.5-2°C), Box 3 (Avoid 3-4°C), or Box 4 (Don't delay or avoid climate change) depends on the tightness of the caps, pollutants included, the breadth of participation, the rules around offsets, and myriad other details (for lessons learned in past programs, see [191] and [192]). Tightness of the caps determines whether the cumulative CO_2 emissions fit within the budgets for 1.5-2°C, 3-4°C, or neither. The sum of the caps to 2050 on a global level could be compared to Figure 9-1 and Figure 9-3 to see where they fall in terms of likelihood of avoiding 2°C, and similar analyses could be done for other temperatures. Regional caps for 2°C through 2050 would need to fall within either the Annex I or developing nation reduction amounts listed in Table 10-1. Caps that are too high are equivalent to no cap and no action at all (Box 4). The range of pollutants included determines the extent to which CO_2 emissions are reduced or other pollutants are reduced in its place. Recall that Box 2 (Avoid 1.5-2°C) and Box 3 (Avoid 3-4°C) have finite CO_2 budgets (Table 16-2), that the Box 2 budget is particularly tight (Figure 9-5), and that the benefits of near-term reductions of other pollutants in achieving the Box 2 and Box 3 goals are minimal if the CO_2 emission trajectory is consistent with achieving the goals (section 16.1.a). Inclusion of other pollutants in trading makes achievement of Box 2 (Avoid 1.5-2°C) more difficult. Breadth of participation determines whether emissions are actually reduced globally, or whether emissions in one location are shifted to another location (the leakage phenomenon). Programs with high leakage can be nearly equivalent to no program at all (Box 4). Similarly, rules around offsets determine whether CO_2 emissions are actually reduced globally or not, and will be discussed below in a broader context. In summary, depending on the structure of the program, cap and trade may be consistent with Box 2 (Avoid 1.5-2°C), Box 3 (Avoid 3-4°C) or Box 4 (Don't delay or avoid climate change).

Offsets are policy instruments that are used to exchange emission reductions in one region or sector for reductions in another region or sector. Some offsets are purchased to fulfill obligations under a cap and trade program, while others are purchased voluntarily by companies or individually seeking to offset their emissions. In the best case, offsets can reduce the costs of compliance in achieving global emission reductions and can contribute to Box 2 (Avoid 1.5-2°C) or Box 3 (Avoid 3-4°C).[242] In other cases, the system is gamed[243] and they create no emission reductions at all, supporting Box 4 (Don't delay or avoid climate change). As discussed in section 10.4, supporting Box 2 (Avoid 1.5-2°C) would require changes in the rules for offsets. Because the 2030 CO_2 emission target for the developing world would need to be

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[242] This requires offsets to satisfy the requirements of being: real, measurable, verifiable, and additional.

[243] If offsets are calculated against a hypothetical future baseline, the baseline can be set artificially high to create the appearance of reductions. Alternatively, an offset program can actually induce increased emissions so that the emitter can reap the financial rewards of reducing them. This was documented with HFC-23 under the Clean Development Mechanism.

flat to 2008 levels to support Box 2, any offsets would need to be counted against 2008 emissions instead of a hypothetical future baseline. Additionally, because CO_2 is the primary concern for Box 2 (see section 16.1.a), all offsets would need to be achieved via CO_2 (or other long-lived pollutant) reductions rather than reductions in short- and medium-lived pollutants. If less stringent rules were used, Box 2 (Avoid 1.5-2°C) would not be satisfied and offsets would at best support Box 3 (Avoid 3-4°C).

The choice of metric applied as the exchange rate among pollutants in calculating offsets is another application of box choice. The standard metric used is the 100-year Global Warming Potential (GWP100). GWP100 is calculated as total RF over 100 years from 1 kg of pollutant X emitted today, divided by the total RF over 100 years from 1 kg of CO_2 emitted today. Numerous critiques of GWP have been made, other metrics have been suggested, and I have intentionally used RF instead of GWP throughout the dissertation because I feel it is for most purposes a better form of comparison. However, GWP remains the standard trading metric, and the difference among boxes can be illustrated by different versions of GWP: GWP20, GWP100 (Kyoto), and GWP 100 (long-lived). GWP20 (comparisons of RF summed over 20 years) would best serve Box 1 (Delay), since it is focused on RF improvements in the near-term horizon. It would not support Box 2 (Avoid 1.5-2°C) or Box 3 (Avoid 3-4°C) since both of those boxes aim to avoid temperature increases permanently and, if the long-term goal is on-track, temperature is unlikely to exceed the values in the near-term. GWP100 (Kyoto) includes the 6 pollutants designated by the Kyoto Protocol (CO_2, CH_4, N_2O, SF_6, PFCs, HFCs). This is the standard metric, but is not well-suited to support any of the boxes. The time horizon is too long to support Box 1 (Delay) and the inclusion of CH_4 and the medium-lived HFCs makes it unsuited to support Box 2 (Avoid 1.5-2°C) and Box 3 (Avoid 3-4°C), whose achievement depends almost entirely staying within the finite CO_2 budget. And, it is unsuited to support Box 4 (Don't delay or avoid climate change), because the intention of the trading metric is to do something about climate change. A better GWP100 metric, if a trading metric is needed, would be GWP (long-lived), which would include the Kyoto pollutants with lifetimes over 100 years (CO_2, N_2O, SF_6, PFCs, HFC-23, and HFC-236fa). This metric would support Box 2 (Avoid 1.5-2°C) and Box 3 (Avoid 3-4°C) because it would focus on pollutants that will largely persist to equilibrium and would focus primarily on CO_2 due to its predominant share of the emissions.

Carbon taxes are taxes levied per unit of CO_2 emissions. Carbon taxes have the potential to support either Box 2 (Avoid 1.5-2°C) or Box 3 (Avoid 3-4°C), since both boxes rely upon emissions fitting within a finite CO_2 budget. Whether carbon taxes support Box 2 or Box 3 depends on the tax rate and on the breadth of inclusion in the tax. Higher tax rates are required to support the faster reductions in Box 2 than are required to support the slower reductions on Box 3. Breadth of inclusion determines whether the tax is effective in reducing global emissions, or whether it creates the same leakage discussed for cap and trade, in which emissions are shifted to areas without the tax. In the latter case, carbon taxes would not reduce global emissions and would effectively support Box 4 (Don't delay or avoid climate change).

A variation on the carbon tax approach was suggested in section 15.3.a, under what I call the Point-One Approach. This approach would involve setting a tax rate on the emissions responsible for the next 0.1°C of transient warming based on a crowd-sourced assessment of the damages expected for that next increment of warming. Tax proceeds would then be used to pay for the ensuing damages, with priority to those towns/cities that had participated in the estimates. This approach could visibly establish a vested public interest in tax rates that effectively capture the externalities of the emissions. It would support Box 3 (Avoid 3-4°C), but it would require significant time to initiate and would be unlikely to involve the magnitude of tax rates in the next two decades that would achieve Box 2 (avoid 1.5-2°C).

Under the Point-One Approach, I also suggested the concept of global celebrations. These events would mark the accomplishment of permanently reducing 0.5 Gt CO_2/year via investments in zero-emission infrastructure, the equivalent of avoiding 0.1°C at equilibrium. Such celebrations could be a powerful complement to a global carbon tax, in providing motivation and positive recognition. Breaking the challenge into discrete pieces (0.1°C) would set a massive but doable goal, and provide opportunity for frequent successes (section 15.3.b).

Many energy policies have a significant influence on climate change mitigation, since energy accounts for 79% of global CO_2 emissions (Figure 10-3). Some energy policies primarily influence energy efficiency, such as codes and standards (e.g., building codes, appliance standards, vehicle fuel economy standards) and information programs (e.g., labeling, real-time metering). Other policies primarily influence which types of technologies are deployed, such as codes and standards (interconnection and net metering rules), funding assistance (loan guarantees, guaranteed procurement), and price-based mechanisms (subsidies, tax credits, feed-in tariffs). In section 16.2.b, I noted that energy efficiency can play different roles in each of Box 1 (Delay), Box 2 (Avoid 1.5-2°C), and Box 3 (Avoid 3-4°C). Policies that influence the roll-out of low- and zero-emission technologies can play a significant role in Box 1 (Delay), Box 2 (Avoid 1.5-2°C), or Box 3 (Avoid 3-4°C), depending on the stringency of the policies.

Finally, there are supporting policies that do not directly guide emissions, but which support the work needed to accomplish Box 1, Box 2, or Box 3. These policies include reporting and disclosure rules, funding for technology research and development, and funding of the scientific research needed to better understand the climate system and to closely measure changes in the climate. These policies are foundational and merit support to the fullest extent possible if the goal is any of Box 1 (Delay), Box 2 (Avoid 1.5-2°C), or Box 3 (Avoid 3-4°C). They are not required if the goal is Box 4 (Don't delay or avoid climate change).

16.3 Needs for Future Research

The methods used throughout this dissertation were entirely analytical; no physical climate system models were run. The work stands on the shoulders of several decades of climate science research, observations, and modeling, which produced the equation forms and parameter values used herein. Continued modeling of the physical climate system, basic research in climate science, and observational data collection are needed to narrow parameter uncertainties and improve system understanding. A regularly updated summary of equations, parameters, and their range of applicability would be useful to a broad range of researchers.

There remains widely acknowledged uncertainty on a number of key parameters. Most significantly, constraining the range of uncertainty on aerosol radiative forcing and narrowing the range for transient climate response would provide greater insight into the potential for mitigation in Box 1 (Delay) and into the likelihood of a transient temperature peak accompanying Box 2 (Avoid 1.5-2°C). Further constraining equilibrium climate sensitivity (ECS) and transient climate response (TCR), by tightening the range of parameter values and challenging the linearity between ECS and RF and TCR and RF, would put tighter bounds on the finite CO_2 budgets of Box 2 (Avoid 1.5-2°C) and Box 3 (Avoid 3-4°C) and increase confidence that a given budget would achieve its intended goal. Tighter projections for the transient airborne fraction trajectory that would accompany a period of CO_2 emission reduction and a period of ppm reduction en route to the equilibrium airborne fraction would improve insights into the potential for transient temperature peaks in the context of Box 2 (Avoid 1.5-2°C) and Box 3 (Avoid 3-4°C). Modeling experiments describing the transient temperature response (the climate response function) against a wider range of generic scenarios (e.g., different rates and durations of increase in RF to stabilization, etc.) would similarly provide insight into the potential for transient temperature peaks in the context of Box 2 (Avoid 1.5-2°C) and Box 3 (Avoid 3-4°C), and would more tightly constrain the applicability of TCR to certain time windows, improving analysis particularly for Box 1 (Delay) and Box 2 (Avoid 1.5-2°C). All of these parameter improvements require research in fundamental science and extensive planetary measurements; both should be funded well and pursued with urgency.

Beyond parameters, critical work lies ahead to test the limits of CO_2 budgets, which are central to the mitigation requirements for Box 2 (Avoid 1.5-2°C) and Box 3 (Avoid 3-4°C). The carbon budget approach assumes that all feedbacks are related to the magnitude, not the rate, of climate change. The existence of significant feedbacks that depend on rate of climate change (in the range under discussion) would challenge the validity and simple elegance of the carbon budget approach (section 9.1). Large rate-based feedbacks would mean that the timing, as well as the magnitude, of CO_2 emissions impacts long-term climate change. To date, suggestions have been made that rate of climate change might affect feedbacks, but no evidence of this dynamic has been presented that is relevant for emission levels on the order of magnitude of the CO_2 budgets being discussed nor has a challenge been made to the carbon budget approach (section 6.2.b and section 9.1). Findings proving or disproving a link between large feedbacks and rate of climate change would also provide critical information regarding the value of delay (Box 1). Additionally, work is needed to characterize the circumstances that could produce transient temperature peaks, even within the confines of a CO_2 budget consistent with avoiding a given level of equilibrium warming (section 13.2.a and 15.1.c). Such transient temperature peaks could trigger feedbacks that result in warming above the intended limit. Since mitigation policy may be made based on the carbon budget theory, significant research should be done to rigorously challenge the theory. As with the parameter work listed above, testing the carbon budget theory requires research in fundamental science and planetary measurements, and should be a funding and research priority. Policy can still be made based on the theory in the meantime, with the caveat that if rate of climate change is found to materially influence feedbacks, emission reductions for a given box may be needed more urgently and the CO_2 budgets presented in this dissertation may shrink.

From a pragmatic mitigation perspective, work is needed on at least four questions. For Box 2 (Avoid 1.5-2°C) and Box 3 (Avoid 3-4°C), the CO_2 budgets can be further constrained by identifying those CO_2 emissions that are produced by sources for which there is no zero-emission substitute and quantifying the 500-year emission requirements for those sources. Also for Box 2 and Box 3, the implicit assumption that sources of short-lived pollutants will disappear by equilibrium must be tested. This includes quantifying the persistence of short and medium-lived pollutant sources that are not CO_2 sources and would hence not be eliminated by elimination of CO_2 and would need to be addressed separately, then quantifying any of the remaining sources that lack substitutes or likely future mitigation options. For Box 1 (Delay) and Box 2 (Avoid 1.5-2°C), further research into maximum technically feasible reductions (MTFR) of short- and medium-lived pollutants is needed. MTFR has increased over the past few years (Figure 4-10), and it would be useful to know what scientific research is needed to secure continued MTFR improvements and whether there are physical limits beyond which reductions are impossible. For all boxes, more research is needed into the relative permanence of forest fire emissions and of carbon dioxide removal via biological sequestration.

Finally, from the perspective of box choice, further research is needed on the possible ecological benefits and the pragmatic benefits of delay (Box 1; section 6.2 and section 6.3), as well as better quantification of the delay that would be enabled by different mitigation scenarios (Figure 8-1). Lastly, research is needed that enables a vivid description of climate outcomes that accompany 1.5°C, 2°C, 3°C, and 4°C (Box 2 and Box 3), their transient counterparts (0.8°C, 1.1°C, 1.65°C, 2.2°C), and 0.1°C increments in the near-term. This research should be accompanied by communication efforts to make these descriptions accessible to non-scientists.

16.4 Closing Thoughts

Climate change is complicated; over 200 pages in this document explore the important scientific nuances among different mitigation options and climate outcomes. Some of the conclusions are not intuitive, and some will be modified as additional years of climate observations, basic science, and modeling narrow the bands of uncertainty provided in the document. The existence of so many nuances poses a critical challenge for mitigation: namely, the challenge of how to increase the likelihood that consequential decisions are made with an understanding of these nuances and that active decisions are made about box choice. How to effectively do this is a subject for the future work of many people. In the meantime, discussion can be an excellent way to digest complicated information and I hope that anyone reading this document will discuss and debate box choice with friends and co-workers and emerge with an appreciation for the non-trivial nuances of climate change mitigation.

Appendix

Appendix A Reference Scenarios

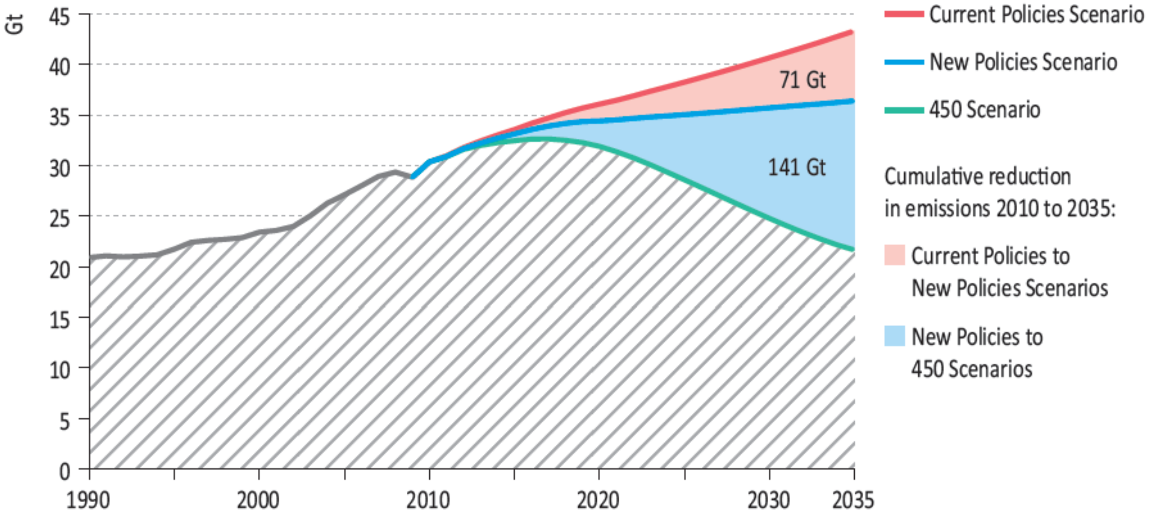


Figure A-1: World Energy-Related CO_2 Emissions by IEA WEO Scenario

Reprinted with blanket permission from IEA World Energy Outlook (WEO) 2011 [33]

The Current Policies scenario includes policies enacted by mid-2011. The New Policies scenario includes "recently announced commitments and plans, even if they are yet to be formally adopted and implemented." The 450 Scenario is the IEA estimate of an emissions trajectory that would stabilize at 450 ppm.

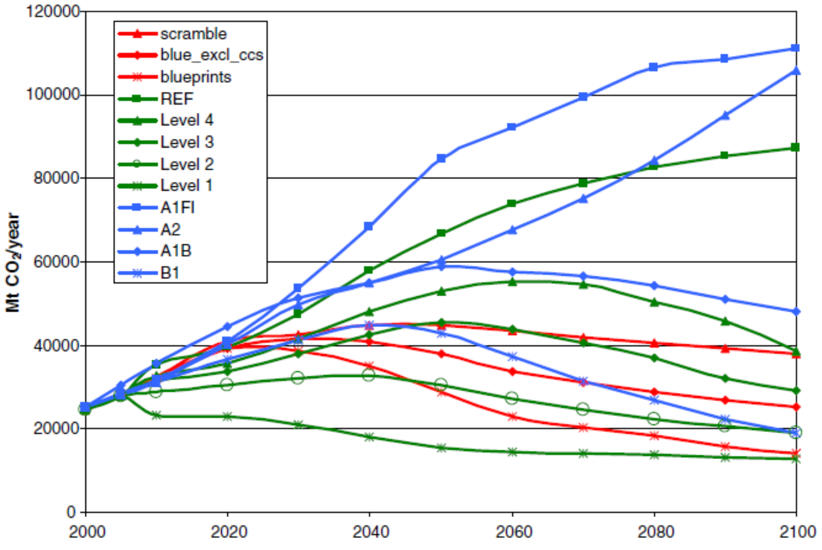


Fig. 1 Fossil and other industrial CO_2 emissions (Shell in *red*, CCSP in *green*, SRES in *blue*). Units are megatons (10^{12} gm) of CO_2 per year

Figure A-2: CO_2 Emission Assumptions Underlying Temperature Projections in Prinn et al. 2011

Reprinted with kind permission from Springer Science and Business Media, from Prinn et al., Climatic Change 2011. [38]

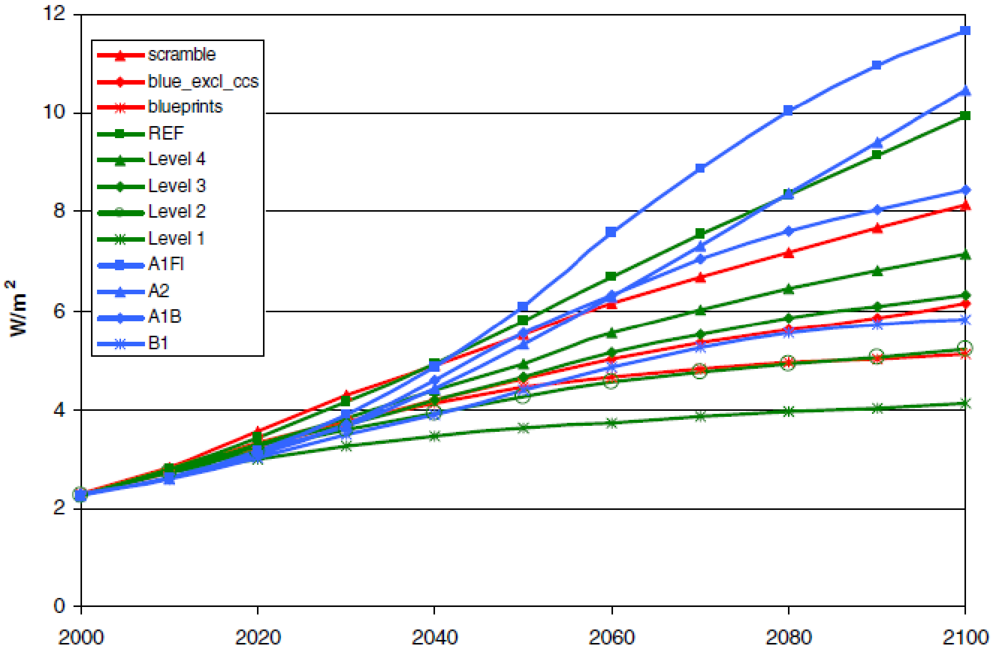


Figure A-3: Net RF, 2000-2100, due to all Long-Lived GHGs, Sulfate and Black Carbon Aerosols, and Ozone in Prinn et al. 2011.

(Shell in red, CCSR in green, SRES in blue). Reprinted with kind permission from Springer Science and Business Media, from Prinn et al., Climatic Change 2011. [38]

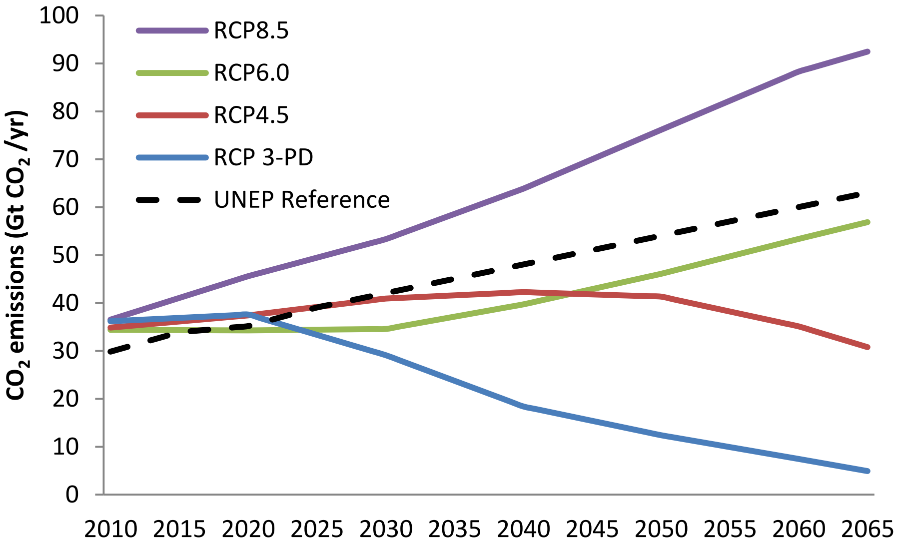


Figure A-4: CO_2 Emissions, 2010-2070, for UNEP 2011 Reference Scenario compared to RCP Scenarios

Data sources: RCP database [29], UNEP[36], Shindell [48]

Appendix B Definitions of Committed Warming

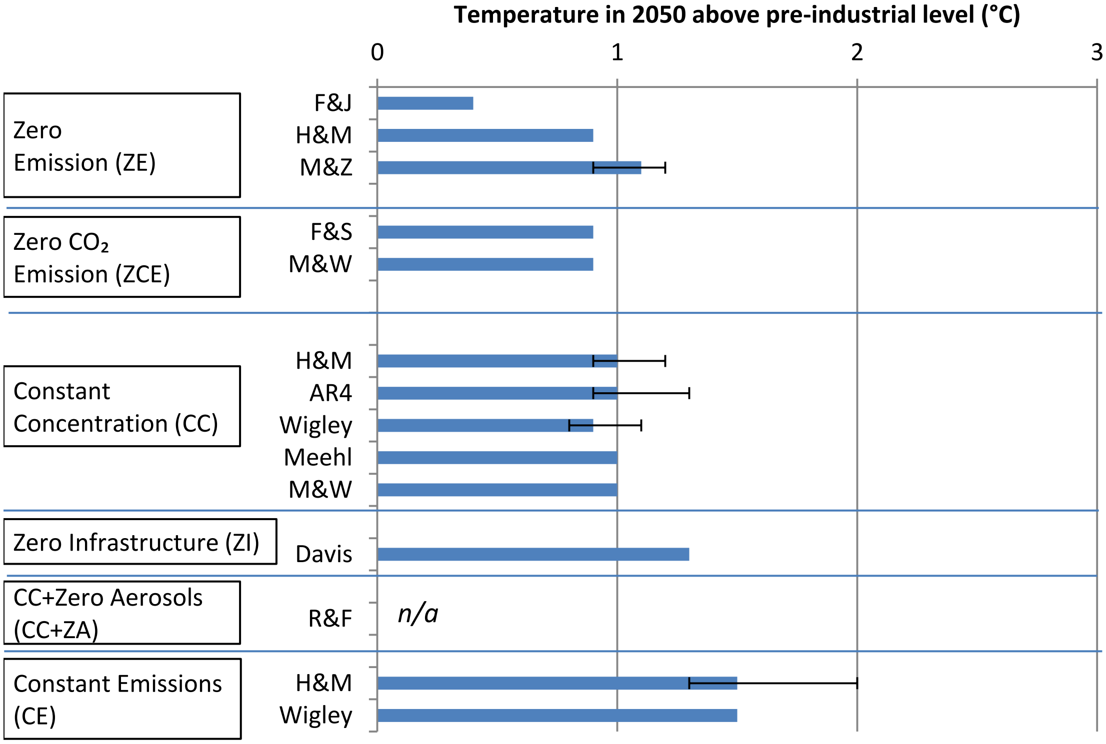


Figure B-1: Temperature in 2050 for Six Definitions of Committed Warming, by Author
For the six definitions, see Table 2-8. Ranges of uncertainty shown are provided in the original papers and are omitted if not shown in those papers. Author abbreviations and citations are as follows: F&J = Froelicher and Joos 2010 [56], H&M = Hare and Meinshausen 2006 [57], M&Z = Matthews and Zickfeld 2012 [55], F&S = Friedlingstein and Solomon 2005 [58], M&W = Matthews and Weaver 2010 [59], AR4 = IPCC AR4 Working Group I [28], Wigley 2005 [60], Meehl = Meehl et al. 2005 [61], Davis = Davis, Caldeira, and Matthews 2010 [63], R&F = Ramanathan and Feng 2008 [51]

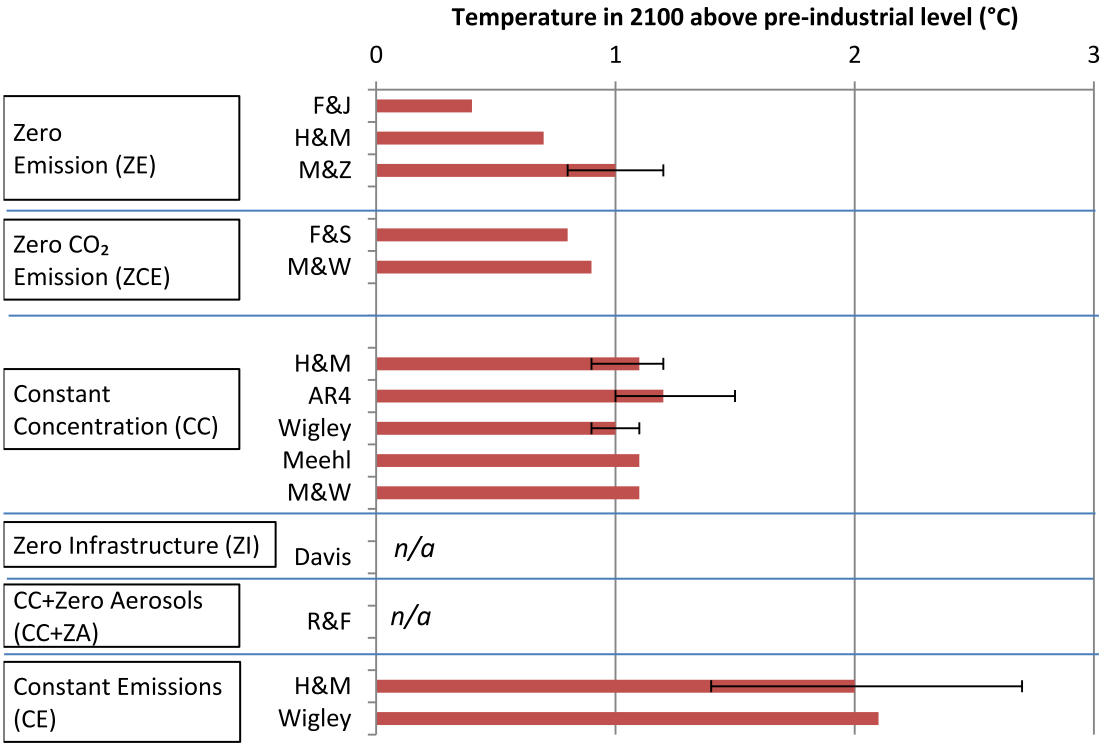


Figure B-2: Temperature in 2100 for Six Definitions of Committed Warming, by Author
Replica of Figure B-1 for year 2100; see caption for Figure B-1.

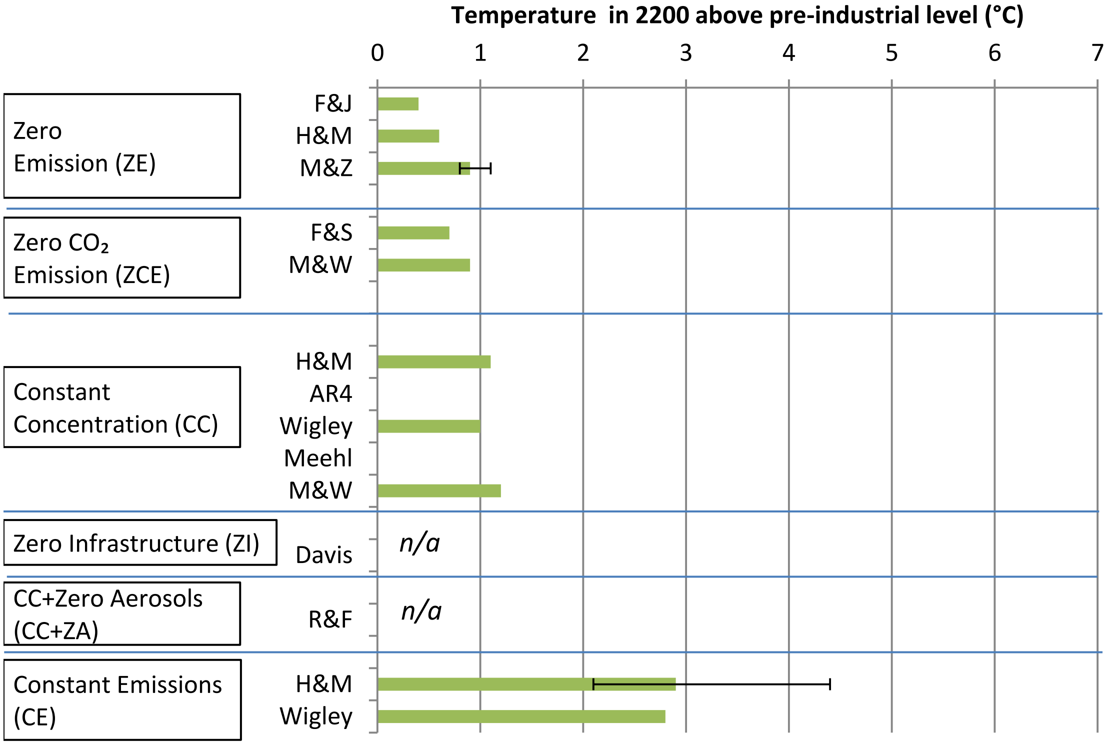


Figure B-3: Temperature in 2200 for Six Definitions of Committed Warming, by Author

Replica of Figure B-1 for year 2200; see caption for Figure B-1.

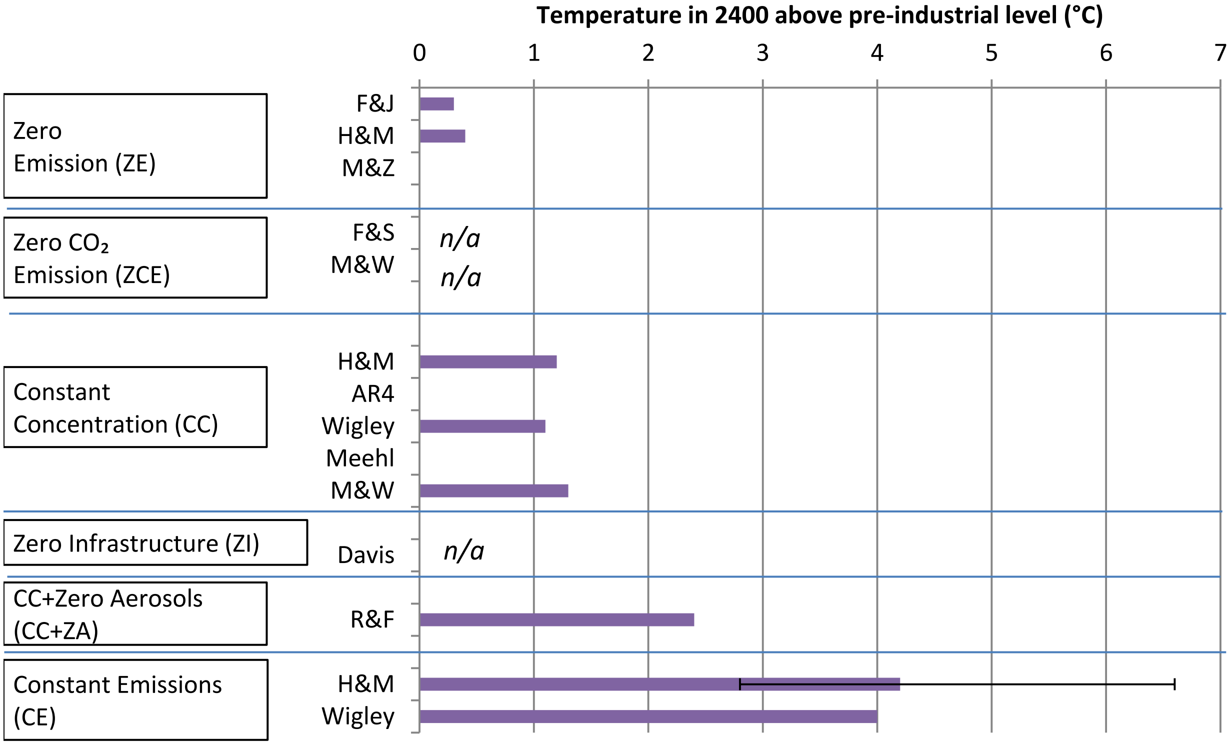


Figure B-4: Temperature in 2400 for Six Definitions of Committed Warming, by Author
Replica of Figure B-1 for year 2400; see caption for Figure B-1.

Appendix C Background on the EDGAR Database

The Emissions Database for Global Atmospheric Research (EDGAR) is co-developed by the European Commission Joint Research Centre (JRC) and Netherlands Environmental Assessment Agency. The methodology is mature, with twenty years of experience since EDGAR's founding in 1992. The current version of the dataset, EDGAR 4.2, was updated in December 2011. [46]

The EDGAR dataset provides historical emissions data for all radiatively active pollutants except black carbon and organic carbon for 1970-2008. Data is based on bottoms-up calculations for each source category in each nation, providing internal consistency over time and between nations. The source categories used are the ones designated by the IPCC National Greenhouse Gas Inventories Programme in the 1996 guidelines [244]. Calculations for each source and nation account for the following:

- Activity data (e.g., fuel consumption)
- Technology mix (e.g., type of vehicle)
- Emissions factor (technology-specific) (from 2006 revised IPCC guidelines)
- Abatement measures (technology-specific)

There are uncertainties in each of these factors, compounded by doing bottoms-up calculations. EDGAR's uncertainty estimates for v4.2 are in preparation; uncertainty estimates for v2 are as follows: CO_2: ~10%, CH_4: ~50%, and N_2O: ~100%. This level of uncertainty is on the same order of magnitude as the recent analysis of California emissions by Fischer [245], who compared reported emission inventories with emissions calculated via radiocarbon, flux tower, and flask measurements. Results showed that fossil fuel CO_2 emissions are within 10% of emission inventories, CH_4 emissions are 1.6-2 times higher than inventories, and N_2O emissions are 2-3 times higher than inventories. The accuracy of EDGAR calculations relative to both inventories and scientific measurements will only be known over time as more scientific measurements are done.

Meantime, it should be noted that there are differences between the EDGAR dataset and the national emission inventories submitted to the UNFCCC. EDGAR data are more useful for trending and comparative purposes because national inventories include limited nations over a limited timeline (since 1990). EDGAR also uses more recent emission factor data (from IPCC 2006), while national inventories use either 1996 or 2000 IPCC guidelines. Additionally, national inventories are compiled by individual national teams. While all national teams are following IPCC guidelines, it is possible that consistency across nations may not be at the same level as EDGAR calculations that are done by a single team for all nations and all time periods.

Appendix D CH₄ Emissions from Selected Nations

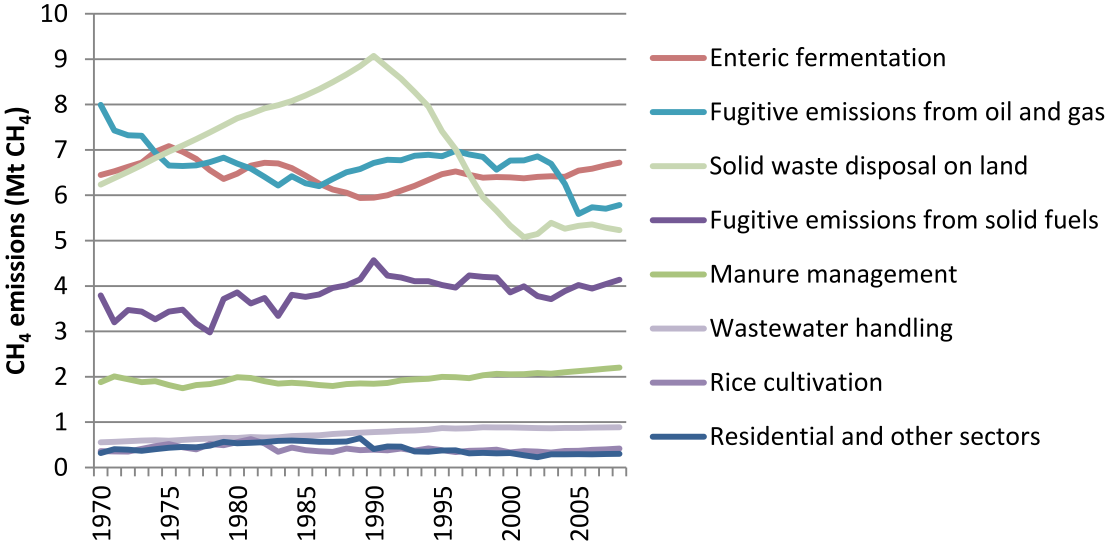


Figure D-1: CH_4 Emissions from United States, 1970-2008

Data source: EDGAR 4.2 database [46]

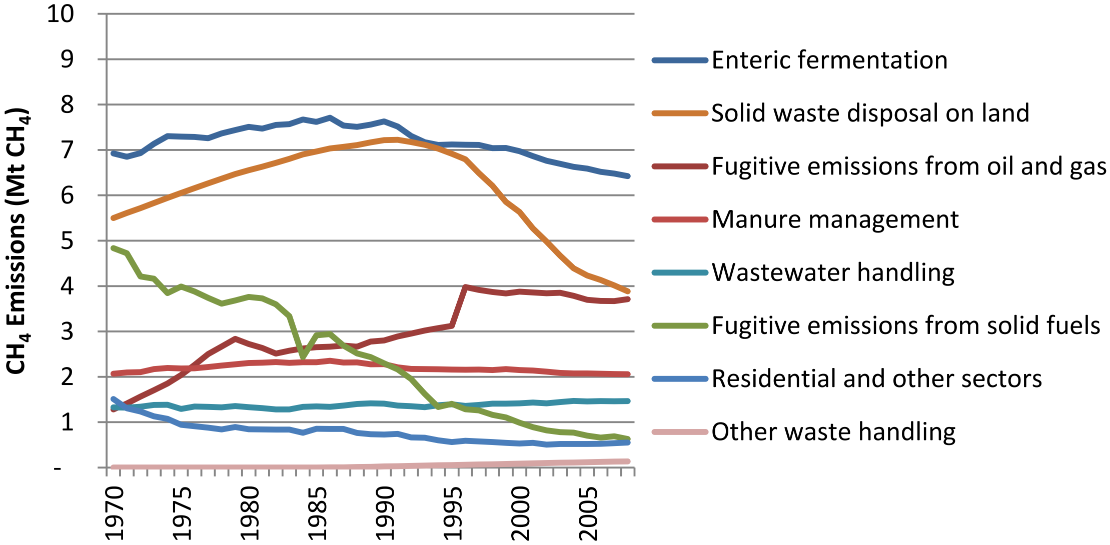
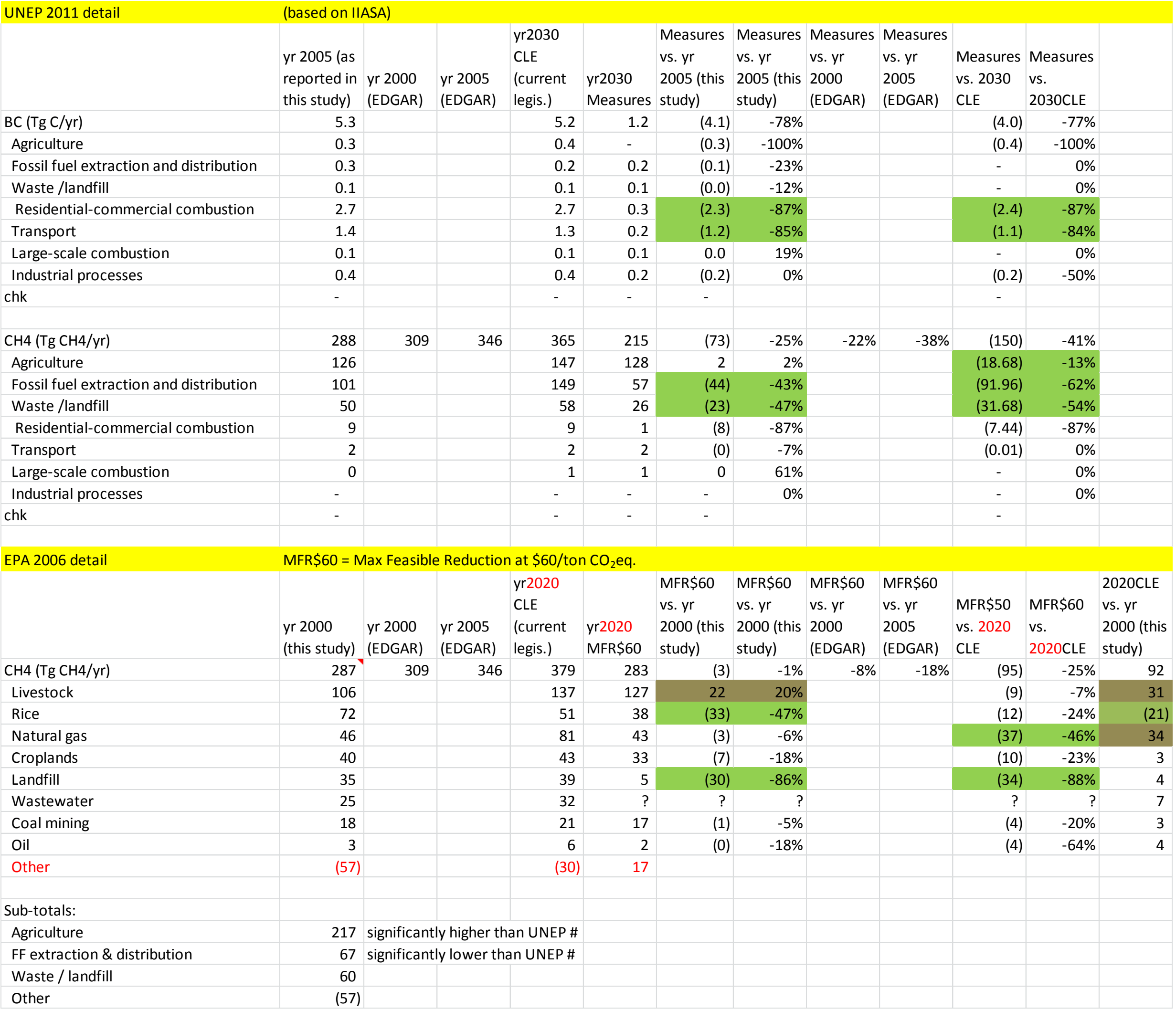


Figure D-2: CH_4 Emissions from OECD Europe, 1970-2008

Data source: EDGAR 4.2 database [46]

Appendix E Maximum Feasible Reductions of Short- and Medium-Lived Pollutants



UNEP 2011 detail	(based on IIASA)											
	yr 2005 (as reported in this study)	yr 2000 (EDGAR)	yr 2005 (EDGAR)	yr2030 CLE (current legis.)	yr2030 Measures	Measures vs. yr 2005 (this study)	Measures vs. yr 2005 (this study)	Measures vs. yr 2000 (EDGAR)	Measures vs. yr 2005 (EDGAR)	Measures vs. 2030 CLE	Measures vs. 2030CLE	
BC (Tg C/yr)	5.3			5.2	1.2	(4.1)	-78%			(4.0)	-77%	
Agriculture	0.3			0.4	-	(0.3)	-100%			(0.4)	-100%	
Fossil fuel extraction and distribution	0.3			0.2	0.2	(0.1)	-23%			-	0%	
Waste /landfill	0.1			0.1	0.1	(0.0)	-12%			-	0%	
Residential-commercial combustion	2.7			2.7	0.3	(2.3)	-87%			(2.4)	-87%	
Transport	1.4			1.3	0.2	(1.2)	-85%			(1.1)	-84%	
Large-scale combustion	0.1			0.1	0.1	0.0	19%			-	0%	
Industrial processes	0.4			0.4	0.2	(0.2)	0%			(0.2)	-50%	
chk	-			-	-	-				-		
CH4 (Tg CH4/yr)	288	309	346	365	215	(73)	-25%	-22%	-38%	(150)	-41%	
Agriculture	126			147	128	2	2%			(18.68)	-13%	
Fossil fuel extraction and distribution	101			149	57	(44)	-43%			(91.96)	-62%	
Waste /landfill	50			58	26	(23)	-47%			(31.68)	-54%	
Residential-commercial combustion	9			9	1	(8)	-87%			(7.44)	-87%	
Transport	2			2	2	(0)	-7%			(0.01)	0%	
Large-scale combustion	0			1	1	0	61%			-	0%	
Industrial processes	-			-	-	-	0%			-	0%	
chk	-			-	-	-				-		
EPA 2006 detail	MFR$60 = Max Feasible Reduction at $60/ton CO_2eq.											
	yr 2000 (this study)	yr 2000 (EDGAR)	yr 2005 (EDGAR)	yr2020 CLE (current legis.)	yr2020 MFR$60	MFR$60 vs. yr 2000 (this study)	MFR$60 vs. yr 2000 (this study)	MFR$60 vs. yr 2000 (EDGAR)	MFR$60 vs. yr 2005 (EDGAR)	MFR$50 vs. 2020 CLE	MFR$60 vs. 2020CLE	2020CLE vs. yr 2000 (this study)
CH4 (Tg CH4/yr)	287	309	346	379	283	(3)	-1%	-8%	-18%	(95)	-25%	92
Livestock	106			137	127	22	20%			(9)	-7%	31
Rice	72			51	38	(33)	-47%			(12)	-24%	(21)
Natural gas	46			81	43	(3)	-6%			(37)	-46%	34
Croplands	40			43	33	(7)	-18%			(10)	-23%	3
Landfill	35			39	5	(30)	-86%			(34)	-88%	4
Wastewater	25			32	?	?	?			?	?	7
Coal mining	18			21	17	(1)	-5%			(4)	-20%	3
Oil	3			6	2	(0)	-18%			(4)	-64%	4
Other	(57)			(30)	17							
Sub-totals:												
Agriculture	217	significantly higher than UNEP #										
FF extraction & distribution	67	significantly lower than UNEP #										
Waste / landfill	60											
Other	(57)											

Table E-1: Maximum Feasible Reductions by Pollutant (BC, CH_4) by Source, per EPA and UNEP [36, 83, 89]

Tg = Mt. CLE = emissions under current legislation; MFR = maximum feasible reductions; Measures = reductions assumed under UNEP's "CH_4 + all BC measures" scenario (see Figure F-1). Shaded green cells indicate major reductions. Shaded brown cells indicate major increases. UNEP estimates are versus 2030; EPA estimates are versus 2020. Totals for methane (CH_4) are shown relative to historical emissions from the EDGAR 4.2 database [46], with the 2005 comparisons matching the data shown in Figure 4-10. The EPA report provided data in Tg of CO_2eq, and I have translated it here into Tg CH_4, using the IPCC AR2 conversion (GWP100 for CH_4 = 21) [47] that was used by the EPA. Source-level accounting of historical CH_4 emissions differs materially between the UNEP and EPA reports, with the EPA showing higher agricultural emissions and lower emissions from fossil fuel extraction and distribution than shown by UNEP. There is a 57 Tg/yr variance (20% of total) in the EPA report between the source-level data and the total. Summary graph (Figure 4-10) and conclusions are provided in section 4.4.

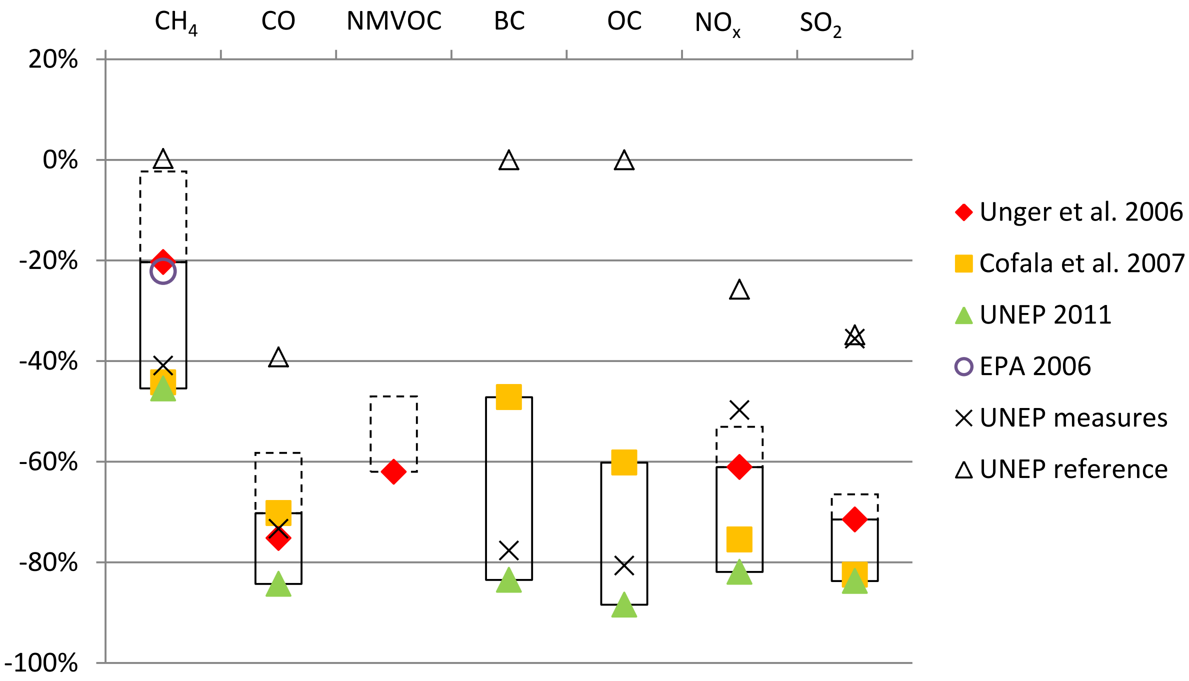


Figure E-1: Maximum Feasible Reductions by Pollutant, as a % of 2008 Emissions

Replica of Figure 4-10, comparing reductions versus 2008 instead of 2005. Among the pollutants shown, only methane emissions showed significant growth between 2005 and 2008. The percentage reductions for methane are 3-5 percentage points larger relative to 2008 than relative to 2005. See Table E-1 for the source-level detail on BC and CH_4. The largest BC reductions in the UNEP measures are in residential and commercial combustion (-87% relative to 2005)[244] and transportation (-85% relative to 2005)[245]. For CH_4, the largest UNEP measures are in fossil fuel extraction and distribution (-43% relative to 2005)[246] and in waste/landfill (-47% relative to 2005)[247]. The largest EPA reductions for CH_4 are in landfills (-86% relative to 2000) and rice (-47% relative to 2000).

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[244] Specific measures to reduce residential and commercial combustion BC include: introducing clean-burning home stoves, replacing traditional brick kilns and coke ovens with newer technology, and banning open burning of agricultural waste.

[245] Specific measures to reduce transportation BC include: rolling out diesel particle filters and eliminating high-emitting vehicles.

[246] Specific measures include reduced leakage from long-distance transmission lines, extended recovery and utilization of fugitive emissions, and extended degasification and recovery of coal mine methane.

[247] Specific measures include separation and treatment of biodegradable waste, landfill gas collection, and upgrading wastewater treatment.

Appendix F UNEP Analysis of Temperature Reduction from MTFR of Short- and Medium-Lived Pollutants

The UNEP 2011 report provides estimates of the near-term temperature benefits of near-maximum feasible reductions of short- and medium-lived pollutants. Near-maximum mitigation of short- and medium-lived pollutants assumes maximum technically feasible reductions achieved by 2030 with the 14 top measures identified by UNEP and shown in Chapter 4 (see Figure 4-10, Figure 4-11, and Figure 4-12). [248]

Figure F-1 shows that aggressive CO_2 measures alone[249] result in a global temperature increase that exceeds the 2°C ceiling by 2050, consistent with the findings of the scenarios presented in Chapter 2 (Table 2-5). However, aggressive CO_2 measures combined with near-maximum technically feasible mitigation of short- and medium-lived pollutants avoids 2°C and delays arrival at 1.5°C by ~15 years (from late 2020s to early 2040s) relative to the UNEP reference scenario[250] (in Figure F-1, compare "Reference" line with "CO_2 + CH_4 + all BC measures" line). From 2010-2045, the temperature change for the scenarios with near-maximum mitigation of short- and medium-lived pollutants with and without aggressive CO_2 mitigation is nearly identical, showing that nearly all of the near-term benefit is from the short- and medium-lived pollutant reduction (in Figure F-1, compare "CH_4 + all BC measures" line with "CO_2 + CH_4 + all BC measures" line).

The difference between aggressive CO_2 mitigation with and without near-maximum mitigation of short- and medium-lived pollutants was found to be roughly 0.5°C (0.2-0.8°C) [251] in 2050 (in Figure F-1, compare "CH_4 + all BC measures" line with "CO_2 + CH_4 + all BC measures" line). This temperature estimate should be considered a bounding estimate, since by definition maximum technically feasible reductions do not include limitations on technology roll-out such as costs, logistics, vested interests, and competition for time, money, and attention.

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[248] The temperature results shown here include 14 of the 16 measures discussed in section 4.4; UNEP and Shindell et al. excluded coal briquettes and pellet stoves from the global temperature results (main benefit of those two measures is reduced black carbon in the Arctic).

[249] Aggressive CO_2 measures in this case are defined by UNEP as a trajectory of CO_2 that stabilizes at 450 ppm CO_2eq, accounting for changes in SO_2 but not in long-lived non-CO_2 pollutants.

[250] CO_2 emission assumptions for the UNEP reference scenario are presented in Figure A-4; Short- and medium-lived pollutant assumptions for the reference scenario are shown in Figure 4-10.

[251] Note, the BC measures alone have a confidence interval in the UNEP report that crosses 0°C: +0.04°C to -0.35°C. See discussion of uncertainty in BC radiative forcing in section 4.4.b.i.

Putting a global temperature increase of 0.5°C (0.2-0.8°C) in perspective, Chapter 2 identified the likely[252] long-term temperature increase as 1.8-7.0°C for all scenarios excluding RCP3-PD. In other words, the 0.5°C (0.2-0.8°C) difference achievable by near-maximum mitigation of short- and medium-lived pollutants is small relative to the mid- and upper-end of projected temperature outcomes for all modeled scenarios and would provide a delay in reaching those higher temperatures (Box 1).

The UNEP report calculated the temperature benefit via two methods: an analytic method and with the GISS model. Three assumptions used in the analytic method stand out that suggest the 0.5°C estimate may be on the high side. First, higher-than-average equilibrium climate sensitivity (3.4°C) was used in the analytic method (see Table 13-1).[253] Use of the best-estimate climate sensitivity (3°C) would reduce the temperature benefit by ~10%. Second, the temperature response function used realizes 67% of equilibrium temperature within 40 years.[254] This is higher than most climate models (~55%) though consistent with Hansen et al. 2011's best estimate [43] (see Figure 6-5). If the 40-year response were 55-60% instead of 67% of equilibrium temperature, this would reduce the temperature benefit by 10-20%. Third, the analysis assumes that all aerosol indirect effects from scattering aerosols are attributable to sulfates, that nearly all sulfate reductions that occur in the UNEP measures case would have also occurred in the UNEP reference case, and that the best estimate of black carbon's semi-direct and indirect effect is zero. Thus, there is no aerosol indirect effect apparent in the central temperature results. This assumption reflects the best current understanding amid wide uncertainties in aerosol science. If significant aerosol indirect effects do exist that are not attributable to sulfates, then the temperature benefit of the UNEP measures may be lower than reported.[255]

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[252] See footnote 17 for definition of likely.

[253] 3.4C = (0.541+0.368)*3.7, from p.139 of UNEP report.

[254] Sum, from t=0 to 40 of f(t) = 0.541/8.4 exp(-t/8.4) + 0.368/409.5 exp(-t/409.5), divided by 0.909 (=.541+.368).

[255] If the non-SO_2 aerosols were instead responsible for part of the cooling AIE, this would materially reduce the estimated mitigation benefit, particularly if the AIE were large. The 90% confidence interval for AIE in IPCC AR4 was -1.80 to -0.30 W/m^2. See discussion of uncertainty in section 4.4.b.i and uncertainty ranges of forcing in Figure 4-11 and Figure 4-12.

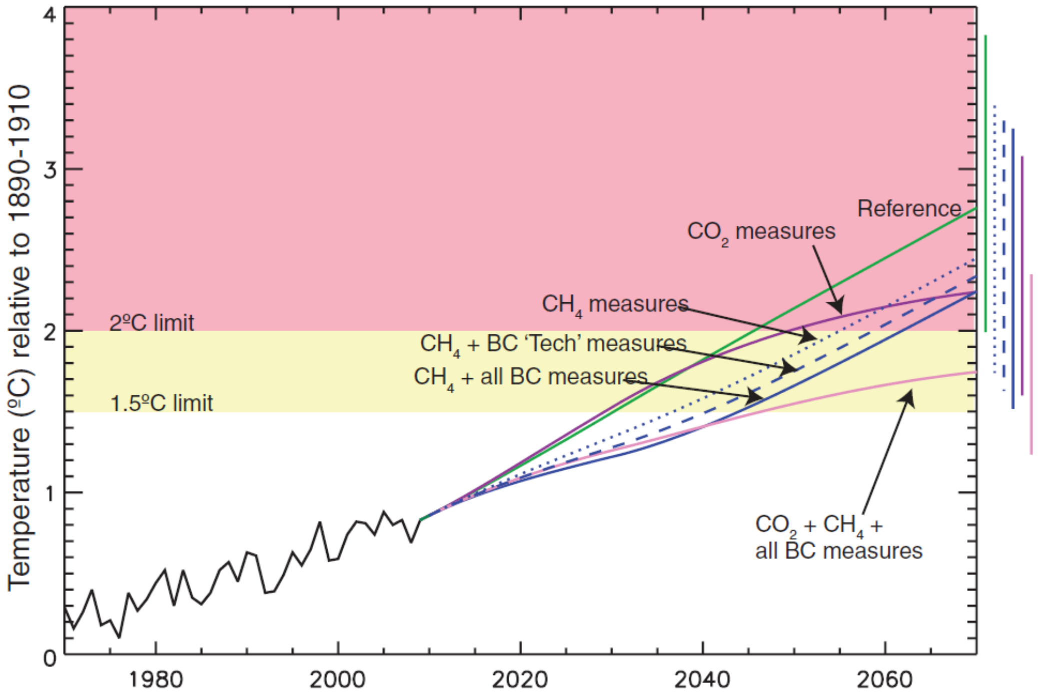

Figure F-1: Avoided Temperature Increase via Near-Maximum Mitigation of Short- and Medium-Lived Pollutants

From Shindell et al, Science 2012 [88] Reprinted with permission from AAAS.

Mitigation of short-lived pollutants in this chart includes black carbon (BC), organic carbon (OC), carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur dioxide (SO_2). These are abbreviated "BC measures" because black carbon is reduced in all of the mitigation measures that were modeled for short-lived pollutants and mitigation of CH_4 and BC produce the largest RF benefits relative to the reference scenario under best estimates of forcing (see Figure 4-11). Mitigation of methane (CH_4) and short-lived pollutants is assumed to be achieved to be the maximum feasible via 14 mitigation measures, illustrated by the "UNEP measures" data points in Figure 4-10. CO_2 emissions for the reference scenario are shown in Figure A-4 and a comparison of short- and medium-lived pollutant forcing between the measures and reference scenarios is shown in Figure 4-11 and Figure 4-12 ("UNEP meas. beyond ref.").

Appendix G Emission Assumptions for RCP Scenarios

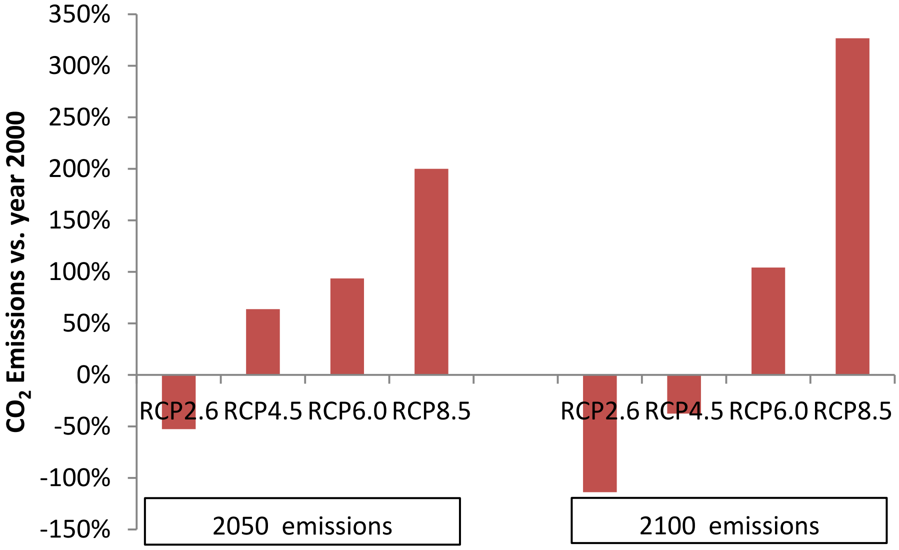

Figure G-1: CO_2 Emissions, 2050 vs. 2000 and 2100 vs. 2000, assumed in RCP Scenarios

Data from [26]. Note that CO_2 emissions increase with higher RCP scenarios. Only RCP 3-PD assumes CO_2 emissions decrease in 2050 relative to year 2000. Only RCP 3-PD and RCP4.5 assume CO_2 emission reductions in 2100 relative to year 2000. RCP 3-PD assumes negative (>-100%) emissions by year 2100.

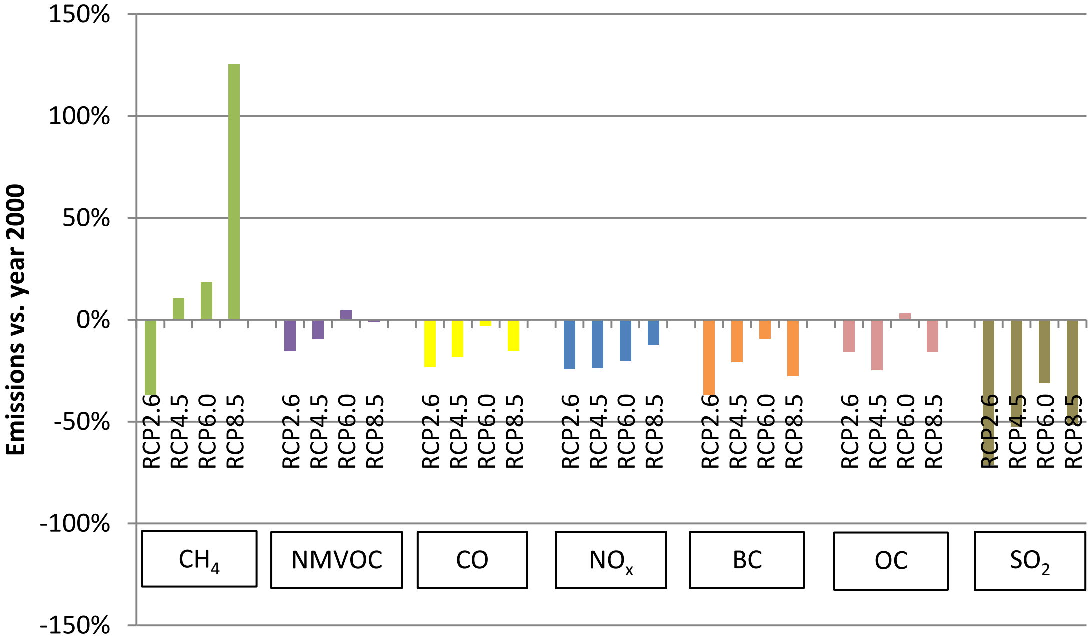

Figure G-2: Emissions of Short- and Medium-Lived Pollutants, 2050 vs. 2000, assumed in RCP Scenarios Data from [26]. Note that short- and medium-lived pollutant emissions (except for OC) are correlated with the CO_2 trends (Figure G-1), with greater emission reductions for RCP 3-PD, relative to RCP4.5, relative to RCP6.0. CH_4 and NO_x continue the trend to RCP8.5, while the others reverse direction. Maximum technically feasible reductions (MTFR) for CH_4 are assumed in RCP 3-PD (see Figure 4-10). No other pollutant in any other scenario is assumed to reach MTFR. See section 4.1 for abbreviations.

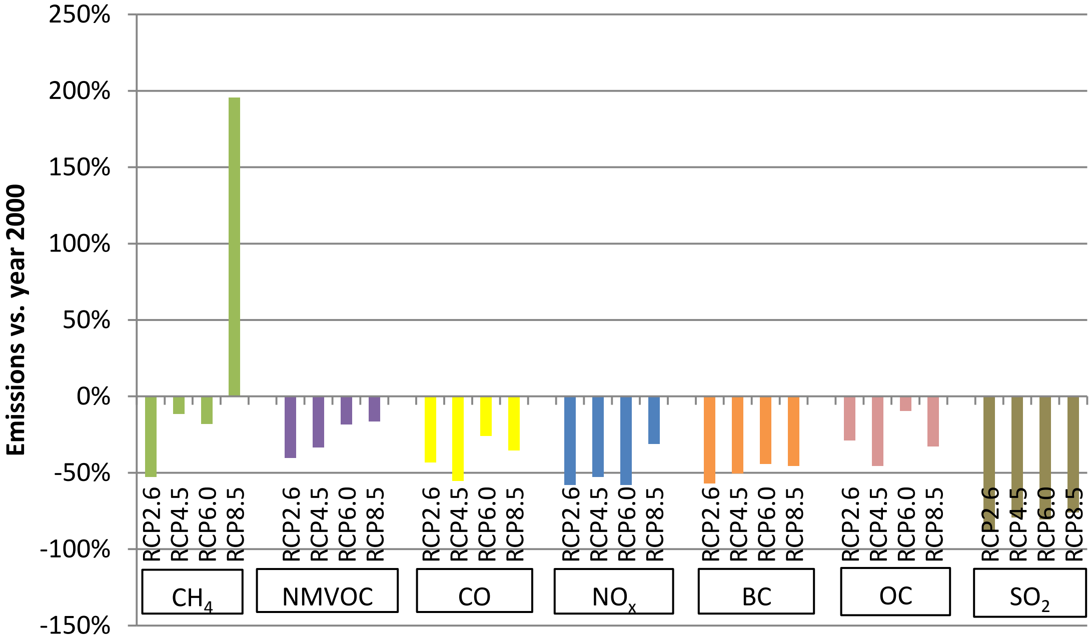

Figure G-3: Emissions of Short- and Medium-Lived Pollutants, 2100 vs. 2000, assumed in RCP Scenarios Data from [26]. Note that short- and medium-lived pollutant emissions (except for CH_4 and CO) are generally correlated with the CO_2 trends (Figure G-1), with greater emission reductions for RCP 3-PD, relative to RCP4.5, relative to RCP6.0, relative to RCP8.5. Maximum technically feasible reductions (MTFR) for CH_4 and SO_2 are assumed in RCP 3-PD (see Figure 4-10). MTFR is assumed for NO_x in RCP 3-PD, RCP4.5, and RCP6.0. MTFR is assumed for BC in RCP 3-PD and RCP4.5. No other pollutant in any other scenario is assumed to reach MTFR.

Appendix H Emission Trajectories and Cumulative CO_2

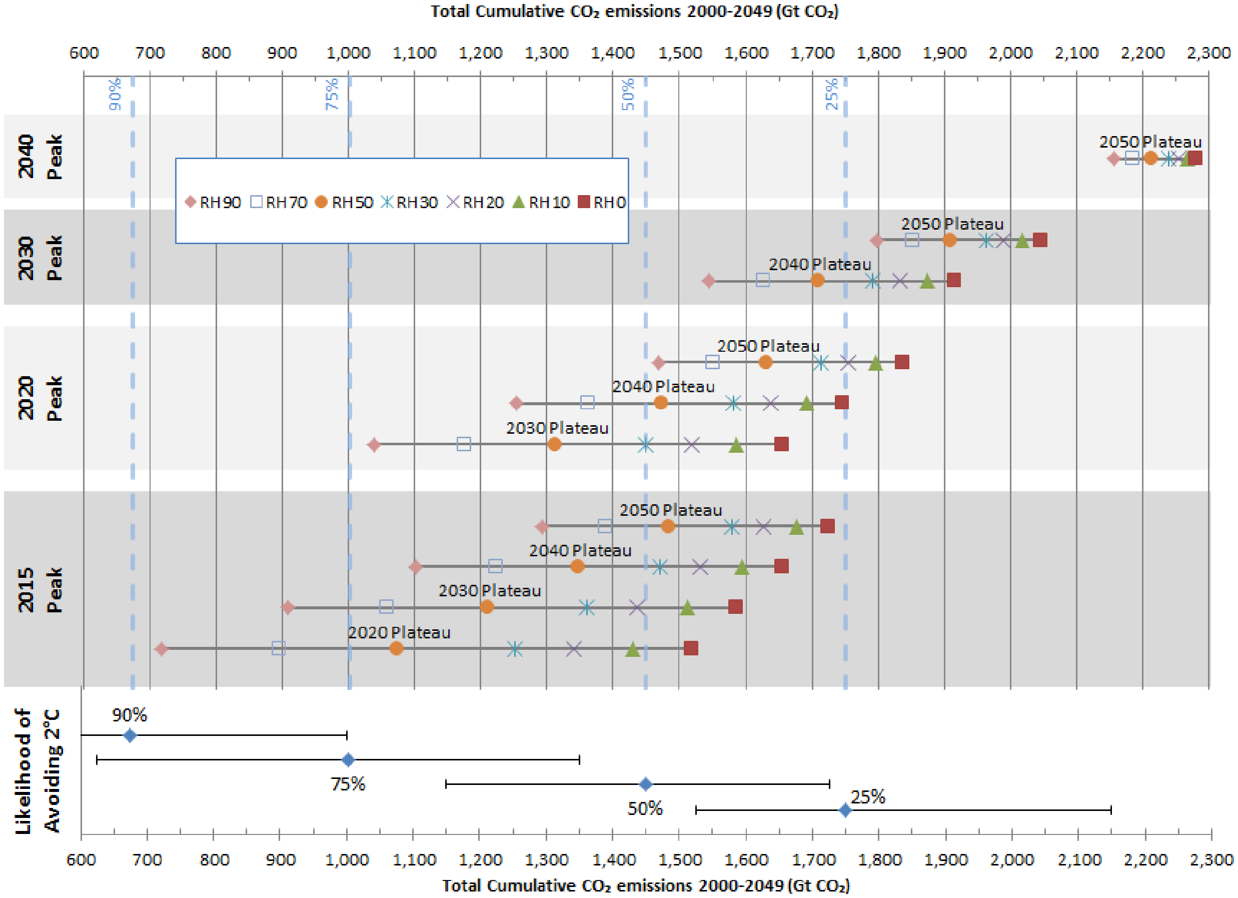

Figure H-1: Replica of Figure 9-3, assuming RCP 8.5 to Peak

RH0, RH10, RH20, RH30, RH50, RH70, RH90: "R" stands for "reduction"; number is % reduction relative to 1990. "H" stands for "high" emission trajectory to peak (RCP 8.5 instead of RCP 4.5 as was used for the R-scenarios in Figure 9-3). RH scenarios have higher cumulative emissions than the comparable R scenarios. Likelihood lines and bars are in the same positions as in Figure 9-3. See caption of Figure 9-3 for methods and chart assumptions.

Appendix I Background on the MAGICC Model

The MAGICC model (Model for the Assessment of Greenhouse Gas-Induced Climate Change) is a reduced complexity (simple) coupled gas-cycle / climate model that emulates the results of the highly complex AOGCMs (Atmosphere-Ocean Global Circulation Models). It is designed and managed by Malte Meinshausen, Tom Wigley, and Sarah Raper, and has been the simple climate model used since 1990 in all of the IPCC reports to provide projections of global mean surface temperature and sea level resulting from a given emission trajectory.[256] The most recent version (MAGICC 6.0) was first published in 2008 and can replicate the mean results of the AR4 AOGCMs to within 2.2% for the SRES scenarios, as well as the individual results of each AOGCM. Its short run time and 400+ tunable parameters allow probabilistic analysis of climate outcomes.

Chapter 9, Chapter 13, and Chapter 15 of this dissertation draw upon two sets of probabilistic runs in MAGICC that were presented in Nature 2009 (Meinshausen et al.) [170] and in Nature Climate Change 2012 (Rogelj et al.) [37]. The Nature 2009 study presented the likelihood of exceeding 2°C versus cumulative CO_2 between years 2000-2049. The authors created 948 emission scenarios and ran each one with 600 combinations of 82 parameters, including climate sensitivity,[257] and one of 10 C^4MIP carbon-cycle model emulations.[258] The result was the curve shown in Figure 9-1.

The Nature Climate Change 2012 study presented the likelihood of staying below a given temperature versus net radiative forcing and CO_2eq. ppm. The authors varied the same 82 parameters as in the Nature 2009 paper, with more robust treatment of climate sensitivity. They created 10,000 randomly drawn equilibrium climate sensitivity (ECS) distributions that were compatible with the IPCC's AR4 ECS conclusions,[259] and then created a representative ECS distribution from the arithmetic mean of the 10,000 distributions. The climate sensitivity used for a given run was drawn from this representative distribution. The authors did 600 runs with different parameter combinations and one of 9 C^4MIP carbon-cycle model emulations for each of 14 scenarios: 6 SRES marker scenarios (emission-driven), 4 emission-driven RCPs, and 4 concentration-driven RCPs. The result was the diagram shown in Figure 13-2.

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[256] http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch8s8-8-2.html

[257] The model has over 400 parameters, so most were held constant at default values (match HadCM3).

[258] The authors also varied 40 scaling parameters that determine regional patterns; these regional results were not used in this dissertation.

[259] AR4 conclusion: Climate sensitivity best estimate = 3°C; over 66% probability that it lies between 2-4.5°C; over 90% probability that it is over 1.5°C; values over 4.5°C cannot be excluded.

Appendix J Airborne Fraction

The airborne fraction is the fraction of emitted CO_2 that is added to the atmospheric concentration, rather than being absorbed by the ocean or land biosphere. The airborne fraction can either be presented as an annual number (change in atmospheric CO_2 this year versus last year, divided by this year's emissions)[260] or as a cumulative number (change in atmospheric CO_2 since pre-industrial times, divided by cumulative emissions since pre-industrial times). As of 2005, the cumulative airborne fraction and the average annual airborne fraction (1960-2005) were both 46%. [26].

In Chapter 9 and Chapter 15, I translated between CO_2 ppm and CO_2 emissions for the coming century using a constant airborne fraction of 46% of total CO_2 emissions (fossil fuel plus land use change). For long-term calculations, I used the lower equilibrium cumulative airborne fraction (see Table 15-2).

Use of a constant airborne fraction for the coming century is reasonable due to a lack of agreement in the research community on whether there has been a detectable trend in the airborne fraction to-date, the expectation that the airborne fraction will remain generally in historical range for all but the highest and lowest emission scenarios over the next few decades to centuries, and general uncertainty in its value over this time period. Details on these points follow.

Simple statistics on the RCP dataset show that the annual airborne fraction (AF) has varied between 30-60% over the past 50 years (average 46%), and there has been little correlation between AF and time ($R^2 = 0.05$) (see Figure J-1). There has also been little correlation between annual airborne fraction and the excess CO_2 in the atmosphere above pre-industrial levels ($R^2 = 0.04$) (see Figure J-2).[261] However, El Nino and volcanic activity contribute significant inter-annual variability to the annual airborne fraction. Once those effects are removed, Raupach et al. 2008 find a 90% chance of a "detectable increasing trend." [246] In contrast, Gloor et al. 2010 do not find a statistically significant trend, after also considering the uncertainty in the emissions data for historical land use. [247] Consistent with the lack of clarity around a trend in

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[260] The annual airborne fraction accounts for a given year's entire CO_2 sink; total carbon sink = (1-AF)*current year emissions.

[261] The Global Carbon Project dataset (without adjustments for El Nino or volcanoes) similarly shows little evidence of positive or negative trend in AF over time ($R^2 = 0.02$) and a similar average airborne fraction for 1960-2011 (44%) (see Figure J-7 and Figure J-8).

the annual airborne fraction, the cumulative airborne fraction has varied narrowly, ranging from 44-46% consistently from 1960-2005 (see blue diamonds in Figure J-3).

Looking forward, for the highest emission scenarios (A2, RCP 8.5), carbon sink strength is expected to fall and the airborne fraction is expected to rise through 2100 as temperature increases. [248, 249][262] In lower emission scenarios such as the A1B scenario [248] and the middle RCP scenarios (RCP 4.5, RCP 6.0), the airborne fraction is expected to remain roughly in the historical range through 2100.[263] In the lowest RCP scenario (RCP 3-PD), the airborne fraction is expected to decline through 2100. (For RCP projections, see Figure J-3 and Figure J-5 for cumulative AF and Figure J-4 and Figure J-6 for annual AF.)

In contrast to the varying paths that AF may take over the coming century, the equilibrium airborne fraction (EAF), after atmospheric CO_2 equilibrates with the biosphere and ocean but before the millennial scale reactions with calcium carbonate and igneous rocks, will be lower than 46% in nearly all cases. Archer et al. 2009 [68] estimate an EAF ranging from 20-40%, with a higher EAF for higher levels of emissions. See more detailed estimates in Table 15-2.

Due to scientific uncertainty in both the observed and decadal to centennial forward trends, the analysis in this dissertation assumes a constant airborne fraction of 46%, the RCP dataset average for 1960-2005.

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[262] Per IPCC AR4 WG I Ch. 7, projected cumulative AF for 1850-2100 varies widely, with an expected value of approximately ~56% (ranging from ~46% to ~72%) for the A2 scenario. For more information, see pp. 533-539 of that report.

[263] RCP 4.5: 44-47%; RCP 6.0: 46-50%; A1B: down 1 ppt from current value.

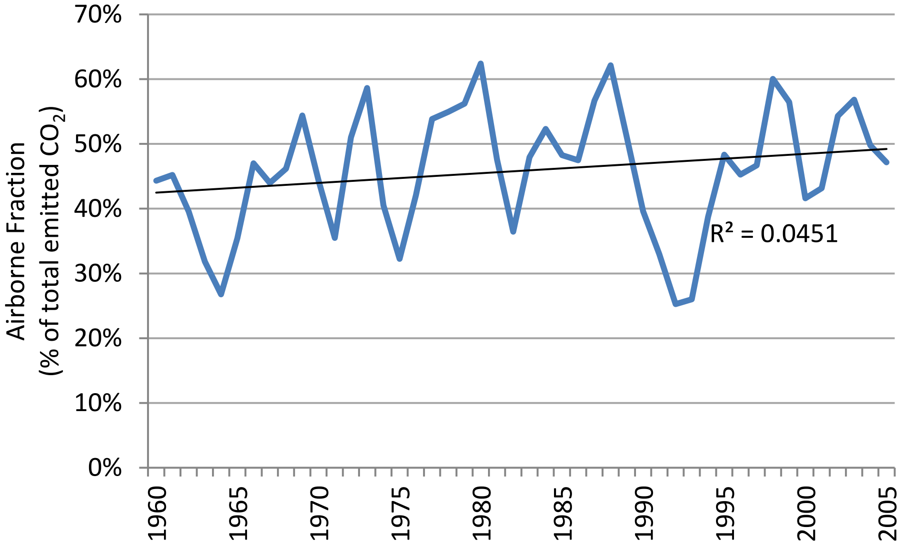

Figure J-1: Annual Airborne Fraction (% of Total CO_2 Emissions), 1960-2005

Calculated from the RCP dataset, 2011. [26]

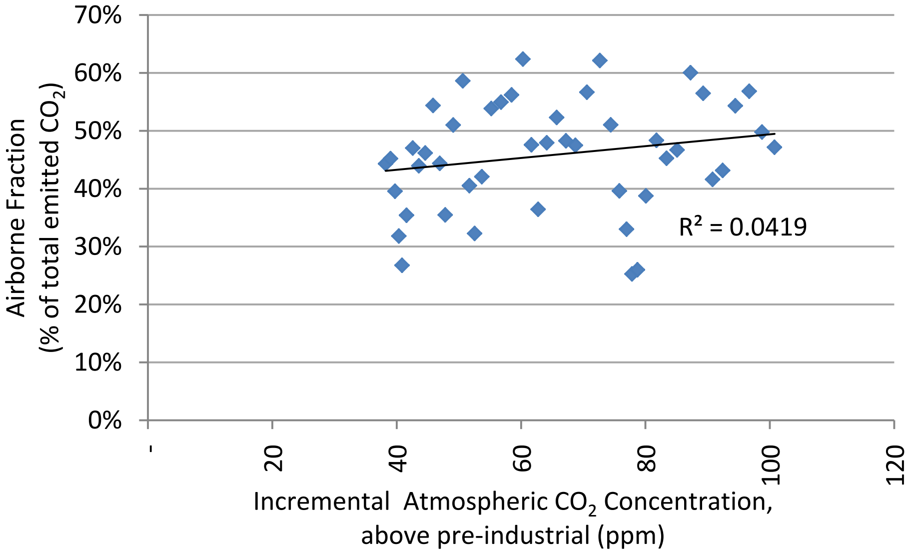

Figure J-2: Annual Airborne Fraction, 1960-2005, versus Incremental CO_2 Concentration above pre-industrial

Calculated from the RCP dataset, 2011 [26]

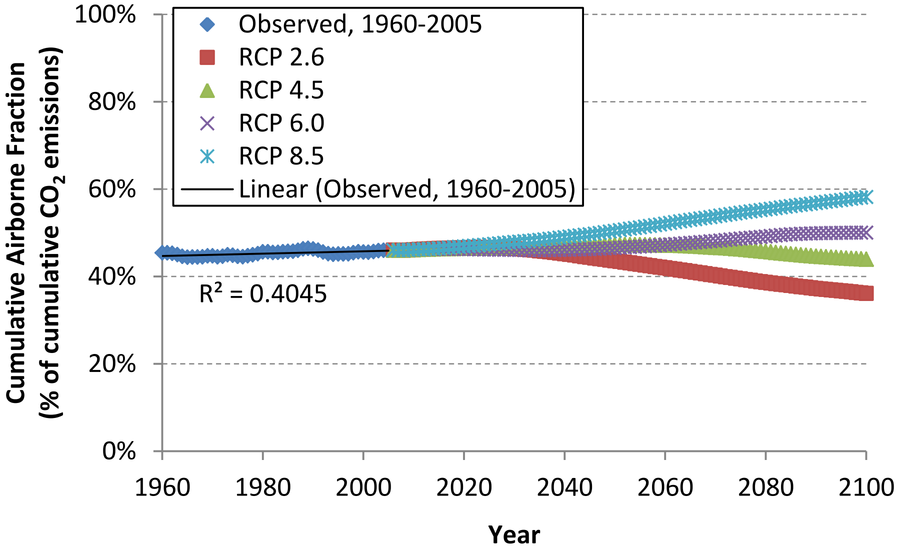

Figure J-3: Airborne Fraction for Cumulative Emissions since 1750 for RCP Scenarios, 1960-2100

Calculated from the RCP dataset, 2011 [26, 29]

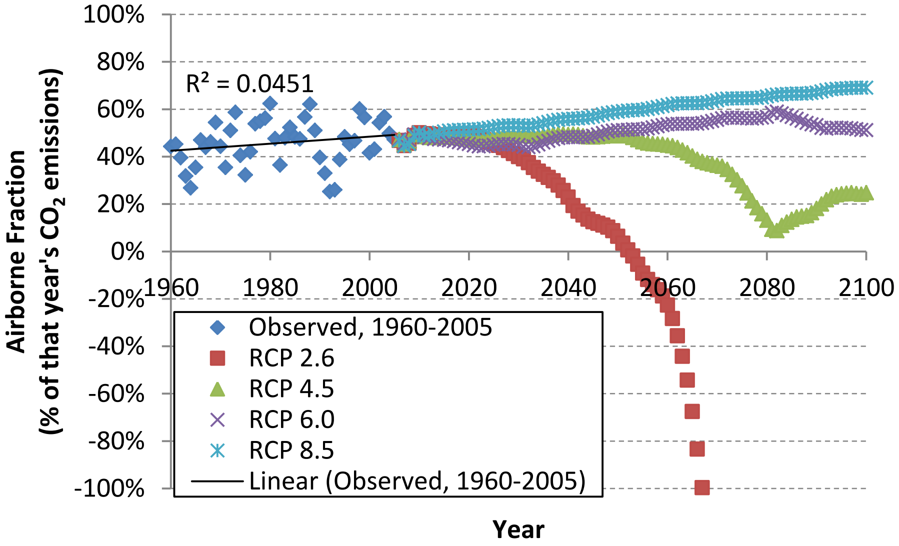

Figure J-4: Annual Airborne Fraction, 1960-2100, for RCP Scenarios

Calculated from the RCP dataset, 2011 [26]

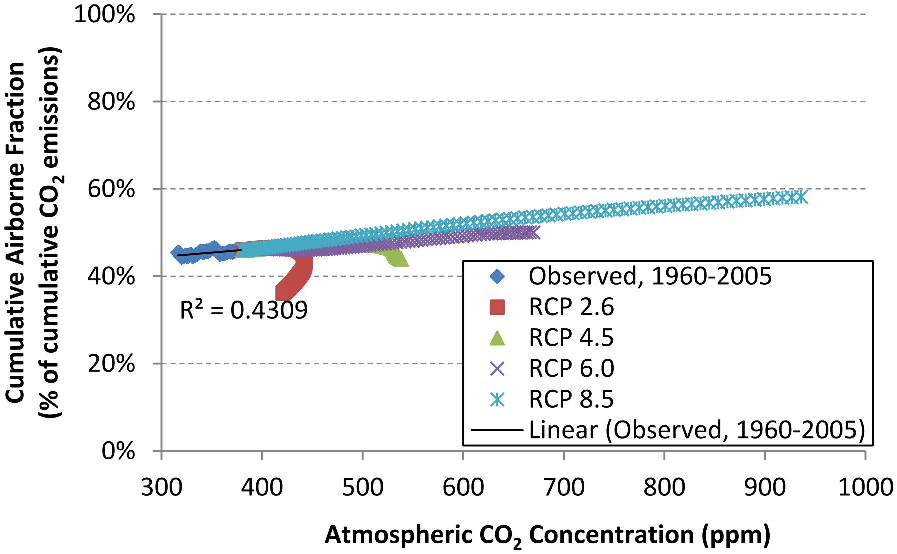

Figure J-5: Cumulative Airborne Fraction versus Atmospheric Concentration, for RCP Scenarios, 1960-2100

Calculated from the RCP dataset 2011 [26, 29]

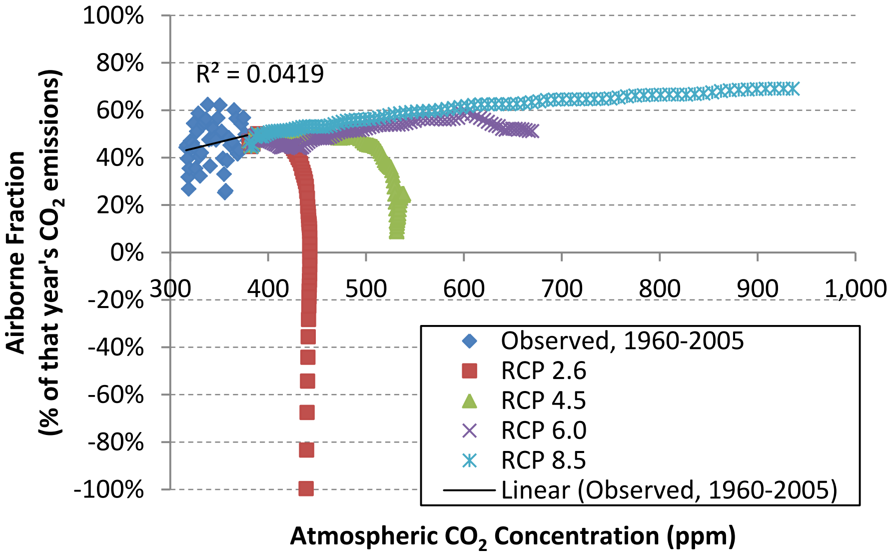

Figure J-6: Annual Airborne Fraction versus Incremental CO_2 Concentration above pre-industrial, for RCP Scenarios, 1960-2100.

Calculated from the RCP dataset, 2011 [26]

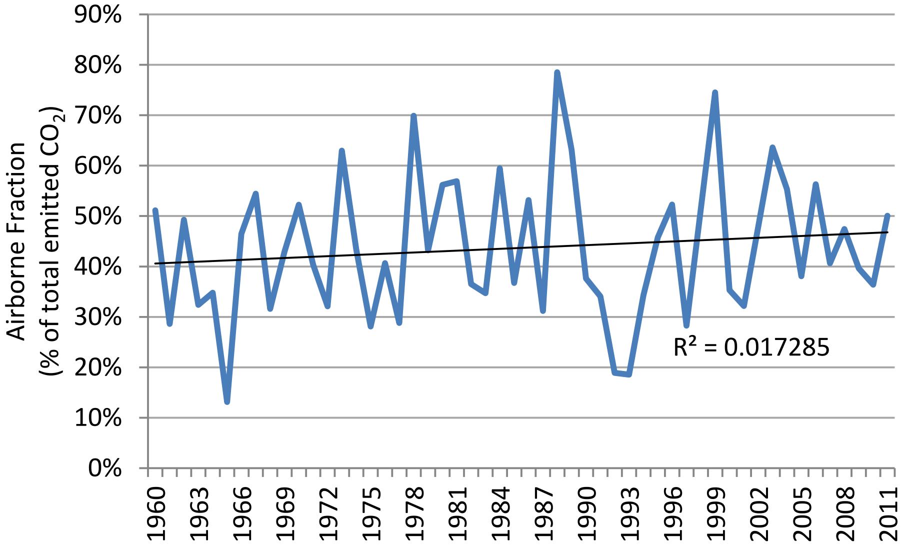

Figure J-7: Annual Airborne Fraction (% of Total CO_2 Emissions), 1960-2010
Data source: Global Carbon Project, 2011 [6, 45]

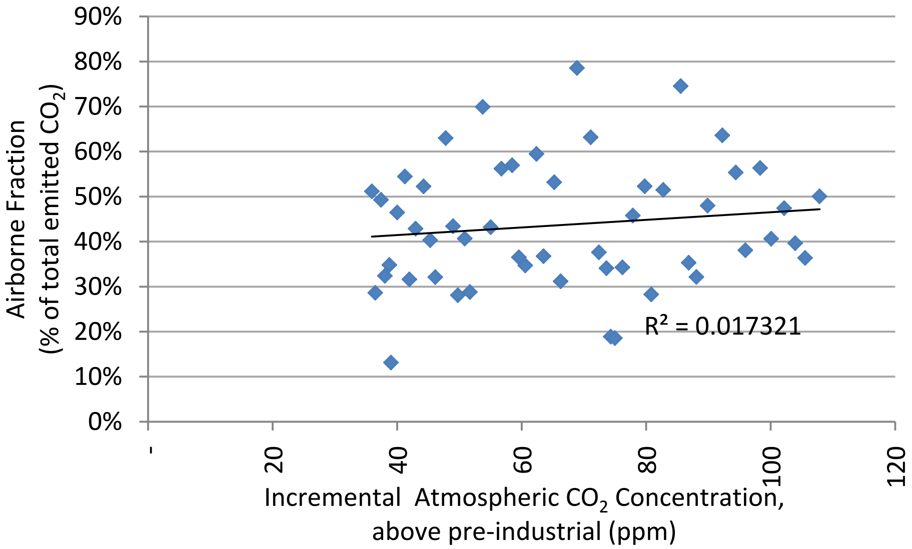

Figure J-8: Annual Airborne Fraction, 1960-2010, versus Incremental CO_2 Concentration above pre-industrial
Data source: Global Carbon Project, 2011 [6, 45]

Appendix K CO_2 Emissions from Selected Nations

This appendix breaks down the emissions by source for four nations mentioned in Chapter 12: China, Brazil, Indonesia, and Canada.

China

China's CO_2 emissions are growing rapidly from all major sources, as shown in Figure K-1. Growth in electricity and heat and in manufacturing and construction is notably dramatic, with 5-year CAGRs of 13% and 12% respectively.[264]

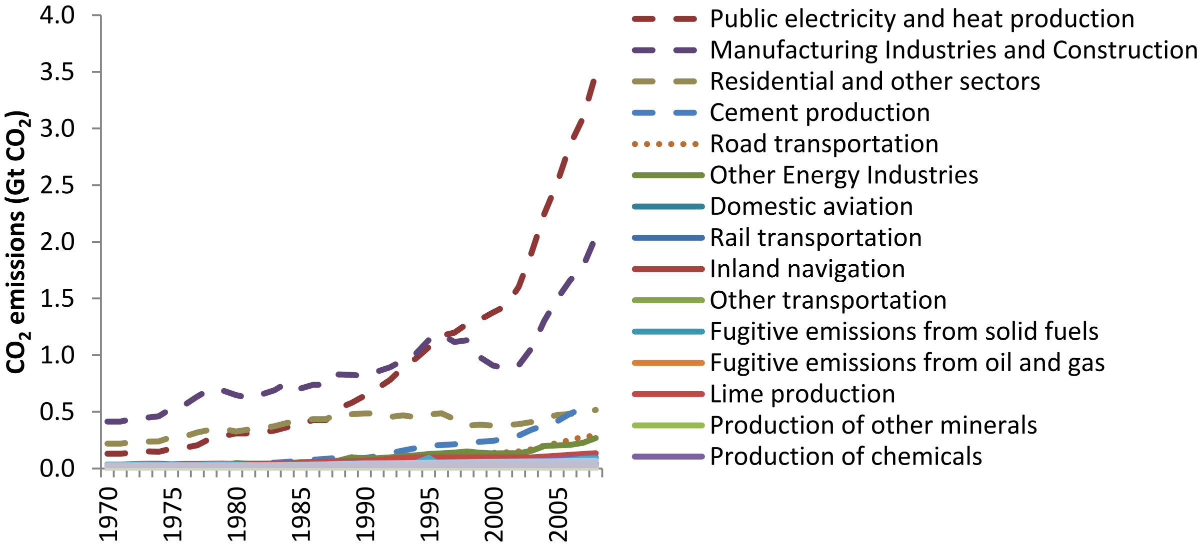

Figure K-1: China CO_2 Emissions by Source, 1970-2008

Data source: EDGAR 4.2 database [46]

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[264] Note, all CAGRs in this document are calculated based on 5-year rolling averages. A 5-year CAGR is based on the average emissions in 2004-2008 relative to the average emissions in 1999-2003.

United States

CO_2 emissions for the USA have been steady to modestly down across sources over the past 5-10 years, as shown in Figure K-2.

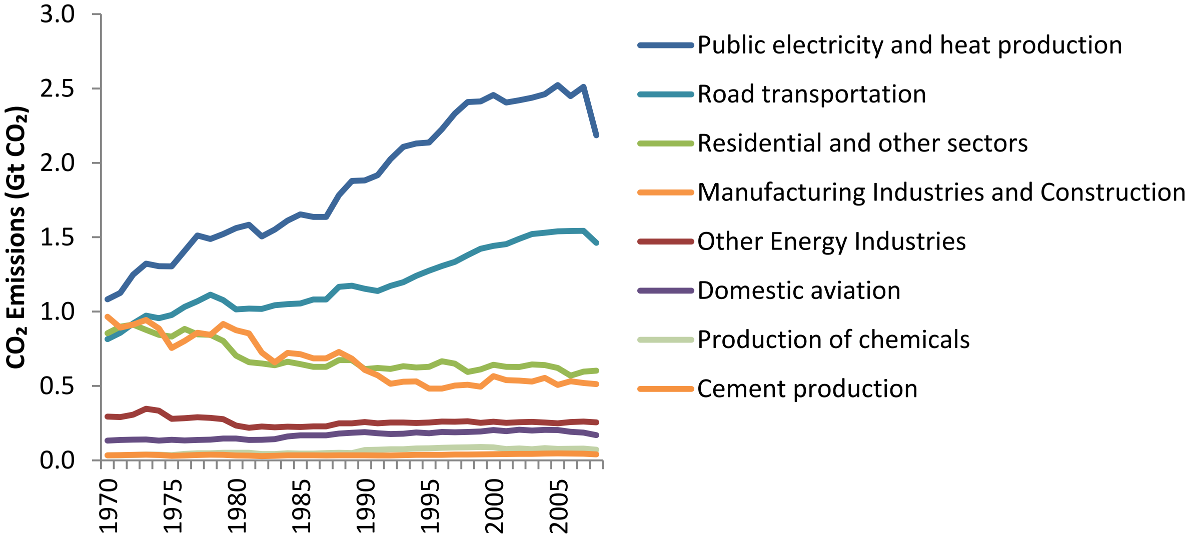

Figure K-2: USA CO_2 Emissions by Source, 1970-2008
Data source: EDGAR 4.2 database [46]

Canada

Canada's emissions are more erratic than those of the United States, as shown in Figure K-3, which makes identification of a peak difficult. Figure K-4 shows most Canadian sources have no clear signs of peaking and appear to be trending up, but the trend is obscured by volatility for several sources.

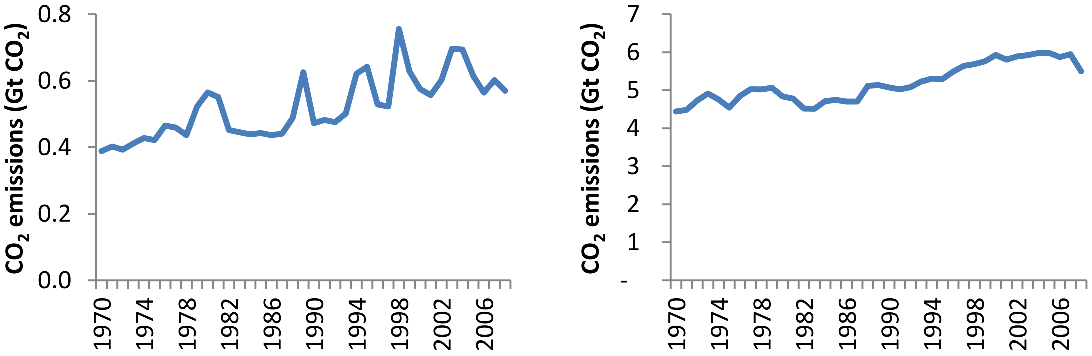

Figure K-3: CO_2 Emissions, 1970-2008 for Canada (left) and USA (right)
Data source: EDGAR 4.2 database [46]

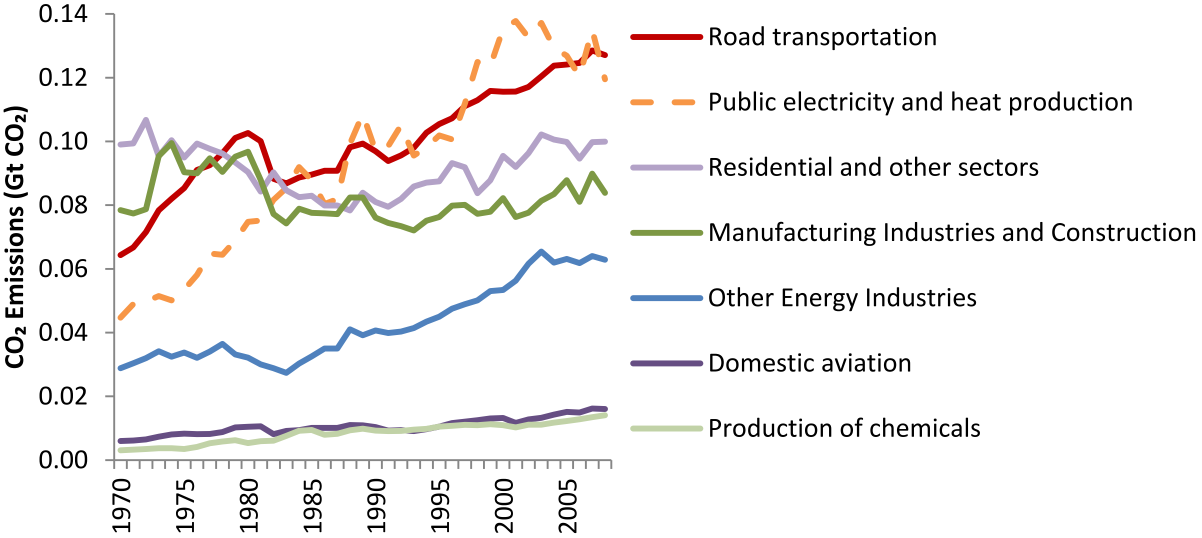

Figure K-4: Canada CO_2 Emissions by Source, 1970-2008

Data source: EDGAR 4.2 database [46]

Brazil

Brazil's CO_2 emission reduction of 11% versus peak is attributable to a major record high in forest fires in 2005 (1.0 Gt CO_2/yr) followed by significantly record lows in 2006, 2007, and 2008 (0.03-0.07 Gt CO_2/yr). See the steady upward trend in non-fire emissions shown in Figure K-5.

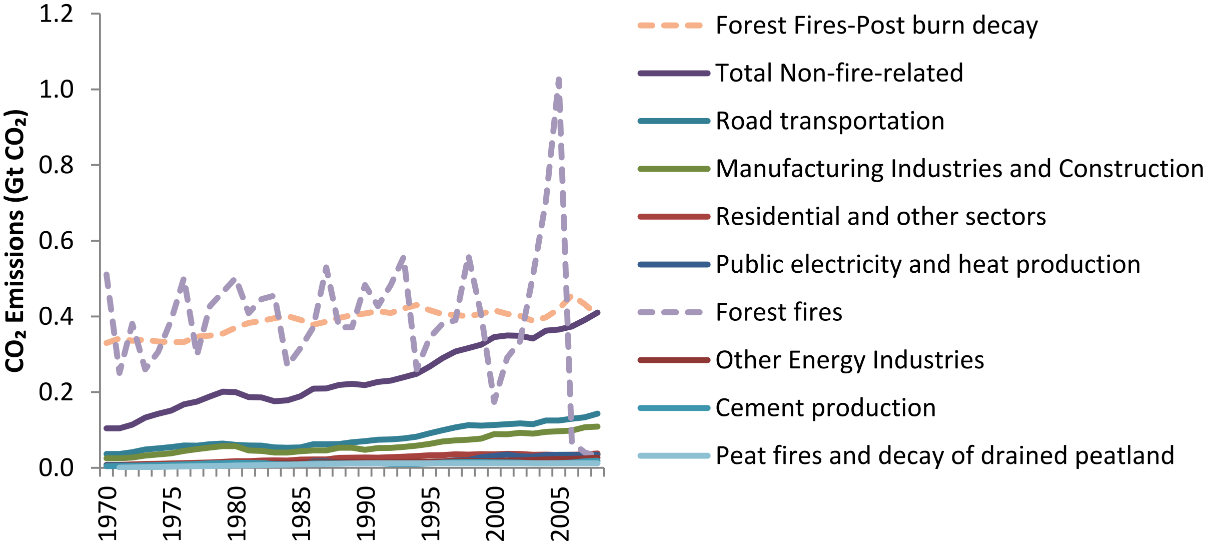

Figure K-5: Brazil CO_2 Emissions by Source, 1970-2008

Data source: EDGAR 4.2 database [46]

Indonesia

Indonesia has highly variable emissions from peat and forest fires, with fire-related peaks that exceed total US emissions. The trendline for fire-related emissions is obscured by the wide variability. Non-fire-related emissions are trending steadily up, as shown in Figure K-6.

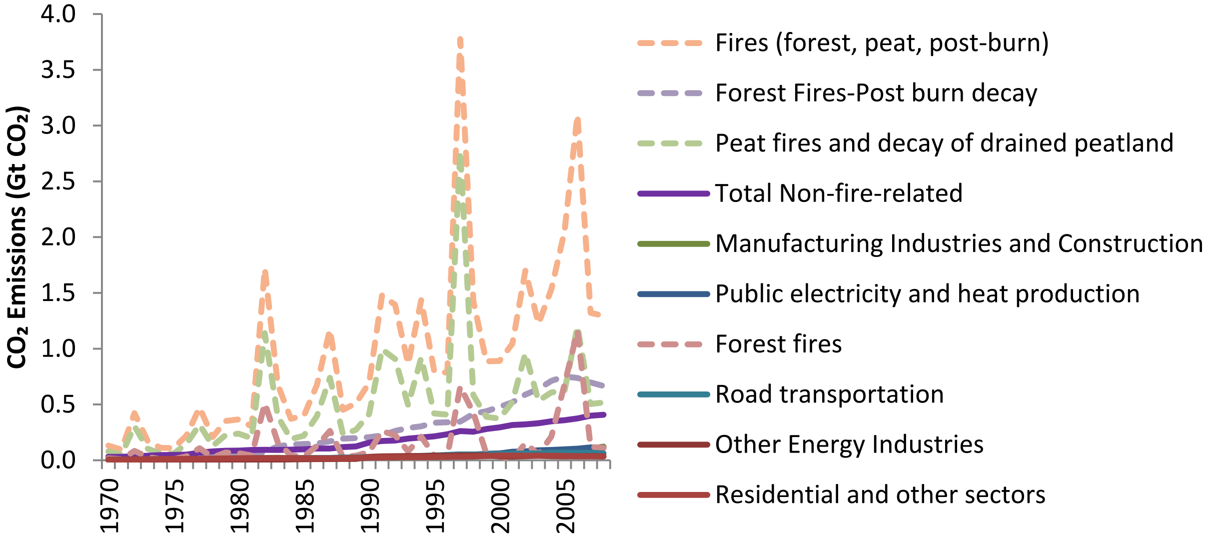

Figure K-6: Indonesia CO_2 Emissions by Source, 1970-2008

Data source: EDGAR 4.2 database [46]

Appendix L Improving the Likelihood Charts in ppm versions

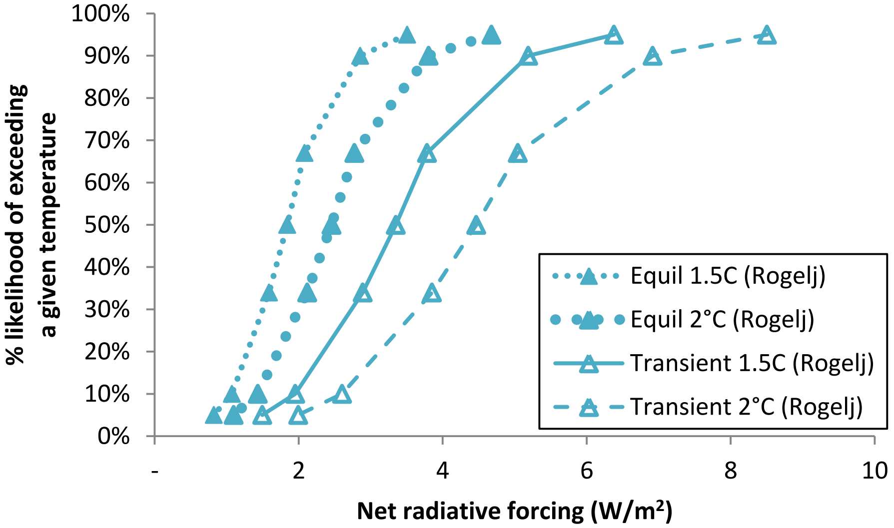

Figure L-1: Likelihood of Avoiding 1.5°C and 2°C (above pre-industrial) vs. Net RF
Equilibrium data points are visually interpolated from Figure 13-2 (Rogelj et al. 2012 [37]). Transient data points are calculated as described in section 13.1. Equilibrium data points are calculated the same way and cross-checked with the visual interpolation.

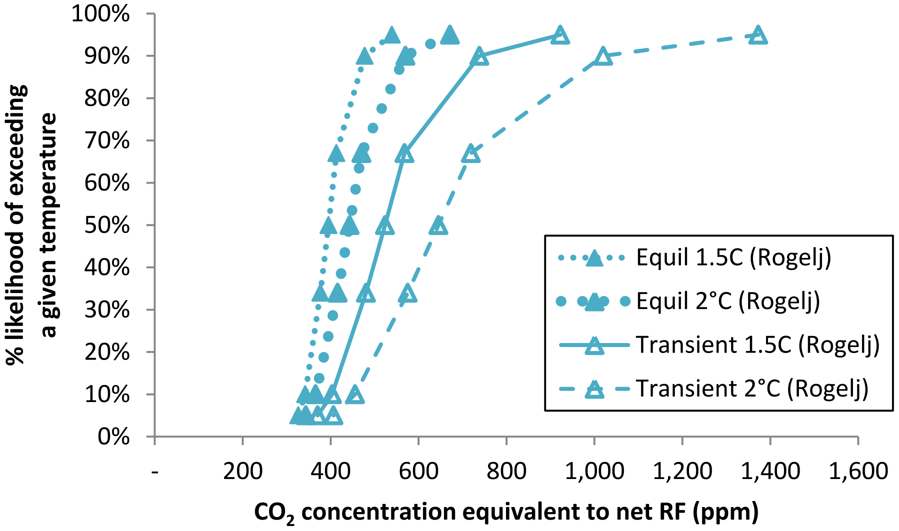

Figure L-2: Likelihood of Avoiding 1.5°C and 2°C (above pre-industrial) vs. CO_2 ppm equivalent to Net RF
This figure translates Figure L-1 into a different x axis. RF is translated into CO_2 ppm using Eq. 15.2.

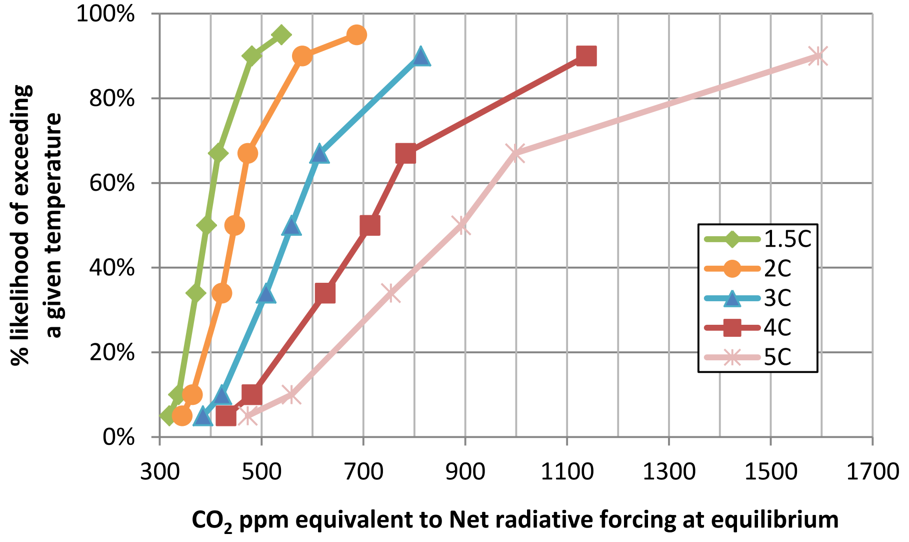

Figure L-3: Likelihood of Avoiding 1.5°C, 2°C, 3°C, 4°C, 5°C (above pre-indus.) at Equilibrium vs. CO_2 ppm equivalent to Net RF

Data are visually interpolated and extrapolated from Rogelj et al. 2012 [37].

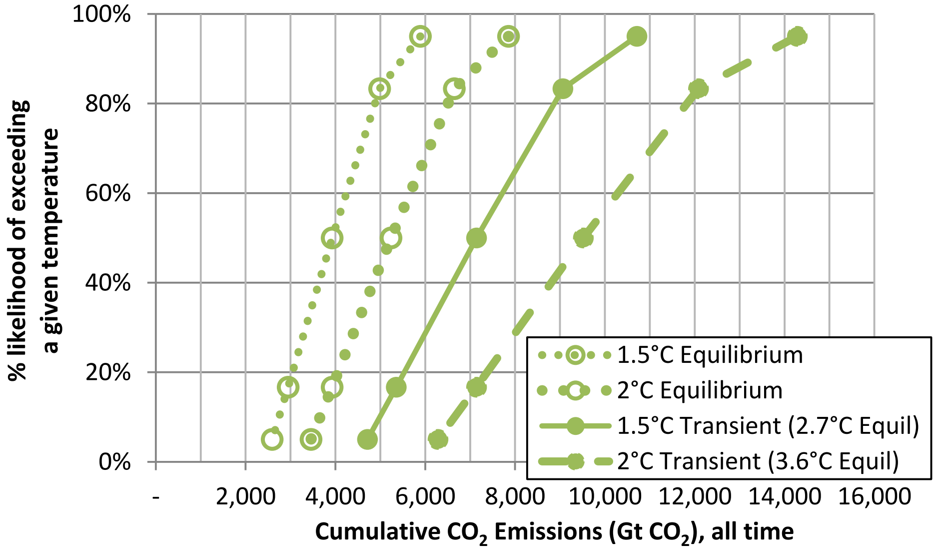

Figure L-4: Likelihood of Avoiding 1.5-2°C (above pre-industrial) vs. Cumulative CO_2 Budget

This is a replica of Figure 13-4 (based on NRC 2011 [42]), with the x axis translated from radiative forcing into the equivalent amount of cumulative CO_2 emissions. Calculation methods are described in section 15.1. Note that for this level of CO_2 emissions to be equal to the stated RF, the RF from all other warming and cooling pollutants would have to offset each other. This is true today (section 13.2.a), but in 2500, approximately 15-20% of RF is expected to be non-CO_2 (section 15.2.a). Adjusting for non-CO_2 would shift the equilibrium curves 15-20% to the left.

Appendix M Emission Budgets for Transient and Equilibrium Warming with a Range of Assumptions

	Emissions for Transient Warming							
Transient Temp (°C) (above pre-indus)	**W/m^2**	**CO$_2$ ppm**	**CO$_2$ ppm per 0.1°C**	**Cumu CO$_2$ (Gt), all time (transient AF)**	**Cumu. CO$_2$ (Gt), yr 2000 -> (transient AF)**	**# years at constant 2008 CO$_2$ emissions**	**Cumu. CO$_2$ (Gt), per 0.1°C (transient AF)**	**# years at constant 2008 emissions, per 0.1°C**
10.0	16.8	6,492	207	88,132	86,595	2,348	2,941	80
9.0	15.1	4,741	151	63,288	61,750	1,674	2,148	58
8.0	13.5	3,462	111	45,145	43,608	1,182	1,569	43
7.0	11.8	2,528	81	31,896	30,359	823	1,145	31
6.0	10.1	1,846	59	22,221	20,684	561	836	23
5.5	9.3	1,578	50	18,411	16,874	457	715	19
5.0	8.4	1,348	43	15,155	13,618	369	611	17
4.0	**6.7**	**985**	**31**	**9,996**	**8,459**	**229**	**446**	**12**
3.5	5.9	841	27	7,964	6,427	174	381	10
3.0	**5.0**	**719**	**23**	**6,228**	**4,691**	**127**	**326**	**9**
2.5	4.2	614	20	4,744	3,207	87	278	8
2.0	3.4	525	17	3,477	1,939	53	238	6
1.5	2.5	449	14	2,393	856	23	203	6
1.0	1.7	383	12	1,467	(70)	(2)	174	5
0.5	0.8	328	10	676	(861)	(23)	148	4
Average, 7°C to 3°C			**45**				**642**	
Total, 7°C to 3°C			**1,809**				**25,668**	
Average, 5°C to 2°C			**27**				**389**	
Total, 5°C to 2°C			**823**				**11,679**	

Table M-1: CO$_2$ Emission Budgets for Transient Warming, with High Transient Climate Response and High Transient Airborne Fraction

All assumptions and methods are the same as in Table 15-2, with the exception that high transient climate response (2.2°C per 3.7 W/m^2; 0.59°C per 1 W/m^2) is used to translate from transient temperature into radiative forcing and an elevated cumulative airborne fraction of 56% is used to translate from CO$_2$ concentration into cumulative CO$_2$ emissions.

	Emissions for Transient Warming							
Transient Temp (°C) (above pre-indus)	W/m^2	CO$_2$ ppm	CO$_2$ ppm per 0.1°C	Cumu CO$_2$ (Gt), all time (transient AF)	Cumu. CO$_2$ (Gt), yr 2000 -> (transient AF)	# years at constant 2008 CO$_2$ emissions	Cumu. CO$_2$ (Gt), per 0.1°C (transient AF)	# years at constant 2008 emissions, per 0.1°C
10.0	14.8	4,452	125	45,904	44,367	1,203	1,374	37
9.0	13.3	3,376	95	34,066	32,529	882	1,042	28
8.0	11.8	2,560	72	25,089	23,551	639	790	21
7.0	10.4	1,942	54	18,281	16,744	454	599	16
6.0	8.9	1,472	41	13,118	11,581	314	454	12
5.5	8.1	1,282	36	11,026	9,489	257	396	11
5.0	7.4	1,117	31	9,204	7,667	208	345	9
4.0	**5.9**	**847**	**24**	**6,235**	**4,698**	**127**	**261**	**7**
3.5	5.2	737	21	5,032	3,494	95	228	6
3.0	**4.4**	**642**	**18**	**3,984**	**2,447**	**66**	**198**	**5**
2.5	3.7	559	16	3,071	1,534	42	173	5
2.0	3.0	487	14	2,276	739	20	150	4
1.5	2.2	424	12	1,584	47	1	131	4
1.0	1.5	369	10	982	(555)	(15)	114	3
0.5	0.7	322	9	457	(1,080)	(29)	99	3
Average, 7°C to 3°C			**32**				**357**	
Total, 7°C to 3°C			**1,299**				**14,297**	
Average, 5°C to 2°C			**21**				**231**	
Total, 5°C to 2°C			**630**				**6,927**	

Table M-2: CO2 Emission Budgets for Transient Warming, with Very High Transient Climate Response and Extremely High Transient Airborne Fraction

All assumptions and methods are the same as in Table 15-2, with the exception that very high transient climate response (2.5°C per 3.7 W/m2; 0.68°C per 1 W/m2) is used to translate from transient temperature into radiative forcing and the highest cumulative airborne fraction from AR4 models (72%) is used to translate from CO2 concentration into cumulative CO2 emissions.

	Emissions for Transient Warming								
Transient Temp (°C) (above pre-indus)	**W/m^2**	**CO_2 ppm**	**CO_2 ppm per 0.1°C**	**Cumu CO_2 (Gt), all time (transient AF)**	**Cumu. CO_2 (Gt), yr 2000 -> (transient AF)**	**# years at constant 2008 CO_2 emissions**	**Cumu. CO_2 (Gt), per 0.1°C (transient AF)**	**# years at constant 2008 emissions, per 0.1°C**
10.0	11.2	2,277	48	21,969	20,432	554	531	14
9.0	10.1	1,846	39	17,233	15,696	426	430	12
8.0	9.0	1,497	32	13,392	11,855	321	349	9
7.0	7.8	1,214	26	10,278	8,741	237	283	8
6.0	6.7	985	21	7,752	6,215	169	229	6
5.5	6.2	887	19	6,674	5,137	139	207	6
5.0	5.6	798	17	5,704	4,167	113	186	5
4.0	**4.5**	**647**	**14**	**4,043**	**2,506**	**68**	**151**	**4**
3.5	3.9	583	12	3,334	1,797	49	136	4
3.0	**3.4**	**525**	**11**	**2,696**	**1,159**	**31**	**122**	**3**
2.5	2.8	473	10	2,122	584	16	110	3
2.0	2.2	426	9	1,604	67	2	99	3
1.5	1.7	383	8	1,138	(399)	(11)	89	2
1.0	1.1	345	7	718	(819)	(22)	80	2
0.5	0.6	311	7	340	(1,197)	(32)	72	2
Average, 7°C to 3°C			**17**				**190**	
Total, 7°C to 3°C			**689**				**7,582**	
Average, 5°C to 2°C			**12**				**137**	
Total, 5°C to 2°C			**373**				**4,100**	

Table M-3: CO_2 Emission Budgets for Transient Warming, with Extremely High Transient Climate Response and Extremely High Transient Airborne Fraction

All assumptions and methods are the same as in Table 15-2, with the exception that extremely high transient climate response (3.3°C per 3.7 W/m2; .89°C per 1 W/m2), corresponding to equilibrium climate sensitivity of 6°C, is used to translate from transient temperature into radiative forcing and the highest cumulative airborne fraction from AR4 models (72%) is used to translate from CO2 concentration into cumulative CO2 emissions.

	Emissions for Equilibrium Warming								
Equil Temp (°C) (above pre-indus)	**W/m2**	**CO_2 ppm**	**CO_2 ppm per 0.1°C**	**Cumu CO_2 (Gt), all time**	**Implicit equil. airborne fraction**	**Equil Budget vs. Transient Budget**	**Cumu CO_2 (Gt), 2000->**	**# years at constant 2008 CO_2 emissions**	**Cumu. CO_2 (Gt), per 0.1°C**
10.0	18.5	8,890	313	39,279	174%	-88%	37,742	1,023	393
9.0	16.7	6,291	221	35,351	135%	-83%	33,814	917	393
8.0	14.8	4,452	157	31,423	105%	-76%	29,886	810	393
7.0	13.0	3,151	111	27,495	83%	-68%	25,958	704	393
6.0	11.1	2,230	78	23,567	66%	-57%	22,030	597	393
5.5	10.2	1,876	66	21,603	59%	-51%	20,066	544	393
5.0	9.3	1,578	56	19,639	52%	-43%	18,102	491	393
4.0	**7.4**	**1,117**	**39**	**15,712**	**42%**	**-25%**	**14,174**	**384**	**393**
3.5	6.5	939	33	13,748	38%	-15%	12,210	331	393
3.0	**5.6**	**790**	**28**	**11,784**	**34%**	**-3%**	**10,247**	**278**	**393**
2.5	4.6	665	23	9,820	31%	10%	8,283	225	393
2.0	3.7	559	20	7,856	28%	24%	6,319	171	393
1.5	2.8	470	17	5,892	26%	39%	4,355	118	393
1.0	1.9	396	14	3,928	23%	56%	2,391	65	393
0.5	0.9	333	12	1,964	21%	74%	427	12	393
Average, 7°C to 3°C			**59**						**393**
Total, 7°C to 3°C			**2,360**						**15,712**
Average, 5°C to 2°C			**34**						**393**
Total, 5°C to 2°C			**1,019**						**11,784**

Table M-4: CO_2 Emission Budgets for Equilibrium Warming, with Low Climate Sensitivity

All assumptions and methods are the same as in Table 15-2, with the exception that low climate sensitivity (2°C per 3.7 W/m^2; 0.54°C per 1 W/m^2) is used to translate from equilibrium temperature into radiative forcing.

	Emissions for Equilibrium Warming								
Equil Temp (°C) (above pre-indus)	**W/m2**	**CO_2 ppm**	**CO_2 ppm per 0.1°C**	**Cumu CO_2 (Gt), all time**	**Implicit equil. airborne fraction**	**Equil Budget vs. Transient Budget**	**Cumu CO_2 (Gt), 2000->**	**# years at constant 2008 CO_2 emissions**	**Cumu. CO_2 (Gt), per 0.1°C**
10.0	8.2	1,302	20	17,457	46%	-94%	15,920	432	175
9.0	7.4	1,117	17	15,712	42%	-92%	14,174	384	175
8.0	6.6	957	15	13,966	38%	-90%	12,429	337	175
7.0	5.8	821	13	12,220	35%	-86%	10,683	290	175
6.0	4.9	704	11	10,474	32%	-81%	8,937	242	175
5.5	4.5	652	10	9,601	31%	-78%	8,064	219	175
5.0	4.1	604	9	8,729	29%	-75%	7,192	195	175
4.0	**3.3**	**518**	**8**	**6,983**	**27%**	**-67%**	**5,446**	**148**	**175**
3.5	2.9	479	7	6,110	26%	-62%	4,573	124	175
3.0	**2.5**	**444**	**7**	**5,237**	**25%**	**-57%**	**3,700**	**100**	**175**
2.5	2.1	411	6	4,364	24%	-51%	2,827	77	175
2.0	1.6	381	6	3,491	23%	-45%	1,954	53	175
1.5	1.2	353	5	2,619	22%	-38%	1,081	29	175
1.0	0.8	327	5	1,746	21%	-31%	209	6	175
0.5	0.4	302	5	873	20%	-23%	(664)	(18)	175
Average, 7°C to 3°C			**9**						**175**
Total, 7°C to 3°C			**377**						**6,983**
Average, 5°C to 2°C			**7**						**175**
Total, 5°C to 2°C			**223**						**5,237**

Table M-5: CO_2 Emission Budgets for Equilibrium Warming, with High Climate Sensitivity

All assumptions and methods are the same as in Table 15-2, with the exception that high climate sensitivity (4.5°C per 3.7 W/m^2; 1.22°C per 1 W/m^2) is used to translate from equilibrium temperature into radiative forcing.

	Emissions for Equilibrium Warming								
Equil Temp (°C) (above pre-indus)	**W/m2**	**CO_2 ppm**	**CO_2 ppm per 0.1°C**	**Cumu CO_2 (Gt), all time**	**Implicit equil. airborne fraction**	**Equil Budget vs. Transient Budget**	**Cumu CO_2 (Gt), 2000->**	**# years at constant 2008 CO_2 emissions**	**Cumu. CO_2 (Gt), per 0.1°C**
10.0	6.2	887	10	13,093	37%	-96%	11,556	313	131
9.0	5.6	790	9	11,784	34%	-94%	10,247	278	131
8.0	4.9	704	8	10,474	32%	-92%	8,937	242	131
7.0	4.3	627	7	9,165	30%	-89%	7,628	207	131
6.0	3.7	559	6	7,856	28%	-86%	6,319	171	131
5.5	3.4	528	6	7,201	27%	-84%	5,664	154	131
5.0	3.1	498	6	6,546	26%	-81%	5,009	136	131
4.0	**2.5**	**444**	**5**	**5,237**	**25%**	**-75%**	**3,700**	**100**	**131**
3.5	2.2	419	5	4,583	24%	-72%	3,045	83	131
3.0	**1.9**	**396**	**5**	**3,928**	**23%**	**-68%**	**2,391**	**65**	**131**
2.5	1.5	374	4	3,273	23%	-63%	1,736	47	131
2.0	1.2	353	4	2,619	22%	-59%	1,081	29	131
1.5	0.9	333	4	1,964	21%	-54%	427	12	131
1.0	0.6	314	4	1,309	21%	-48%	(228)	(6)	131
0.5	0.3	297	3	655	20%	-42%	(882)	(24)	131
Average, 7°C to 3°C			**6**						**131**
Total, 7°C to 3°C			**232**						**5,237**
Average, 5°C to 2°C			**5**						**131**
Total, 5°C to 2°C			**146**						**3,928**

Table M-6: CO_2 Emission Budgets for Equilibrium Warming, with Very High Climate Sensitivity

All assumptions and methods are the same as in Table 15-2, with the exception that very high climate sensitivity (6°C per 3.7 W/m^2; 1.62°C per 1 W/m^2) is used to translate from equilibrium temperature into radiative forcing.

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