EFFECTS OF RATE AND TIMING OF SHORT-LIVED CLIMATE FORCER MITIGATION ON CUMULATIVE WARMING AND TEMPERATURE TARGETS

BY

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THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science of Environmental Engineering in Civil Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2016

Urbana, Illinois

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Abstract

Short lived climate forcers (SLCF) such as black carbon, tropospheric ozone, or methane have been proposed as complements to mitigating greenhouse gases such as CO_2. I investigated the possible importance of SLCF mitigation rates and timing under a variety of CO_2 emission trajectories. I built a simple model that takes emission trajectories of CO_2 and black carbon as input and calculates radiative forcing and global mean temperature change. Impulse response functions were used to calculate the concentration of carbon dioxide in the atmosphere and the global mean temperature change. The resulting temperature change was used to evaluate the effects of SLCF mitigation on reducing peak temperature or delaying the onset of temperature thresholds. I also calculated an integrated temperature response referred to as a cumulative temperature perturbation (CTP). For measures of peak or target temperatures, I found that there is little benefit to mitigating SLCF early or at rapid rates except under low CO_2 emission trajectories such as RCP-2.6. Recent publications have questioned the importance of mitigating SLCF in the near term because of their limited impact on peak temperature compared to CO_2. However, these studies do not acknowledge the path dependence of cumulative climate impacts and ignore potential welfare gains that could result from reducing SLCF in the near term. With respect to cumulative impacts, the rate and timing of SLCF mitigation matter especially in the first three generations where 50-100% or more of the CTP difference between RCP-8.5 CO_2 and RCP-6 CO_2 can be achieved by mitigating SLCF over 40 years or less and beginning mitigation before 2035. These mitigation rates are consistent with projections for global on-road transportation emissions.

Acknowledgements

First and foremost I would like to thank my advisor, Dr. Tami Bond, who has been a tremendous help with this work. She ensured that I grew as a student and a professional by never feeding me answers; instead she proposed questions and encouraged me to seek the answers on my own. She challenged me and pushed me to think more independantly and more critically which is probably the most improtant thing I could learn in my master's program. Additionally, I would like to thank the Bond Group who have provided much appreciated feedback and help throughout the resarch process.

I would like to extend my gratitude to the faculty and staff in the CEE department for their instruction in classes, feedback on research at symposiums or conferences, and administrative support along the way.

It has been an honor to work alongside the great students in the Environmental Engineering & Science group. Their passion and intellect persuaded me to come to UIUC, and working with them has been an enlightening experience. I am extremely thankful for having such a close cohort which has served not only as an academic support system but also as a social escape. I look forward to seeing what we will achieve in the next chapters of our lives.

Lastly I would like to thank my family and freinds outside of UIUC who encouraged me to obtain my master's degree and supported me throughout the prcoess.

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Chapter 1 – Introduction and Background

Anthropogenic emissions of long–lived greenhouse gases such as carbon dioxide (CO_2) and short-lived climate pollutants such as black carbon (BC) have contributed to global warming and climate change, but due to different atmospheric lifetimes and warming mechanisms, they affect the climate in different manners. Here I introduce metrics for comparing the effects of these pollutants on climate (Section 1.1) and compare current estimates of radiative forcing from these pollutants (Section 1.2). I then give an overview of commonly used CO_2 emission trajectories (Section 1.3) and discuss previous work pertaining to the differences between the long-lived and short-lived pollutants (Section 1.4). Lastly I give an overview of my approach to modelling short-lived climate pollutants in this study (Section 1.5).

1.1 Climate change and emission metrics

Numerous metrics are used to describe climate change or evaluate policy in literature. The following metrics are commonly considered:

- Atmospheric CO_2 or GHG concentration (ppm) and cumulative anthropogenic CO_2 emission budgets (GtC or $GtCO_2$)
- Global mean temperature increase above pre-industrial levels (°C),
- Radiative forcing (W/m^2), taking into account aerosols, and
- Global warming potential (GWP) and global temperature potential (GTP).

Each of the aforementioned metrics are useful to structure the debate of alternative climate policy issues. Atmospheric CO_2 and cumulative anthropogenic CO_2 budgets are more closely related to human activity whereas radiative forcing and global mean temperature increase are more related to the earth-system response. Radiative forcing (defined in Section 1.2) is used as a means of comparing impacts of various pollutants because it is additive – radiative forcing resulting from emissions of any pollutant can be summed to obtain a total effect – and the uncertainty of the earth's climate sensitivity need not be assumed as it must with temperature based metrics. GWP and GTP are commonly used to compare impacts from emissions of different pollutants relative to CO_2 – the GWP compares cumulative radiative impacts whereas the GTP compares temperatures in a target year.

1.1.1 Target based metrics

Many of the studies about the effects of infrastructure on climate change use a target based metric, such as the GMT increase or cumulative CO_2 budgets as their metric. The GMT increase commonly used is 2 °C to prevent catastrophic climate change, and the CO_2 budgets are mostly related to this warming target. Meinshausen et al. [1] found that limiting cumulative CO_2 emissions over 2000–2050 to 1,000 Gt CO_2 yields a 25% probability of warming exceeding 2 °C and limiting to 1,440 Gt CO_2 yields a 50% probability of exceeding the warming target. However, there is not a common definition of catastrophic climate change (or "dangerous anthropogenic interference" as stated in Article 2 of the United Nations Framework Convention on Climate Change [2]), nor is there quantitative evidence that shows 2 °C warming causes significantly more or less impact than other temperatures (e.g. 1.5 °C or 3 °C).

Economist W.D. Nordhaus was the first to describe the two degrees of warming as a dangerous limit on the basis that it is the limit of warming which has occurred naturally over the last 10,000 years [3]. Randalls [4] provides a history of the development of the 2 °C warming target, and [3] attempts to compile scientific evidence to define "dangerous anthropogenic interference" with respect to GMT increase or atmospheric CO_2 concentration. Weighing the arguments both for and against 2 °C target, given current knowledge and ethical arguments, the 2 °C target appears to be a balanced target, at least temporarily, until further scientific research or public debate suggest otherwise [5].

Endpoint or target based metrics are valuable for evaluating progress toward and achievability of the most altered state of the climate system. However, these endpoint metrics ignore the experience of humans, societies and ecosystems along the path to the endpoint. Using an endpoint metric only, a path that reached 2 °C immediately and maintained it for 100 years would be treated as equivalent to a path that slowly approached 2 °C over 100 years, despite the increased damages that would likely occur during the first path.

1.1.2 Cumulative impact metrics

Climate impacts such as sea level rise are related both to the magnitude of warming and the length of time oceans and ice are exposed to elevated temperatures; therefore they can

be quantified using cumulative warming [6]. However, the common time-integrated metric — global warming potential (GWP) — relies on radiative forcing, which does not take Earth system inertia into account.

Because improving welfare and reducing impact is a primary goal of mitigating climate forcers, a time-integrated measure of impact is a useful measure for comparing trajectories. Following Kirschbaum [6] I explore the use of an integrated temperature difference or perturbation for this purpose. The cumulative temperature perturbation (CTP) is the difference of the temperature resulting from two trajectories: one that includes a mitigation measure and one that does not. The CTP depends on emission timing and therefore is not a true emission metric. It cannot be used for emission trading, but only for evaluating the effects of general principles. To compare cumulative warming impacts of emissions of different pollutants, an integrated global temperature potential (iGTP) [7] can be used. The CTP complements endpoint metrics that may indicate the ultimate state of the climate system. I use the CTP to quantify the warming (in Kelvin-years) that future generations will live with as a consequence of future emissions we have control over. I exclude warming resulting from prior emissions or accumulation of greenhouse gases in the atmosphere prior to a specific start year as described in Section 2.4.

An advantage of the CTP is that the cumulative and approximately linear calculation allows division of impact timing. I therefore present a generational view of climate change, identifying when impacts are felt. The total CTP is the sum of the impacts in all generations.

A disadvantage of the simple linear temperature weighting used in the CTP is that damages are commonly thought to be nonlinear with respect to temperature, increasing greatly at higher temperatures. A small temperature perturbation at today's temperatures may be of no consequence, but would be weighted equally with a small temperature perturbation that occurs at high future temperatures and that causes greater damage. Despite this argument, I proceed with the generational analysis for two reasons. First, there has been little quantification of the damages caused by climate change at current temperatures, such as glacier melting. These effects are commonly acknowledged as undesirable [8]–[10]. Treatments that minimize the value of damages at current temperatures are underweighting these contemporary impacts. Second, it is common to

assume a discount rate for future impacts, which de-emphasizes the importance of damages in future generations. The choice of discount rate is a contentious issue, which I do not examine here. Instead, I present equally-weighted integrated temperature perturbations in each of four generations. Analysts can then apply their judgment in choosing damage weighting and discount rate for each generation.

1.2 Radiative forcing and climate forcers

Radiative forcing (RF), also known as climate forcing, is a measure of change in the earth's energy balance at the tropopause following an imposed perturbation such as gases absorbing infrared radiation or particles reflecting sunlight to space [11]–[13]. Because RF can be attributable to a single species, it provides a way to quantify and compare the contribution of different agents that affect global mean surface temperature, the primary index for climate change [12]. Radiative forcing is typically expressed in units of watts per square meter (W/m^2). Positive forcing due to greenhouse gases or aerosols which absorb infrared radiation results in warming; negative forcing, due to aerosols scattering radiation, results in cooling. An air pollutant which causes radiative forcing when its atmospheric concentration changes is called a climate forcer. This study focuses on positive climate forcers which cause warming.

In their Fifth Assessment Report (AR5), the Intergovernmental Panel on Climate Change (IPCC) grouped climate forcing agents into two primary categories based on based on their atmospheric lifetimes which govern the time when they impact climate after the time of their emission: well-mixed greenhouse gases (WMGHG), sometimes referred to as long-lived climate forcers (LLCF), and near-term climate forcers, also known as short-lived climate forcers (SLCF) or short-lived climate pollutants (SLCP) [11]. Well-mixed pollutants with long atmospheric lifetimes and impacts on climate long after they are emitted (i.e. decades to centuries) are referred to as long-lived climate forcers (LLCF) in this study. Short-lived climate forcers (SLCF) such as ozone, methane (which can also be a LLCF), hydrofluorocarbons (HFCs), and aerosols, specifically black carbon (BC), have relatively short atmospheric lifetimes (e.g. 22 days for ozone [11], 12 years for methane [11], and 3.3-10.6 days for BC [14]) and impact climate in the near-term following emission. The magnitude of anthropogenic emissions of carbon dioxide (CO_2) coupled with the pollutant's long atmospheric lifetime have caused CO_2 to have a climate forcing of +1.82 W/m^2 in 2011,

the greatest climate forcing among the LLCF and SLCF [11]. Of anthropogenic pollutants BC has been estimated to have the second greatest climate forcing behind carbon dioxide [14], [15].

The SLCFs with the largest climate impact are methane, ozone, and aerosols (Table 1). Estimates of direct radiative forcing since pre-industrial times from methane and tropospheric ozone are +0.48 W/m^2 and +0.40 W/m^2 respectively [11]. AR5 refers to the scattering and absorption of radiation by aerosols as the aerosol-radiation interaction and estimates that it causes approximately -0.35 W/m^2 radiative forcing. The aerosol-radiation interaction consists of +0.40 W/m^2 direct radiative forcing from BC from fossil fuel and biofuel combustion; -0.75 W/m^2 from sulphate, primary and secondary organic aerosol, nitrate, and dust combined; and 0.0 W/m^2 from biomass burning [11]. Bond et al. [14] estimated a larger direct radiative forcing from BC of +0.71 W/m^2 which includes +0.51 W/m^2 from fossil fuel and biofuel combustion and +0.20 W/m^2 from open burning (Table 2). Accounting for BC on snow and ice (+0.13 W/m^2) as well as cloud and semi-direct effects (+0.23 W/m^2) raises BC's total forcing to 1.1 W/m^2 [14].

Table 1.1. Radiative forcing estimates of SLCF from IPCC AR5.

Species	**Radiative Forcing (W/m^2)** [a]
Methane (direct forcing)	+0.48
Tropospheric ozone	+0.40
Aerosol-radiation interaction	-0.35
Black carbon from fossil fuel and biofuel	+0.40
Sulphate	-0.40
Primary organic aerosol	-0.09
Secondary organic aerosol	-0.03
Nitrate	-0.11
Dust	-0.10
Biomass burning (BC and organic aerosol)	0.0
Black carbon on snow and ice	+0.04
BC + Tropospheric Ozone	**+0.84**
BC + Methane + Tropospheric Ozone	**+1.32**
Total SLCF	**+0.24**

a. 2011 or other most recent RF published in IPCC AR5 was used in this table

Table 1.2. Radiative forcing estimates of BC from Bond et al. 2013.

BC Climate Forcing	Radiative Forcing (W/m²) [a]
BC Direct Effect	+0.71
Fossil fuel combustion	+0.29
Biofuel combustion	+0.22
Open burning	+0.20
BC on snow and ice	+0.13
Cloud semi-direct and indirect effects	+0.23
Total	**+1.1**
Direct effect – open burning + snow and ice [b]	**+0.64**

a – Radiative forcing for the industrial era (1750-2005) from Table 1 of Bond et al. 2013
b – This line provides a sum that is comparable to the RF estimates for BC provided in AR5. No estimate of the radiative forcing by aerosol effects on clouds or BC in cloud drops is given in IPCC AR5, so it is excluded. AR5 couples RF from BC and organic aerosol in their estimate of RF from biomass burning.

1.3 Representative Concentration Pathways (RCPs)

CO_2 emissions from four Representative Concentration Pathways (RCPs), RCP-2.6 [16], RCP-4.5 [17]–[19], RCP-6 [8]-[9], and RCP-8.5 [22], were created for comparing climate change trajectories for IPCC AR5. The four RCPs are named according to their total radiative forcing (including radiative forcing from CO_2, other greenhouse gases, and aerosols) in 2100 relative to pre-industrial levels [23]. They represent a wide range of climate outcomes for illustrative purposes, but they are not forecasts, nor do they represent policy recommendations. RCP-2.6 illustrates a case with aggressive climate action, including negative CO_2 emissions in the latter half of the century, resulting in peak radiative forcing of approximately 3 W/m^2 followed by a decline. RCP-8.5 represents increasing greenhouse gas emissions over the century, resulting in a nearly linear increase in radiative forcing through the end of the century. RCP-4.5 and RCP-6 are two intermediate scenarios in which radiative forcing stabilizes after 2100.

1.4 Previous work on the relationship between short-lived and long-lived climate forcers

To fully understand the effects of emissions on the climate system, effects of both long-lived and short-lived pollutants must be understood. Studies have emphasized that reducing SLCF could be an important component of climate change mitigation [15], [24]–[30]. SLCF such as BC and ozone have become of particular interest because there health benefits

associated with their mitigation, and there could be considerable climate benefits as well [31], [32]. Early studies discussed below focused on quantifying radiative forcing from SLCF and estimating the potential for SLCF mitigation to slow the rate of temperature increase or delay CO_2 mitigation. Later studies have questioned the importance of mitigating SLCF based on target based metrics [33]–[36] finding that SLCF mitigation has little impact on peak temperatures in the near-term, especially under higher CO_2 trajectories such as RCP-4.5, RCP-6, or RCP-8.5. This has led to agreement that SLCF mitigation should complement rather than replace CO_2 mitigation. Although similar and related to timing of SLCF mitigation, little work has been done to evaluate the effects of the rate of SLCF mitigation on warming [37]. Not only can the rate of SLCF mitigation affect peak warming or when we reach target temperatures, but it can also impact cumulative warming which is dependent on the path of the temperature trajectory as well as the magnitude of the temperature change.

Hansen et al. [24] suggested that although CO_2 would become the dominant forcing agent, the reduction of ozone precursors, non-CO_2 GHGs, and methane could significantly reduce the rate of global warming. Specifically they noted that a reduction of 0.5 W/m^2 radiative forcing was conceivable by reducing BC emissions from diesel fuel and coal combustion.

Bond and Sun ([25]) calculated a global warming potential (GWP) for black carbon to begin comparing BC's effect on climate to that of GHGs. Their work acknowledged that reducing BC could not replace mitigating GHGs, but reducing BC could be an economically viable method to reduce radiative impact in some areas.

Further work identified metrics for comparing the effects of short-lived versus long-lived climate forcers. Boucher and Reddy [38] illustrated how the global temperature change potential (GTP) metric first introduced by Shine et al. [39] could be applied to policy issues to compare impacts of BC and CO_2 emissions. Using the HADCM3 climate model, they derived an impulse response function (IRF) to estimate the climate response (i.e. change in global mean surface temperature) to an emission pulse. They computed the GTP by means of a convolution of the IRF and a time dependent radiative forcing profile; we use a similar method in this study. Boucher and Reddy [38] and Shine et al. [39] showed that using a global warming potential (GWP) overestimates the importance of mitigating a short-lived

pollutant such as BC versus a long-lived pollutant such as CO_2 and that the GTP is a more appropriate metric for evaluating mitigation trade-offs.

Grieshop et al. [26] proposed steadily eliminating all present-day emissions of black carbon over a period of 50 years, stating that, based on a BC global warming potential of 600, it would have the equivalent climate mitigation effect as removing 25 GtC over the same time period. They suggest that due to the short atmospheric lifetime of BC, drastic reductions in BC could result in near-immediate relief from climate warming. They propose emissions can be reduced by replacing solid fuels with cleaner liquid fuels in cook stoves in developing countries; however, they did not specify how emissions from open burning could be contained or how transportation emissions of BC could be reduced. This study and others estimated the impact of BC emissions on climate or the absolute warming that could be reduced through mitigating BC emissions, but they did not look at these measures in the context of various CO_2 emission trajectories or rates of climate change.

Subsequent work suggested that BC or SLCF mitigation could be used as a tactic to delay total warming or buy time for CO_2 abatement to become cheaper or more feasible. Stating that the combined warming of black carbon, and ozone was 40-70% of that of CO_2, Wallack and Ramanathan [27] suggested reducing emissions of black carbon and ozone as an easier, cheaper, more politically feasible proposal than mitigating CO_2. Reducing BC emissions by 50% could offset warming effects of CO_2 by one to two decades, and reducing anthropogenic ozone in the troposphere by 50% could offset another decade.

Kopp and Mauzerall [40] argue the necessity of reducing BC emissions in addition to CO_2 to meet a radiative forcing target of 3.1 W/m^2 in 2100. Such a target is consistent with 500 ppm CO_2e and would result in a 50% chance of limiting warming to 2.5 °C above pre-industrial times. They estimated that the total radiative forcing of carbonaceous aerosols (black carbon and organic carbon) ranges from 0.02-0.37 W/m^2 taking into account the effects of BC on snow albedo, cloud albedo, and cloud coverage. Based on this level of RF, they used a new metric to compare the effects of BC versus CO_2. Using the IPCC Special Report on Emission Scenarios (SRES) A1B as reference emissions, they found the year in which CO_2 emissions need to be reduced by 50% below 2005 levels to achieve the 3.1 W/m^2 target depending on the level of BC mitigation. Using this this metric, they found that CO_2 emission cuts would need to occur 1-15 years earlier depending on how much BC is

mitigated (ranging from full mitigation to constant emissions). In their calculated scenarios, CO_2 emissions are reduced to zero by approximately 2060, making RCP-2.6 CO_2 the closest RCP trajectory to their work. This study did not include other SLCFs such as ozone, so it is possible that the time delay achievable for mitigating CO_2 could be even longer; however, they did not explore these timing impacts with higher CO_2 concentration pathways.

Rypdal et al. [41] assessed how much future PM abatement strategies reduce climate impacts from black carbon or organic carbon. Using GWP and GTP metrics, they calculated abatement costs and estimated global impacts of regional BC abatement. Contrary to other studies published around the same time [27], [40] which focused mostly on lower CO_2 concentration pathways (consistent with 2-2.5 °C warming), [41]acknowledged that a reduction in BC RF would be small compared to most projected increases in RF from CO_2 concluding that BC mitigation measures should not replace CO_2 mitigation measures but rather complement them. They emphasize that BC mitigation measures should be focused in regions of the world where it is most cost effective such as Asia as opposed to North America or Europe

The United Nations Environment Programme (UNEP) Integrated Assessment of Black Carbon and Tropospheric Ozone [31] called for action to reduce SLCF to slow the rate of climate change in the short term. This report emphasized that specific actions must be taken to reduce SLCF emissions because CO_2 emission reduction strategies focus mostly on the energy sector which does not include the majority of SLCF emissions. The assessment proposes reductions of SLCF over a 20 year period (ideally 2010-2030 but 2030-2050 was also assessed). Measures to reduce BC used in this study focus on the following sectors:

- agriculture (burning agricultural waste)
- industry (brick kilns)
- residential (cooking and heating stoves)
- transport (diesel particulate filters)

According to the UNEP assessment, full implementation of the proposed SLCF reductions by 2030 could result in a reduction of future warming by 0.2-0.7°C in 2050. The best estimates of globally averaged net forcing from BC (including snow and ice), OC, O_3, and CH_4 used in the assessment were +0.6 W/m^2, -0.19 W/m^2, 0.35 W/m^2, and +0.7 W/m^2

respectively. Full implementation of this plan would reduce BC emissions by ~80% relative to 2005 levels; with emissions of approximately 9 Mt/yr in 2005, this equates to an average reduction of approximately 0.36 Mt/yr assuming 2005 levels are held constant. The resulting reduction in BC RF from these measures was estimated to be -0.4 W/m^2 (Table 1.3). LLCF emissions in this assessment are consistent with aggressive CO_2 mitigation (stabilizing GHG concentrations at 450 ppm CO_2e).

Table 1.3. RF changes resulting from UNEP BC and CH_4 measures (taken from Table A.4.2 in the UNEP Assessment [31]).

Species	**RF Change (W/m^2)**
BC Total	-0.4
BC Direct	-0.3
BC Deposition (snow and ice)	-0.1
OC	+0.15
Ozone	-0.2
Methane	-0.19

The UNEP assessment also looked at the timing of the SLCF reductions by comparing the temperature trajectory resulting from the 2010-2030 SLCF mitigation to the temperature trajectory of mitigation delayed by 20 years (i.e. mitigation during 2010-2030 versus 2030-2050). The same magnitude of radiative forcing from SLCF was reduced in both cases. They found that there is less warming in the 2020-2060 period if the SLCF reduction measures are taken earlier (approximately 0.1-0.4 °C difference during the 2020-2060 time period), but the difference diminishes after 2070. They also found that the impact of near-term measures is independent of whether GHG measures are imposed, suggesting that the GHG measures they looked at do not also mitigate SLCF.

Building on the work of the UNEP assessment, Bowerman et al. [35] tested the effects of delaying SLCF mitigation under different LLCF emission pathways. Using emissions from the four RCPs, they reduced methane and BC emissions linearly over 20-year time periods (as proposed in the UNEP assessment) beginning in different decades and compared the peak temperature and rate of warming. They found that SLCF reductions have a significant impact on peak temperature only under circumstances in which CO_2 emissions are falling. Therefore, immediate action on SLCF is helpful to limit warming to 2 °C, but in scenarios where warming peaks at 3-4 °C (consistent with RCP-4.5 or RCP-6) SLCF reductions do not have a large impact on peak warming until much later in the century. Ultimately, these findings suggest that immediate action on SLCF may reduce near-term

warming and delay the onset of a target temperature to buy time for adaptation, but they do not buy time to delay reducing CO_2 as CO_2 will govern the temperature trajectory. With respect to rates of warming, they found that SLCF reductions can reduce near-term rates of warming but not necessarily the maximum rate of warming. In a 2°C scenario, the peak rate may have already passed, and under other scenarios the peak rate should occur when LLCF emissions peak in several decades.

Pierrehumbert [34] compared SLCF versus LLCF similar using a baseline of RCP CO_2 (RCP-4.5, RCP-6, and RCP-8.5) and SLCF emissions including methane and ozone. His baseline emissions included growth of SLCF emissions to 2100, resulting in a larger effect of SLCF reductions compared to Bowerman et al. [35] (can delay 2 °C by up to 68 years in RCP-4.5). Despite this difference, this study draws the same conclusions as [35]: SLCF mitigation is most important on a low-CO_2 trajectory because SLCF contribution to warming is marginal in high CO_2-emission cases such as RCP-8.5. Eventual reduction of SLCF does reduce the magnitude of the peak temperature, but CO_2 drives the peak.

Pierrehumbert [34] further emphasizes the dangers of substituting SLCF mitigation for CO_2 mitigation. Even if mitigation comes at zero or negative cost, he warns against allowing SLCF to be counted in emission trading or tax schemes based on weighted equivalence of SLCF to CO_2 because it might delay action on CO_2 and cause more warming due to the irreversible nature of CO_2-induced warming.

To achieve a 2 °C warming target, drastic CO_2 mitigation must occur (CO_2 emissions must be near zero to cause a peak in the temperature trajectory). Because BC and CO_2 are coemitted pollutants (i.e. sources which emit BC also emit CO_2), it is possible that some BC emissions could be mitigated from CO_2 initiatives. To account for this overlap, Rogelj et al. [36] points out that over half (55-65%) of energy-related BC emissions are linked to CO_2-emitting fossil-fuel sources, and therefore, the baseline emissions of BC in scenarios that account for CO_2 mitigation should be lower than levels suggested in prior studies. They note that emissions from residential biomass in rural areas is carbon-neutral and not included in carbon policies, but BC is still emitted from this combustion which can contribute to warming. However, because of coemitted scattering particles, emissions from biomass only have a slight net warming effect and do not cause substantial warming.

Rogelj et al. [36] used a reference scenario which achieves 2 °C by controlling CO_2, and any SLCF reductions occur via cocontrol resulting from the CO_2 mitigation. They then compared this reference to scenarios with the SLCF reductions proposed in the 2011 UNEP Assessment. Contrary to UNEP's findings, they found that after taking into consideration the overlap between BC and CO_2, further mitigation as suggested by the UNEP Assessment does not have a large effect on temperature change. By implementing the UNEP policies, maximum 21st century warming is reduced by less than 1% compared to their reference scenario, and delaying these reductions (mitigating in 2030-2050 as the UNEP Assessment did) yields similar results. While UNEP used 2070 as the end year of their evaluation rather than the end of the century, their findings are still significantly greater than [36]. The UNEP Assessment found that BC measures could reduce the temperature in 2070 by approximately 0.2 °C, or 10% of the 2070 temperature achieved by CO_2 measures alone.

Seshardi [37] examined trade-offs between mitigating BC versus CO_2 to limit peak warming by varying the rate of mitigation for each species under a variety of emission trajectories determined by different growth rates of gross global product. Seshardi found that peak warming is less sensitive to the rate of mitigation of BC than CO_2 because the BC mitigation rate has a smaller effect on the maximum radiative forcing. Similar to starting BC mitigation early, reducing BC on a rapid timescale (20 years or less) does not have a large impact on peak temperature because the BC is largely eliminated before peak warming occurs. Peak warming is sensitive to BC mitigation timescale when a small decrease in the timescale eliminates BC at the time of peak warming. Therefore, this study agrees with others that emphasize the importance of mitigating CO_2 to reduce long term warming and to mitigate BC as CO_2 emissions decline to zero.

1.5 Modeling short-lived and long-lived components of radiative forcing

Most air pollutants affecting climate fall into one of two categories – long-lived or short-lived forcers, so we model the radiative forcing and subsequent temperature impacts of emissions from infrastructure by dividing emissions into long-lived and short-lived components. Because of its large contribution to radiative forcing, CO_2 is the most important LLCF to model. Emissions of CO_2 used in this study come from the Representative Concentration Pathways (RCPs), as described in Section 2.5.

Traditional air pollutants have lifetimes of less than one year, and the duration of forcing is negligible when viewed on decadal time scales. Therefore, forcing by these species may be treated as a pulse that occurs quickly after a pulse emission [42] or a continuous forcing that is proportional to emission rate. The role of short-lived species in inducing climate response can be explored by examining such a continuous forcing flow.

Analysis that represents a continuous forcing-flow can include radiative effects that are classified as "indirect" or "effective" forcing as well as regionally-dependent forcing per emission [12], [14]. The investigation of global temperature response to a global forcing used here is similar to that in [34]–[37]. However, this analysis excludes differential climate response to regional forcing [43].

Chapter 2 – Methods

The purpose of this work is to confirm that SLCF and LLCF can be treated as separate but additive components to radiative forcing and global mean surface temperature change and then determine the rates and timing of SLCF mitigation that can have the greatest influence on total warming under a variety of CO_2 emission trajectories. To accomplish these goals, I first created a simple model in MATLAB to incorporate emissions from SLCF and LLCF and calculate radiative forcing and temperature change (Section 2.1). I then performed a series of tests with the model to compare its calculations of climate metrics with published values and to compare its outputs to those of a widely used and accepted model, the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) (Section 2.2.).

After checking the model, I defined the initial conditions for the analysis scenarios and generated inputs. Consistent with other climate change studies, I referenced temperature change relative to pre-industrial times. Because the start year of my analysis is 2015, I determined the warming since pre-industrial times until 2015 to add to my modelled results (Section 2.3). I then defined the periods for which I calculated the cumulative temperature perturbation resulting from future emissions (Section 2.4). Lastly, I compiled relevant SLCF and LLCF emission inputs to evaluate rates and timing of SLCF mitigation (Section 2.5).

2.1 Creating the simple model

A simple model was constructed to take input emissions of LLCF and SLCF and output radiative forcing and global average surface temperature change. Existing functions from literature were linked to create the simple model as described below. For simplification CO_2 was used as the LLCF and BC was used as the SLCF in this model.

I coded the simple model in MATLAB (Appendix A). For consistency in performing the tests with MAGICC6 (Section 2.3), the MATLAB code reads in CO_2 and BC emission rates (in GtC/yr and MtBC/yr respectively) from a MAGICC6 emission file (.SCEN) and puts them into an emission matrix. However, the model could also vary emission rates on a sub annual scale. The MAGICC6 emission file contains one emission rate per pollutant per

modelled year. I created a time array with a step of 0.00001 years from 0 to 0.01 years and a step of 0.01 years from 0.02 years to the number of years specified in the MAGICC6 emission input file.

CO_2 is not removed from the atmosphere by chemical reactions or deposition; instead it is redistributed into carbon sinks - ocean, land biosphere, or atmosphere [44]. Therefore, unlike short-lived pollutants, the atmospheric decay of CO_2 occurs on several time scales, rather than just a single exponential decay function [11]. Atmospheric concentrations of CO_2 can be estimated using impulse response functions (IRF), which represent the response to a pulse of emission input, derived from more complex carbon cycle-climate models. The IRF representing the fraction of CO_2 remaining in the atmosphere after emission is represented using a sum of exponentials [44] (Equation 1). I computed the IRF_{CO2} in MATLAB as a function of time using the constants in Table 2.1.

$$\mathrm{IRF}_{CO_2}(t) = a_0 + \sum_{i=1}^{3} a_i \cdot \exp\left(\frac{-t}{b_i}\right) \qquad \text{(Equation 1)}$$

Table 2.1. Constants for IRF_{CO2} from Joos et al., 2013.

i	*0*	*1*	*2*	*3*
a (unitless)	0.2173	0.2240	0.2824	0.2763
b (years)	-	394.4	36.54	4.304

From Joos et al. 2013 [44], the concentration of CO_2 in the atmosphere at a time t after emission is then calculated using Equation 2:

$$[\mathrm{CO_2}](t) = [\mathrm{CO_2}](t_0) + \int_{t_0}^{t} E_{CO2}(t') \cdot \mathrm{IRF}_{CO_2}(t - t')dt', \qquad \text{(Equation 2)}$$

where $[CO_2](t_0)$ is the baseline CO_2 concentration, $E_{CO2}(t')$ is the emission rate of CO_2 at time of emission, and $\mathrm{IRF}_{CO_2}(t - t')$ is the fraction of CO_2 remaining after emission. Emissions in mass of carbon (GtC) were multiplied by (M_{CO2}/M_C), where M_{CO2} is the molecular weight of CO_2 (44.01 kg/kmol) and M_C is the molecular weight of carbon (12.01 kg/kmol), to convert to emissions in mass of CO_2 ($GtCO_2$).

To obtain concentrations in ppm [11], the mass of CO_2 was multiplied by $(M_A/M_{CO2})(10^6/T_M)$ = 1.28e-13 ppm/$kgCO_2$, where M_A is the mean molecular weight of air (28.97 kg/kmol) and T_M is the total mass of the atmosphere (5.1352e18 kg). A baseline CO_2 concentration of 401

ppm was used which reflects the CO_2 concentration in 2015 [45]. Radiative forcing from CO_2 was approximated using the log relationship based on radiative transfer models [46] where α = 5.35 W/m^2 and $\Delta[CO_2]$ is the change from the baseline concentration:

$$RF_{CO_2} = \alpha \ln\left(\frac{[CO_2](t_0)+\Delta[CO_2]}{[CO_2](t_0)}\right) \qquad \text{(Equation 3)}$$

I approximated the change to the total atmospheric abundance of BC, M_{BC}, due to an input of constant emissions using the budget equation [47] where E_{BC} is total emission of BC in mass/year and τ, is the average atmospheric lifetime (Equation 4). For a pulse of emissions, the fraction of BC remaining in the atmosphere at a time t after emission, R_{BC}, can be estimated using an exponential decay (Equation 5) [14]. For continuous emission input, I approximated the solution to Equation 4 by means of a finite difference approximation in MATLAB (Equation 6) where the first term is the mass left from the previous time step and the second term is mass emitted during the current time step. In this study I used an average atmospheric lifetime, τ, of 5.5 days [25]. BC radiative forcing in W/m^2 was calculated by multiplying the M_{BC} at each time step by the specific climate forcing, A_{BC}, of 1800 W/g [25] and dividing by the surface area of the earth (5.101e14 m^2) (Equation 6). Radiative forcing from both CO_2 and BC at each time step were summed to get total radiative forcing at each time step, $RF_{Total}(t)$.

$$\frac{M_{BC}}{dt} = E - \frac{1}{\tau}M_{BC} \qquad \text{(Equation 4)}$$

$$R_{BC}(t) = \exp\left(\frac{-t}{\tau}\right) \qquad \text{(Equation 5)}$$

$$M_{BC}(t) = M_{BC(t-1)} \exp\left(-\frac{t}{\tau}\right) + E_{BC}(t) \cdot \tau\left(1 - \exp\left(-\frac{t}{\tau}\right)\right) \qquad \text{(Equation 6)}$$

$$RF_{BC}(t) = \frac{M_{BC}(t)A_{BC}}{SA_{earth}} \qquad \text{(Equation 7)}$$

The earth's response to radiative forcing is influenced by properties of the climate system such as climate sensitivity and ocean heat uptake [44]. Therefore, similar to the approach of using an IRF for CO_2 concentration, an IRF can be used to estimate the climate response (change in global average surface temperature) to radiative forcing [44]. This IRF_T is represented by a sum of exponentials [38]:

$$IRF_T(t) = \sum_{i=1}^{2} \frac{c_i}{d_i} \cdot \exp\left(\frac{-t}{d_i}\right), \qquad \text{(Equation 8)}$$

where the sum of the c_i coefficients represents the equilibrium climate sensitivity (1.06 K/W/m^2 or 3.9 K/W/m^2 for a doubling of CO_2 concentration), and the d_i coefficients represent the two timescales with which the climate responds (lower atmosphere-earth surface system and heat uptake of the deep ocean respectively) [11], [38], [44] (Table 2). The IRF_T from [38] was chosen because it matched the temperature output from the MAGICC6 model better than the other IRF_T tested – Section 2.2.2 outlines these tests. I computed the IRF_T in MATLAB as a function of time using the constants in Table 2.2.

Table 2.2. Constants used for calculating IRF_T from Boucher and Reddy, 2008.

i	*1*	*2*
c (K·m²/W)	0.631	0.429
d (years)	8.4	409.5

A change in global mean surface temperature, ΔT, at a time, t, is calculated using equation 9. This is also known as the absolute global temperature change potential (AGTP) [38], [44]:

$$\Delta T(t) = \int_{t_0}^{t} RF_{Total}(t') \cdot IRF_T(t - t')dt \qquad \text{(Equation 9)}$$

2.2 Testing the simple model

To test the simple model, I calculated climate change metrics such as the global warming potential of BC and the absolute global warming potential of CO_2. I also compared outputs from the simple model to outputs from the MAGICC6 climate model as described in the following sections.

2.2.1 Calculating climate change metrics

I used the MATLAB program to calculate the 100-year absolute global warming potential ($AGWP_{100}$) of CO_2 and the 100-year global warming potential (GWP_{100}) for BC to compare the model's calculations to values found in literature. To calculate the $AGWP_{100}$ for CO_2, I integrated the radiative forcing over 100 years resulting from a 1kg pulse of CO_2 using the IRF_{CO2} from [44] and a radiative efficiency of 8.9717e-4 W/gCO_2 (radiative efficiency for a 1 ppm change at 391 ppm [11]). The simple model calculated an $AGWP_{100}$ of 9.18e-14 Wm^{-2} kgCO_2^{-1}. This value is a close match to the value of 9.17e-14 Wm^{-2} kgCO_2^{-1} published in AR5 [11].

GWP_{100} values for BC in literature range from 345 to 900 depending on the regions and radiative effects included [11]; the calculation performed here was simply to verify that the model code was estimating BC RF within a reasonable range. To calculate the GWP_{100} for BC, I input equal emissions of BC and CO_2 and divided the sum of RF from BC over 100 years by the sum of RF from CO_2 over 100 years. Using the BC atmospheric lifetime and radiative efficiency described in Section 2.2 as well as the IRF_{CO2} and radiative efficiency for CO_2 listed above, the simple model calculated a GWP_{100} of 588. Bond and Sun, 2005 [25] used the same radiative efficiency and lifetime for BC with the IRF_{CO2} from the IPCC Third Assessment Report (TAR) and a CO_2 radiative efficiency of 0.000994 W/g and estimated a GWP_{100} of 680. Using the constants for the IRF_{CO2} from IPCC TAR, the simple model calculates a GWP_{100} of 692 which is a close match to that published in [25].

2.2.2 Comparison with MAGICC6

To test the simple model, I compared radiative forcing and temperature change outputs from it to those of the 6.0 version of the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC6). MAGICC6 is a reduced complexity carbon-cycle climate model which was used to emulate more complex atmosphere-ocean general circulation models (AOGCMs) for IPCC AR5 [48]. I used the default climate change and carbon cycle parameters in MAGICC6 which were used to produce the RCP GHG concentrations [49]. The default climate parameters represent a best-estimate climate response that resembles the median of the AOGCMs used for the third phase of the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP3) with a fixed climate sensitivity of 3 K for a doubling of CO_2 concentration, close to the average of 2.88 K from emulating 19 CMIP3 AOGCMs [50]. The default carbon cycle parameters come from Bern-CC carbon cycle model which projects CO_2 concentrations that are roughly in the middle range of the results from the World Climate Research Programme's Coupled Carbon Cycle Climate Model Intercomparison Project (C^4MIP) [50].

To test the simple model, I ran a set of scenarios in MAGICC6 with the aforementioned parameters for the 100 year time period 2010-2109. Table 2.3 provides a brief description of each of these scenarios. I ran MAGICC6 with emissions of CO_2 or BC as well as with zero emissions. I subtracted the results from the zero emission run from the runs with emissions to obtain results consistent with the simple model (i.e. to exclude forcing from historical

CO_2 or other emissions). Because MAGICC6 automatically generates organic carbon (OC) emissions proportional to an input of BC emissions, I also ran a scenario with constant OC emissions to subtract the temperature response due to OC: $\Delta T_{NetBC} = (\Delta T_{ConstantBC} - \Delta T_{Zero}) - (\Delta T_{ConstantOC} - \Delta T_{Zero})$, where ΔT_{NetBC} is the temperature response due to constant 0.5 W/m^2 from BC with no forcing from other pollutants.

Table 2.3. Description of scenarios run in MAGICC6 for testing the simple model.

Scenario	**Description**
Zero	Zero emissions from 2010-2109
PulseCO2	Pulse of 10 GtC in year 2010
ConstantCO2	Constant 10 GtC/yr from 2010-2109
ConstantBC	Constant 5.9245 MtBC/yr (0.5 W/m^2 radiative forcing from BC) from 2010-2109
ConstantOC	Constant 50.1 MtOC/yr from 2010-2109
ConstantBCandCO2	Constant 5.9245 MtBC/yr and constant 10 GtC/yr from 2010-2109

I also compared the temperature response from two IRF_T functions to the MAGICC6 model (Table 2.4). One IRF_T comes from Boucher and Reddy 2008 [38] (referred to here as BR-IRF_T), and the other comes from Olivié and Peters 2013 [51] (OP-IRF_T). The IRF_T used in the simple model, BR-IRF_T, was derived from the Hadley Centre Coupled Model version 3 (HadCM3) and has a higher climate sensitivity (1.06 K/Wm^{-2} or 3.9 K for a doubling of CO_2 concentration) than MAGICC6. The OP-IRF_T represents the average of 15 CMIP3 AOGCMs with a climate sensitivity of 0.68 K/Wm^{-2} [51] Similar to MAGICC6, OP-IRF_T is the product of multiple AOGCMs whereas BR-IRF_T is only from one climate model, the Hadley model. The BR-IRF_T has a higher climate sensitivity and longer timescales with which the earth system responds compared to the OP-IRF_T. Generally a higher climate sensitivity results in a higher peak temperature and a slower decay in the tail, and longer timescales result in a later peak.

Table 2.4. Comparison of constants used in IRF_T (Equation 8).

Constant	BR-IRF [a]	OP-IRF [b]
c_1 (K·m²/W) [c]	0.631	0.48
c_2 (K·m²/W) [c]	0.429	0.2
d_1 (years) [d]	8.4	7.15
d_2 (years) [d]	409.5	105.55

a. Constants come from the IRF_T derived by Boucher and Reddy [38] using the Hadley model
b. Constants come from the IRF_T derived by Olivié and Peters [51] using CMIP3 data from 15 AOGCMs
c. The sum of c_1 and c_2 is the climate sensitivity
d. The d_i coefficients represent the two timescales with which the climate responds (lower atmosphere-earth surface system and heat uptake of the deep ocean respectively)

Figure 2.1 shows the CO_2 concentration, radiative forcing, and temperature response resulting from a pulse of 10 GtC/yr in the first year. The IRF_{CO2} used in the simple model, from Joos et al. 2013 [44], generates a slightly greater CO_2 concentration than MAGICC6; however the peaks are similar, and they differ by less than 0.5 ppm after 100 years. The forcing routine used in MAGICC6 comes from [46] and is the same as the one used in the simple model described above; therefore, differences between the radiative forcing trajectories in Figure 2.1B are due to differences in CO_2 concentrations. For a pulse of carbon emissions, BR-IRF_T produces a peak temperature approximately 0.005 K greater than MAGICC6, but it differs from MAGICC6 by less than 0.005 K after 100 years. The higher climate sensitivity of the BR-IRF_T explains the higher temperature trajectory. For the CO_2 pulse, OP-IRF_T is a closer match to the MAGICC6 temperature response than BR-IRF_T – its temperature response is nearly the same as MAGICC6, but the peak occurs approximately 10 years after the peak produced by MAGICC6.

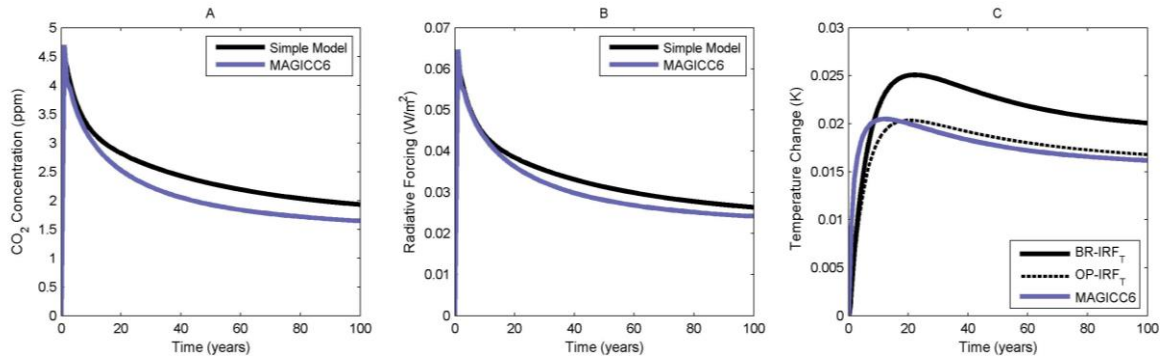

Figure 2.1. Concentration, radiative forcing, and temperature change resulting from pulse of 10 GtC/yr in the first year.

Figure 2.2 shows the radiative forcing and temperature response to constant emissions of 10 GtC/yr for 100 years. The IRF_{CO2} produces CO_2 concentrations approximately the same as MAGICC6; the concentration profiles differ by less than 10 ppm over the 100 year period. As with the pulse, differences in radiative forcing (Figure 2.2B) are due to differences in CO_2 concentration. In the constant emissions case, the BR-IRF_T produces temperatures greater than MAGICC6, especially in later years which is expected due to the higher climate sensitivity. The OP-IRF_T on the other hand produces lower temperatures than MAGICC6. The temperature response from the BR-IRF_T more closely matches MAGICC6 than OP-IRF_T; the greatest difference between BR-IRF_T and MAGICC6 is 0.1 K whereas the greatest difference between OP-IRF_T is nearly 0.15 K.

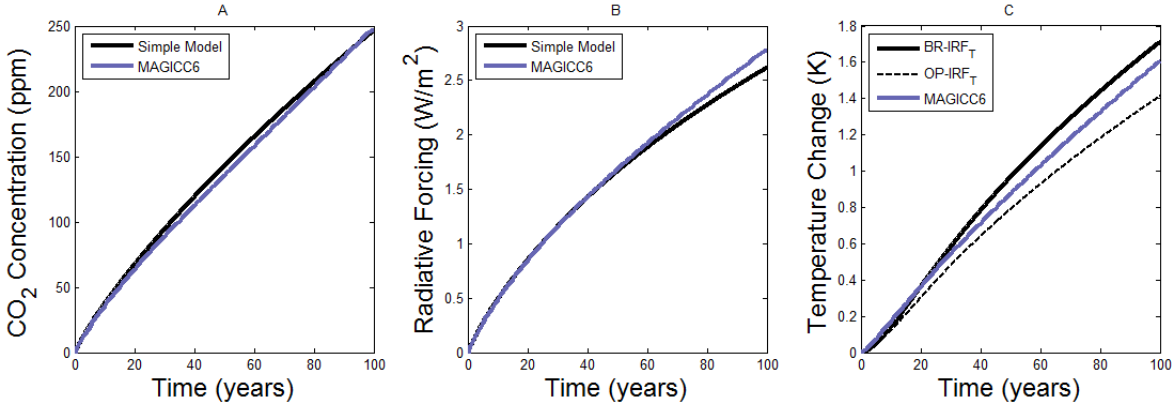

Figure 2.2. Concentration, radiative forcing, and temperature change resulting from constant 10 GtC/yr for 100 years.

Figure 2.3 shows the constant input of 0.5 W/m^2 radiative forcing from BC and the subsequent temperature response for 100 years. To obtain the total radiative forcing from BC in MAGICC6, I added the radiative forcing from industrial BC emissions (BCI), biomass

burning (BCB), and BC on snow and ice (BCSnow). An input of 5.9245 MtBC/yr was used in MAGICC6 because it resulted in a total BC forcing of 0.5 W/m^2. In the simple model, I used constant emissions of 9.4 MtBC/yr with the lifetime and radiative forcing per unit mass described in Section 2.1 to arrive at constant 0.5 W/m^2. Compared to MAGICC6, the BR-IRF$_T$ produces a higher temperature response from years ~10-90 with a maximum difference of approximately 0.05 K (20% greater). OP-IRF$_T$ follows a similar path as BR-IRF$_T$ but at a lower magnitude and produces a temperature response with a maximum difference of approximately 20% lower than MAGICC6 over the100 year period. Again, this result is expected because of the high climate sensitivity of the BR-IRF$_T$ and low climate sensitivity of the OP-IRF$_T$.

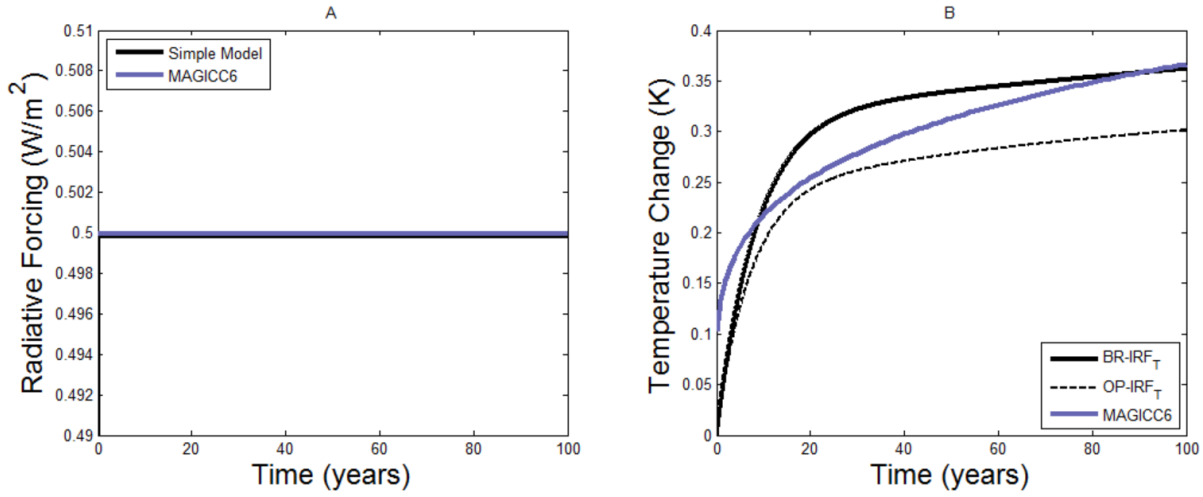

Figure 2.3. Radiative forcing and temperature response to constant BC emissions.

2.2.3 Linearity of LLCF and SLCF

Other studies [31], [35], [36] have evaluated numerous emission scenarios using complex climate models to evaluate the effects of SLCF versus LLCF on climate change. To simplify the process of running and evaluating numerous scenarios, I tested whether radiative forcing and temperature response could be separated into a long-lived component and a short lived component which could be added together. If this additivity proves valid, each scenario can then be described as a transition in short-lived and long-lived forcing.

I tested a scenario with both constant 0.5 W/m^2 BC and constant 10 GtC/yr (ConstantBCandCO2) to test for additivity of temperature responses. Figure 2.4A and Figure 2.4B show the radiative forcing and temperature response for ConstantBCandCO2. BR-IRF$_T$ underestimates temperature compared to MAGICC6 in the early years and

overestimates in later years. BR-IRF$_T$ matches the temperature response from MAGICC6 more closely than OP-IRF$_T$ which underestimates for the entire time period. The difference between MAGICC6 and OP-IRF$_T$ grows over long periods of time whereas the difference between MAGICC6 and BR-IRF$_T$ remains relatively constant. Again, the higher temperatures from BR-IRF$_T$ over time are expected due to the higher climate sensitivity and longer timescales than the OP-IRF$_T$. The differences between the IRF$_T$ and MAGICC6 are equal to the sum of the differences from the BC and the CO_2 components for earlier (ConstantBC and COnstantCO2) suggesting that the temperature responses from the different pollutants are additive.

After comparing the summed response from the IRFs to the MAGICC6, I checked the components of the MAGICC6 response for additivity. I added the two temperature responses (from CO_2 and from BC) and compared the summed response to the temperature response to a scenario with emissions of both CO_2 and BC. Figure 2.4C shows the temperature response from ConstantBCandCO2, the temperature response from the single components (ConstantBC, ConstantCO2), and the temperature response from the sum of the components (ConstantBC + ConstantCO2). As expected, because the climate response is represented by linear differential equations, the temperature response from SLCF and LLCF components is additive.

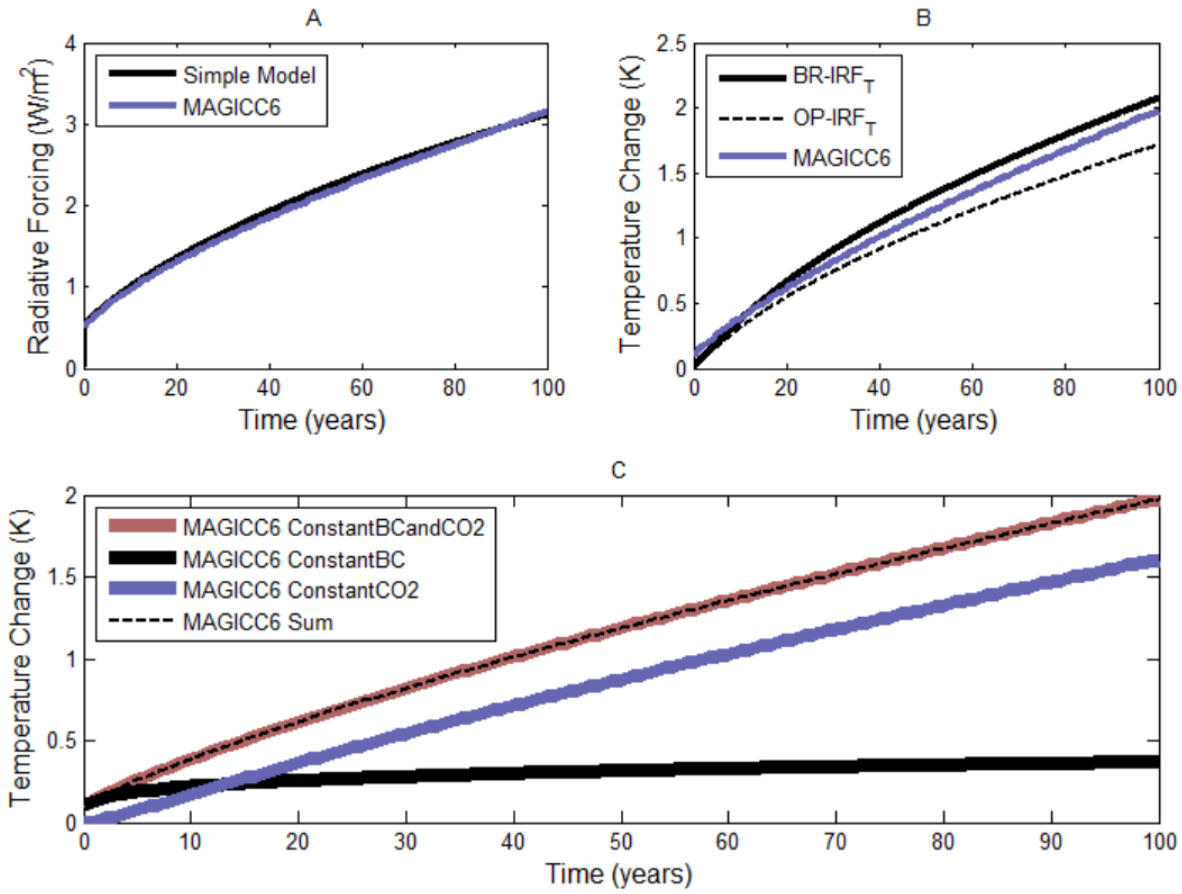

Figure 2.4. Radiative forcing and temperature response to constant CO2 and BC emissions. The SLCF and LLCF components of temperature change can be added to obtain a total temperature change trajectory. The dashed line is the sum of results from two separate runs with constant BC emissions and constant CO_2 emissions respectively. The red line is the result of one run with the same constant BC and constant CO_2 emissions.

Additionally, the temperature response is proportional to the magnitude of SLCF emission rate when all else is held constant (Figure 2.5). Figure 2.5A shows the temperature trajectories for constant 10 GtC/yr with different magnitudes of constant BC emissions (0-8 Mt/yr) over 100 years, and Figure 2.5B shows the linear relationship between the maximum temperature change (at t=100 years) and the BC emission rate. After confirming the linearity and separability, exploration of effects of LLCF versus SLCF mitigation can be done using a simple model that varies SLCF or LLCF emissions independently.

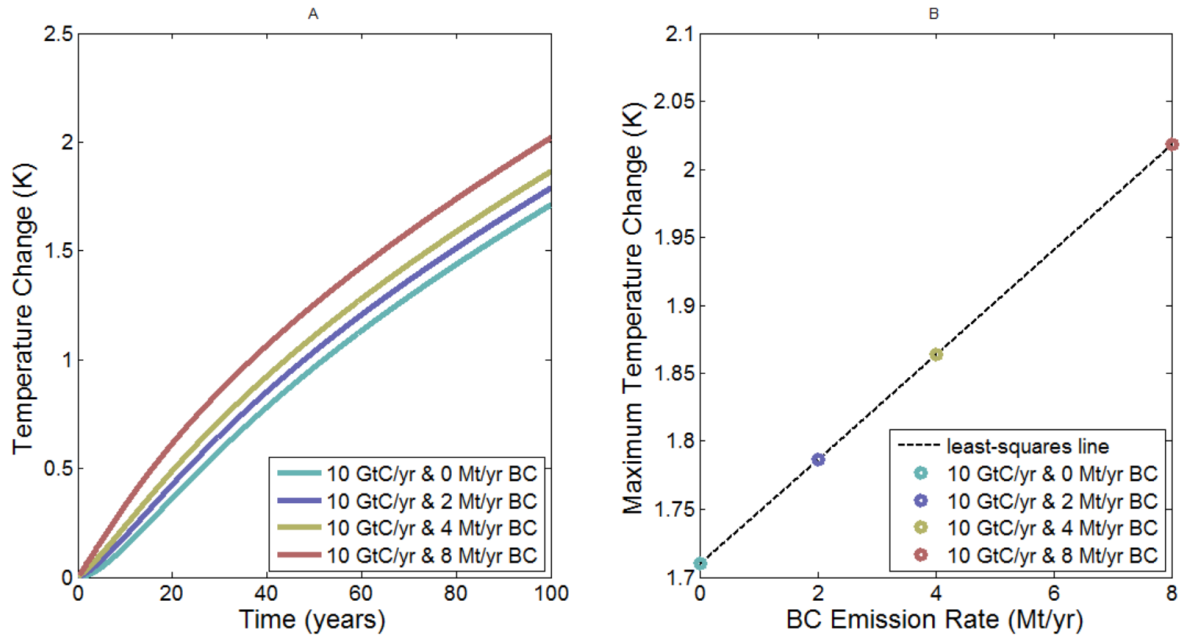

Figure 2.5. Temperature change increases proportionally to the BC emission rate when all else is held constant.

2.3 Temperature baseline for the analysis

Global mean temperature change (ΔT) was calculated relative to the 2015 global mean temperature of 1 °C above the pre-industrial average from 1850-1900 [52]. The reference period of 1850-1900 is also the reference period used by IPCC [53].

2.4 Cumulative temperature perturbation

To calculate the cumulative temperature perturbation (CTP) resulting from future emissions, I integrated the temperature change trajectories calculated using the IRF_T over four generations, totaling a 100-year period: 2015-2040, 2040-2065, 2065-2090, and 2090-2115 (equation 10).

$$CTP_{TOT} = \int_0^t \Delta T dt \qquad \text{Equation 10}$$

where ΔT is the change in global mean temperature resulting from all modeled pollutants (in this case SLCF and CO_2) relative to the modeled emission start year (in this case 2015).

To find the CTP from SLCF, I subtracted the CTP resulting from a scenario of only CO_2 emissions:

$$CTP_{SLCF} = CTP_{TOT} - CTP_{CO_2} \quad \text{Equation 11}$$

2.5 Emissions used in the analysis

2.5.1 LLCF Component

CO_2 emissions from four Representative Concentration Pathways (RCPs), RCP-2.6 [16], RCP-4.5 [17]–[19], RCP-6 [8]-[9], and RCP-8.5 [22], were used for the LLCF component of emissions in this analysis (section 1.3). Figure 2.6A shows the CO_2 emission trajectories for each of the RCPs for the time period modelled in this study, and Figures 2.6B and 2.6C show the radiative forcing and temperature change calculated by the simple model using the RCP CO_2 emissions.

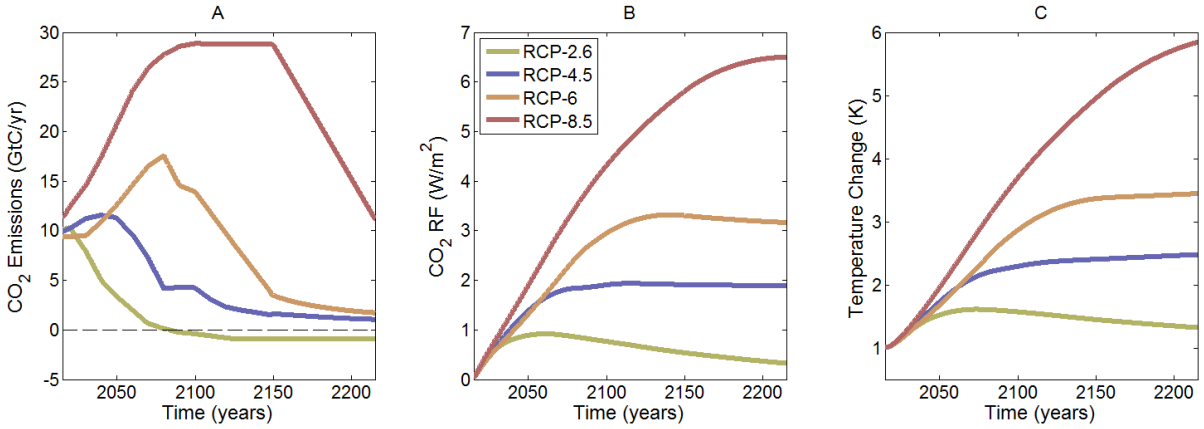

Figure 2.6. RCP CO_2 emissions, radiative forcing, and temperature trajectories calculated using the simple model. The RF in (B) is the result of the emissions in (A); however, the temperature in (C) starts at 0.9 at 2010 to take into account previous warming since pre-industrial times, as explained in Section 2.3.

2.5.2 SLCF Component

This study uses +0.5 W/m² radiative forcing to represent the forcing-flow from SLCF, specifically black carbon and ozone, which can be reasonably mitigated through air quality initiatives. This value is approximately 60% of the BC and ozone forcing reported in AR5 [28]. It is a smaller percentage of total SLCF positive forcing if higher forcing estimates from Bond et al. 2013 [14] are considered or if BC forcing from indirect effects are considered. The value of +0.5 W/m² was chosen as an illustrative, round number to explore interactions between LLCF and SLCF. The UNEP assessment [31] assumed a best estimate of RF from BC of 0.6 W/m², and they proposed to reduce BC emissions by 75-80%. Assuming constant forcing from BC, their proposed emission reduction would result in a RF reduction of 0.45-0.48 W/m² which is consistent with the value chosen to represent the SLCF forcing-flow in this study.

A BC emission rate of 9.4 Mt/yr was input to the simple model to achieve 0.5 W/m^2 when using the BC lifetime and forcing per mass listed in Section 2.1. The SLCF radiative forcing was added to each of the LLCF components from the RCPs to create hypothetical reference cases without any SLCF mitigation (see section 3.1). Figure 2.7 shows the temperature change over time resulting from the constant 0.5 W/m^2 radiative forcing calculated using the simple model. The temperature change attributed to SLCF increases sharply in the first 20 years to approximately +0.3 K (relative to 2015) and then increases more slowly to approximately +0.4 K after 200 years. Despite constant radiative forcing, inertia in the climate system represented by IRF_T causes the increase in temperature over time.

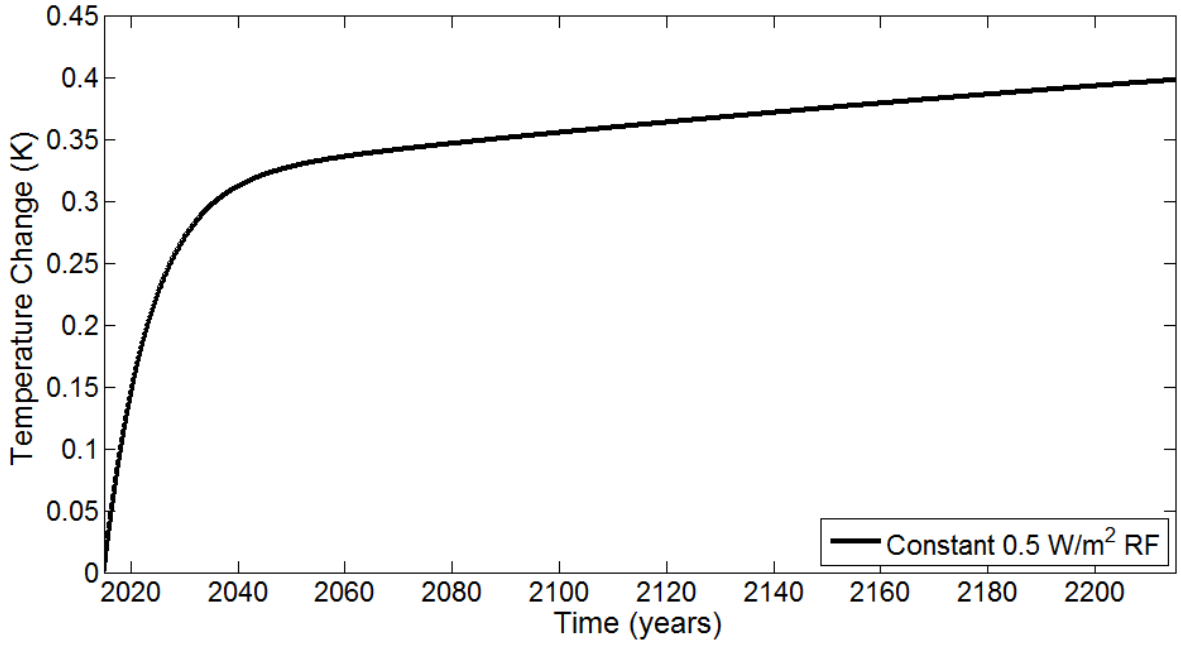

Figure 2.7. Temperature response from constant 0.5 W/m2 RF over 200 years calculated using the simple mode.

Chapter 3 – Results and Discussion

I evaluated the effects of varying the rate or timing of SLCF mitigation on the earth's temperature response in the context of different CO_2 concentration pathways (from the RCPs as explained in SECTION 2.4,). CO_2 emissions from four Representative Concentration Pathways (RCPs), RCP-2.6 [16], RCP-4.5 [17]–[19], RCP-6 [8]-[9], and RCP-8.5 [22], were used for this analysis. SLCF emissions equivalent to constant 0.5 W/m^2 RF (Section 2.4.2) were used to explore effects of varying the rate and timing of SLCF mitigation on target temperatures and on cumulative warming impact.

First, to put the impacts from mitigation into perspective, I calculated the theoretical widest range of SLCF impacts by estimating global mean temperature change and cumulative differential warming from scenarios without SLCF mitigation (constant SLCF) and scenarios with only CO_2 (Section 3.1). Then I evaluated how mitigation strategies with different rates or start years affect those metrics (Section 3.2 and 3.3). Lastly, I compare how useful rates of SLCF mitigation compare with those that can be achieved with existing or proposed policy and infrastructure (Section 3.4).

3.1 Temperature targets and cumulative warming from CO_2 and SLCF components

Figure 3.1 shows the temperature change trajectory attributed to CO_2 emissions in each RCP as well as the trajectory resulting from CO_2 emissions plus a constant 0.5 W/m^2 radiative forcing from SLCF. Temperature change is relative to pre-industrial times (Section 2.XX). The temperature trajectory from CO_2 and constant SLCF emissions represent reference trajectories where radiative forcing from SLCF is unmitigated over the 200 year period. The temperature trajectory resulting from only CO_2 emissions represents a hypothetical GHG trajectory with zero radiative forcing from SLCF. The difference between the reference and the GHG only trajectory is equivalent to the temperature change attributed to constant 0.5 W/m^2 radiative forcing from SLCF.

The temperature response from SLCF is the same in all four cases presented in Figure 3.1, but the different CO_2 trajectories change the relative impact of SLCF on the temperature trajectory. The drastic reductions in CO_2 emissions in RCP-2.6 result in a peak in global

mean temperature and a growing fractional contribution from SLCF to the temperature change over the 200 year period. On the other hand, in RCP-8.5 the change in global mean temperature attributable to CO_2 in 2215 is nearly +6 K and growing (Figure 3.1D) whereas the change in global mean temperature from constant SLCF is only approximately +0.4 K. Despite the temperature response from SLCF being the same in all four cases, the CO_2 emissions are far greater in RCP-8.5 than in other RCPs; this makes the relative impact of SLCF on temperature change much less important under conditions like RCP-8.5.

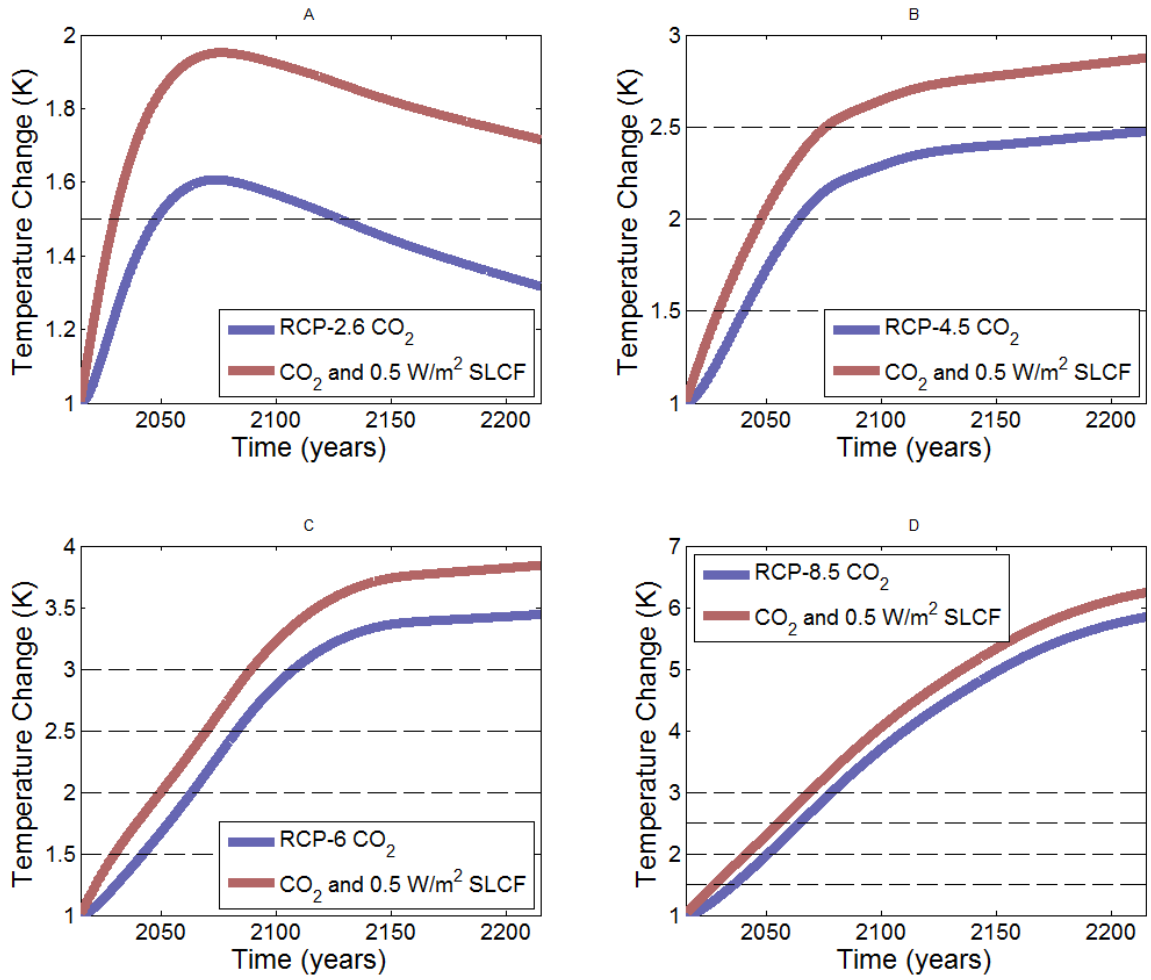

Figure 3.1. Temperature change from CO_2 emissions (blue lines) and CO_2 + constant 0.5 W/m^2 SLCF (red lines) under four RCP CO_2 concentration pathways: RCP-2.6 (A), RCP-4.5 (B), RCP-6 (C), and RCP-8.5 (D). Dashed lines represent potential target temperatures of 1.5 °C, 2 °C, 2.5 °C, and 3 °C. The blue lines with only CO_2 emissions represent a theoretical minimum trajectory with no warming from SLCF. The red lines represent scenarios in which SLCF remains unmitigated.

Table 3.1 shows the years in which target temperatures (1.5 °C, 2 °C, 2.5 °C, and 3 °C) are reached in each of the aforementioned scenarios. Dashes show that a target was not

reached in a specific emission scenario. The years shown for the CO_2 only or minimum scenarios represent the latest possible time that a target could be reached if there were no SLCF emissions after 2015. The years shown for the reference trajectories are the earliest years in which a target could be reached if constant 0.5 W/m^2 of SLCF were emitted from 2015 onward. Therefore, the difference between the two sets of trajectories represents the longest possible delay caused by +0.5 W/m^2 of SLCF in reaching a target temperature. The greatest delay is in reaching 3 °C in RCP-6. RCP-8.5 has the smallest delays because the rate of warming due to CO_2 is high enough to limit any delay to a decade or less. The delays calculated for reaching 1.5 °C are consistent with UNEP's estimates [31]. The delays calculated for reaching 2 °C are similar to those calculated by Pierrehumbert [34] for RCP-6 (17 years) and RCP-8.5 (9 years). The delay for RCP-4.5 is much less than [34] (68 years); however, the analysis presented here models only half of the SLCF mitigation of [34]. There is a significant delay in reaching 2.5 °C for RCP-4.5; however, I do not explore these far-future differences in this work.

Table 3.1. Years in which target temperatures are reached in each CO_2 scenario versus CO_2 plus constant SLCF. Because emissions are reduced when going from the baseline to the minimum scenario, a positive difference represents a delay in reaching the target temperature. Dashes indicate a peak or target temperature not being reached in the modelled period.

CO_2 emission pathway	**Peak temperature**		**Year target temperature is reached**			
	°C	**Year**	**1.5 °C**	**2 °C**	**2.5 °C**	**3 °C**
RCP CO_2 emissions only						
RCP-2.6	1.61	2074	2048	--	--	--
RCP-4.5	--	--	2040	2064	--	--
RCP-6	--	--	2043	2064	2083	2108
RCP-8.5	--	--	2036	2051	2065	2079
RCP CO_2 + constant SLCF (0.5 W/m^2)						
RCP-2.6	1.95	2076	2030	--	--	--
RCP-4.5	--	--	2029	2048	2076	--
RCP-6	--	--	2030	2050	2070	2089
RCP-8.5	--	--	2028	2042	2056	2069
difference between CO_2 only and CO_2 + constant SLCF						
RCP-2.6	-0.34	-3	18	--	--	--
RCP-4.5	--	--	11	17	--	--
RCP-6	--	--	13	14	13	19
RCP-8.5	--	--	8	9	9	10

Table 3.2 and Figure 3.2 show the integrated temperature change, or cumulative temperature perturbation (CTP), relative to 2015 for each of the RCP CO_2 emission pathways and constant SLCF. These CTPs only account for future impacts which can be controlled; they do not take into account future warming from emissions prior to 2015 due to inertia in the climate system. CTPs were calculated for each of four generations (2015-2040, 2040-2065, 2065-2090, and 2090-2115) spanning a 100-year period. To show the relative impact of SLCF on cumulative warming, the CTPs for only the SLCF component are also shown. SLCF has a large contribution to CTP in early generations. Notably, for the 2015-2040 generation, SLCF CTP is greater than CO_2 CTP under all of the RCPs except RCP-8.5. For RCP-4.5, RCP-6, and RCP-8.5, CO_2 has the largest impact in the 2090-2115 generation because CO_2 has built up in the atmosphere significantly in each of those scenarios.

Table 3.2. Cumulative temperature perturbations relative to 2015 for SLCF, RCP-CO2, and the baseline (combined SLCF and RCP CO2).

Cumulative Temperature Perturbation (CTP) relative to 2015 (K·yr)					
CO_2 emission pathway	**2015-2040**	**2040-2065**	**2065-2090**	**2090-2115**	**Total 2015-2115**
constant 0.5 W/m² SLCF					
n/a	5.53	8.23	8.64	8.92	31.33
RCP CO_2 emissions only					
RCP-2.6	4.73	13.12	15.01	14.02	46.88
RCP-4.5	5.19	19.21	28.79	32.42	85.61
RCP-6	4.72	18.24	33.78	47.37	104.10
RCP-8.5	6.32	26.16	48.59	68.91	149.99
RCP CO_2 + constant SLCF					
RCP-2.6	10.26	21.35	23.65	22.95	78.21
RCP-4.5	10.72	27.45	37.42	41.34	116.93
RCP-6	10.25	26.48	42.40	56.29	135.42
RCP-8.5	11.85	34.40	57.21	77.84	181.30
constant SLCF/RCP CO_2					
RCP-2.6	117%	63%	58%	64%	67%
RCP-4.5	107%	43%	30%	28%	37%
RCP-6	117%	45%	26%	19%	30%
RCP-8.5	88%	31%	18%	13%	21%

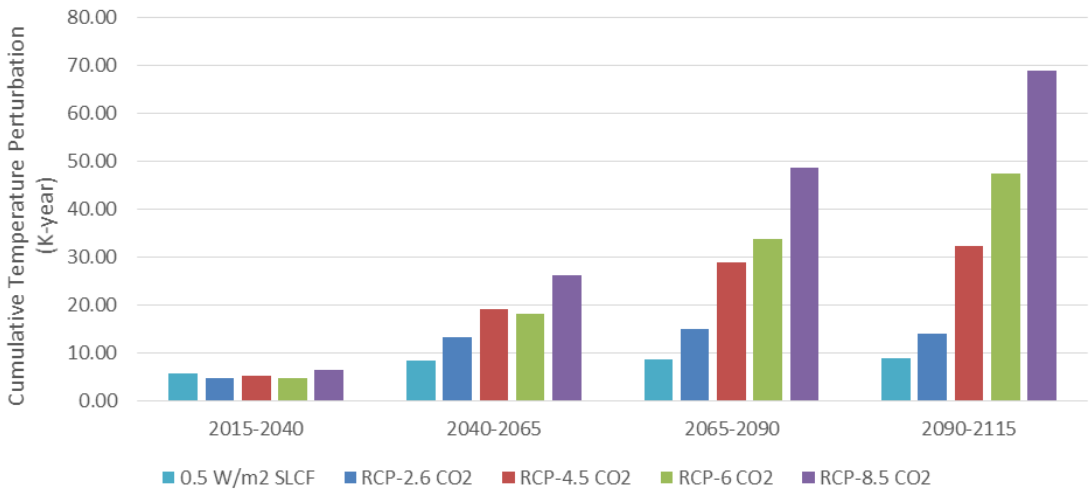

Figure 3.2. Comparison of CTPs from constant 0.5 W/m² SLCF and RCP CO_2 emissions over four generations.

To put the magnitude of the CTPs into perspective, I calculated the difference between the CTPs from RCP CO_2 emission pathways (Table 3.3). The difference between CO_2 CTPs represents the future cumulative warming that could avoided by switching to a lower CO_2 emission pathway. Differences between CO_2 scenarios are less than a third of the CTP from SLCF during the first generation. The SLCF CTP falls within the range of CO_2 differences in the second generation, but differences are greater than the SLCF CTP in the third and fourth generations because the CO_2 emission pathways diverge more toward the end of the century. Therefore, depending on the rate and timing, SLCF mitigation could reduce cumulative warming in the first two generations by as much or more than switching to a lower CO_2 pathway.

Table 3.3. The difference between CTPs from RCP CO_2 emission pathways in descending order of total (2015-2115) magnitude. The difference between CTPs represents the cumulative warming which could be avoided by switching to a lower CO_2 emission pathway. Positive values for the difference between RCP-2.6 and RCP-6 in the 2015-2040 period are due to higher emissions in RCP-2.6 in early years. Similarly, positive differences between RCP-4.5 and RCP-6 in the 2015-2040 and 2040-2065 periods are due to higher emissions in RCP-4.5 during those time periods.

	Change in CTP (K·yr)				
CO_2 emission pathways	**2015-2040**	**2040-2065**	**2065-2090**	**2090-2115**	**Total 2015-2115**
RCP-2.6 - RCP-8.5	-1.59	-13.04	-33.58	-54.89	-103.10
RCP-4.5 - RCP-8.5	-1.13	-6.95	-19.80	-36.50	-64.37
RCP-2.6 - RCP-6	0.01	-5.12	-18.76	-33.34	-57.22
RCP-6 - RCP-8.5	-1.61	-7.92	-14.81	-21.55	-45.89
RCP-2.6 - RCP-4.5	-0.46	-6.09	-13.78	-18.39	-38.73
RCP-4.5 - RCP-6	0.48	0.97	-4.98	-14.95	-18.49

3.2 Effects of rate and timing of SLCF mitigation on CTP

To evaluate how the rate or timing of an SLCF mitigation strategy such as the one proposed by UNEP [31] would affect cumulative warming, I reduced SLCF emissions linearly from 0.5 W/m^2 to 0 W/m^2 over a 20-year period beginning in 2015 (the earliest mitigation could take place). This mitigation is equal to a reduction of 0.025 W/m^2/yr radiative forcing. I then simulated the same mitigation but beginning 20 and 40 years later.

I calculated the CTP of the SLCF component for different mitigation scenarios (Table 3.4). Because the temperature impact from SLCF and CO_2 is separable and additive, this CTP would be identical under any CO_2 trajectory. As expected, for equal mitigation rates, the later the mitigation start year, the lower the reduction in CTP. Across all cases, the CTP reductions in the fourth generation are similar because mitigation and its effects have largely been completed by then. Delaying a 20-year mitigation by 20 years later increases the CTP 2.7 K-yr in the first generation and 3.7 K-yr in the second generation – 48% and 45% of the total unmitigated SLCF CTPs for those generations. Starting another 20 years later, in 2055, has a similar impact on the first generation – increase of 2.7 K-yr or 49% of the total SLCF CTP – but nearly double the impact on the second generation – increase of 7.5 K-yr or 91% of the total SLCF CTP. The impact on CTP due to a 20-year mitigation delay is mostly felt in the 2040-2065 generation followed by the 2015-2040 generation. The impact for a 40-year delay is primarily felt in the 2040-2065 generation followed by the 2065-2090 generation.

Table 3.4. Reductions in SLCF CTP due to SLCF mitigation at different rates, beginning in different years. Mitigation rates of -0.025 (fast), -0.0125 (medium), -0.0083 (slow), and -0.0063 (very slow) W/m2/yr RF are equal to mitigation durations of 20, 40, 60, and 80 years respectively.

Mitigation start year	SLCF Mitigation rate ($W/m^2/yr$)	CTP difference from constant/unmitigated SLCF				
		2015-2040	2040-2065	2065-2090	2090-2115	Total 2015-2115
2015	-0.0250	-2.71	-7.71	-8.52	-8.81	-27.75
2015	-0.0125	-1.38	-5.87	-8.26	-8.70	-24.21
2015	-0.0083	-0.92	-4.00	-7.29	-8.53	-20.73
2015	-0.0063	-0.69	-3.00	-5.65	-8.00	-17.34
2035	-0.0250	-0.04	-4.04	-8.01	-8.58	-20.67
2035	-0.0125	-0.02	-2.14	-6.68	-8.39	-17.23
2035	-0.0083	-0.02	-1.43	-4.70	-7.73	-13.87
2035	-0.0063	-0.01	-1.07	-3.53	-6.19	-10.80
2055	-0.0250	0.00	-0.24	-5.34	-8.20	-13.78
2055	-0.0125	0.00	-0.12	-3.05	-7.31	-10.48
2055	-0.0083	0.00	-0.08	-2.04	-5.39	-7.51
2055	-0.0063	0.00	-0.06	-1.53	-4.04	-5.64

With respect to mitigation rate, for the same mitigation start year, a slower rate causes a lower CTP reduction. However, the start year generally has a greater impact on the CTP than the rate as is shown by the later start years generally having lower CTPs despite high rates of mitigation. That is, mitigating over a 40-year period (as in row 2 of Table 3.4) is not the same thing as waiting 20 years and mitigating over a 20-year period (as in row 5 of Table 3.4) because the CTP is dependent on the path of the temperature response. Mitigating for 20 years beginning in 2015 reduces the 2015-2040 SLCF CTP by 49% and the 2090-2115 CTP by 94%. Delaying mitigation by 20 years results in almost no change to the SLCF CTP for the 2015-2040 period, a 49% reduction for 2040-2065. On the other hand, if mitigation begins in 2015 but proceeds at half the rate (taking 40 years instead of 20), the SLCF CTP for the 2015-2040 period is reduced by 25%, and the SLCF CTP for the 2040-2065 period is reduced by 71%. Therefore, mitigating SLCF over the 40-year period 2015-2055 yields CTPs approximately mid-way between the 20-year mitigation beginning in 2015 versus beginning in 2035. To put these reductions into perspective, a reduction of CTP of 5 K-yr in the 2040-2065 period (such as the result of mitigating SLCF over 40 years), is approximately equal to the reduction in CTP that would result from switching from RCP-4.5 CO_2 or RCP-6 CO_2 to RCP-2.6 CO_2.

Figure 3.3 compares cumulative temperature perturbation during four generations from SLCF mitigation and from CO_2. From bottom to top, each bar is ordered from least to most ambitious mitigation, so that the base of each bar is most attainable. For example, the solid green portion of CTP in the CO_2 bar can be achieved by following RCP-6 instead of RCP-8.5. The more ambitious RCP-4.5 yields the vertically striped bars in addition to the solid portion.

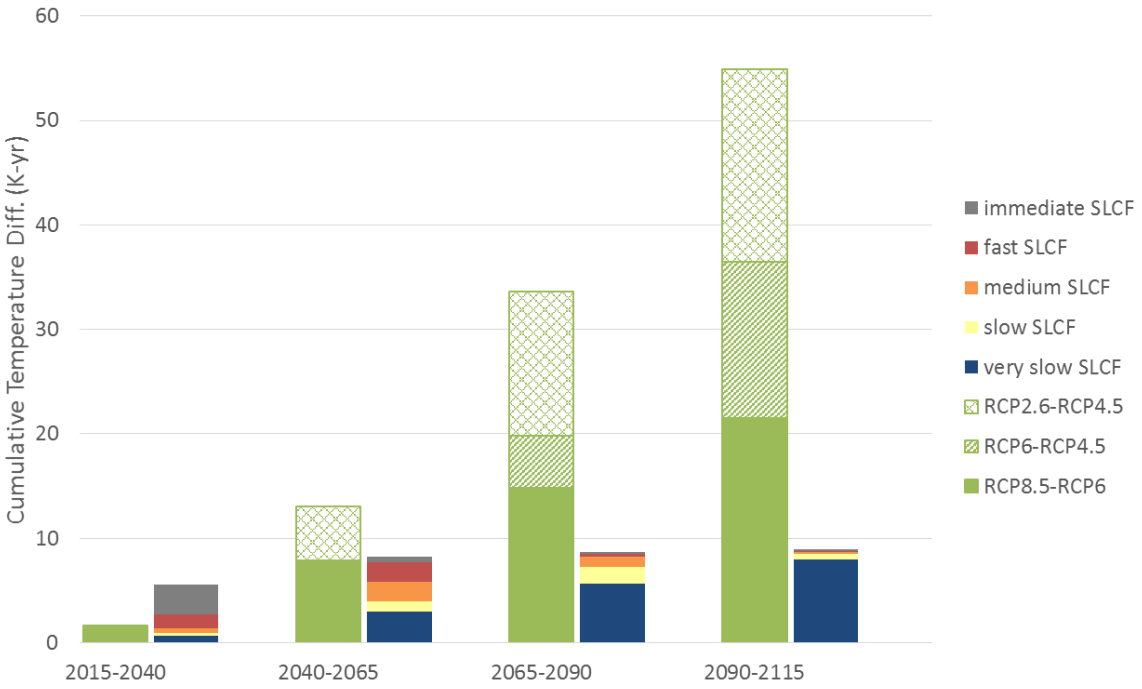

Figure 3.3. Cumulative temperature difference by generation for different rates of SLCF mitigation and switching to lower CO_2 pathway (RCP-8.5 to RCP-6).

For SLCF mitigation, even very slow reductions yield some benefits in the second generation (2040-2065) and most of the benefits in outlying generations. As with the CO_2 bars, CTP of more ambitious actions is determined by adding the bar to the less ambitious actions, so that benefits of "medium SLCF" are found by adding medium, slow, and very slow bars. Progressively more rapid reductions yield additional benefits in the second generation, with fast reductions achieving avoided CTP equivalent to a shift between RCP-8.5 and RCP-6. For the current generation (2015-2040), immediate or fast reductions have the most benefit, greater than the shift between RCP-8.5 to RCP-6 CO_2. Medium or slower SLCF mitigation has much less benefit in the first generation than in subsequent generations. Fast SLCF mitigation beginning in 2015, results in approximately 60% of the CTP reduction from switching from RCP-8.5 CO_2 to RCP-2.6 CO_2 in the second generation.

Halving that mitigation rate (fast to medium) results in a CTP reduction approximately 45% of the difference between RCP-8.5 CO_2 to RCP-2.6 CO_2. In the third generation, the greatest CTP reductions from SLCF are only ~25% of the difference between RCP-8.5 CO_2 and RCP-2.6 CO_2, and this fraction drops to ~16% for the fourth generation as the magnitude of CO_2 induced warming increases.

Although beginning mitigation of SLCF at any year gives the same temperature in the far future, there is a difference for current generations. Figure 3.4 shows generational CTP resulting from mitigating in 2015, 2035, and 2055. The rate and timing of SLCF mitigation matters most to the second generation; in later generations, there is less of a difference between faster and slower rates of SLCF mitigation. Additionally, the start year matters less to the later generations, because much of the mitigation has been achieved by that time. Generational CTP caused by the difference between CP 8.5 and RCP6 is shown for comparison; more ambitious CO_2 action would expand the axes as in Figure 3.3 and decrease the relative importance of SLCF. Fast SLCF mitigation can achieve approximately the same CTP difference as switching from RCP-8.5 to RCP-6 in the second generation if mitigation starts in 2015; if mitigation is delayed to 2035, about half of the CTP difference can be achieved. Fast SLCF mitigation can achieve approximately 57% of the CTP difference between the two CO_2 scenarios in the third generation when SLCF mitigation begins in 2015. When beginning SLCF mitigation in 2035, the CTP drops to only 54% of the difference between the two CO_2 scenarios in the third generation, and delaying mitigation until 2055 results in 36% of the difference.

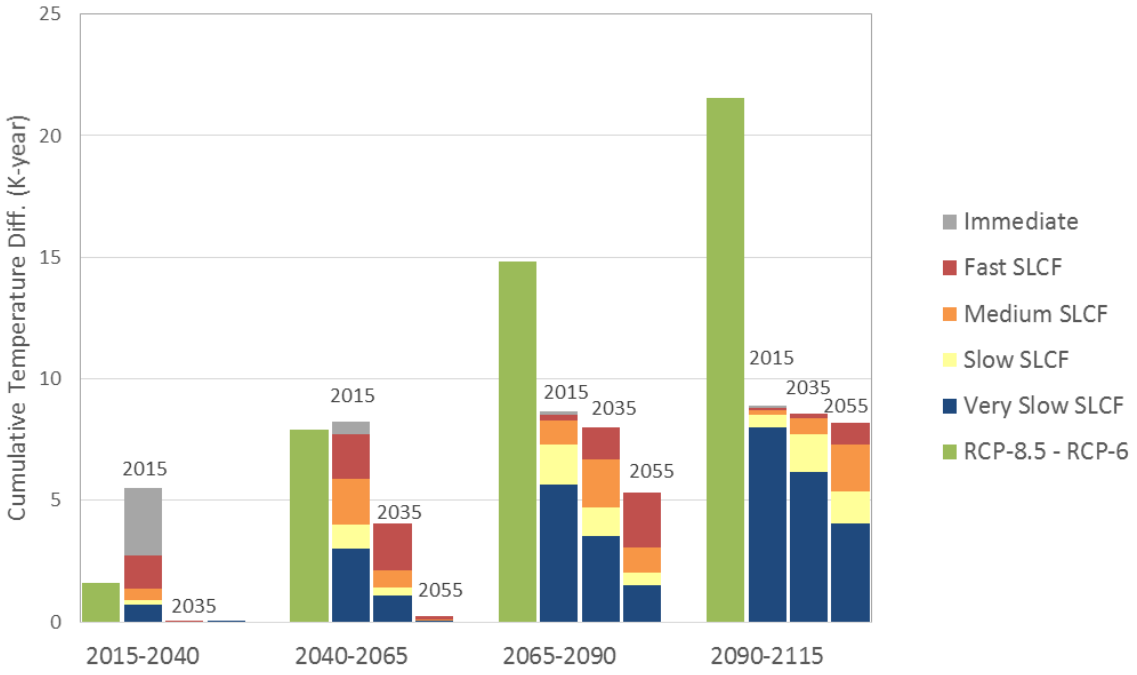

Figure 3.4. Cumulative temperature difference by generation for different rates of SLCF mitigation and switching to lower CO_2 pathway (RCP-8.5 to RCP-6).

3.3 Effects of rate and timing of SLCF mitigation on target temperatures

I added the temperature trajectories of the same SLCF mitigation scenarios listed above to the RCP CO_2 temperature trajectories to evaluate the effects of rate and timing of SLCF mitigation on reaching target temperatures. Table 3.5 summarizes the delay in reaching a target temperature for a variety of SLCF mitigation scenarios (full table of delays in Appendix B). I also calculated the reduction in peak temperature resulting from the various SLCF mitigation scenarios for those scenarios in which temperature actually peaks.

Table 3.5. Effects of SLCF mitigation on peak or target temperatures. Peak temperatures are only shown for RCP-2.6 because peaks in other scenarios are not realized until beyond the modelled period. A full table with delays for all target temperatures and RCP scenarios is in Appendix B.

Mitigation start year	SLCF mitigation rate ($W/m^2/yr$)	RCP-2.6 CO_2		RCP-4.5 CO_2	RCP-6 CO_2
		Delay to 1.5 °C (years)	Peak temp. reduction (°C)	Delay to 2 °C (years)	Delay to 3 °C (years)
2015	0.0250	15	-0.34	16	19
2015	0.0125	4	-0.32	14	18
2015	0.0083	2	-0.24	8	18
2015	0.0063	1	-0.19	5	17
2035	0.0250	0	-0.23	12	18
2035	0.0125	0	-0.16	3	18
2035	0.0083	0	-0.13	2	17
2055	0.0250	0	-0.05	0	17
2055	0.0125	0	-0.04	0	16

SLCF mitigation can reduce the peak temperature in the RCP-2.6 case by 0.04- 0.34 °C (Figure 3.5). Similar to the findings with the CTP, the largest reductions in peak temperature occur when beginning mitigation in 2015. The window of opportunity to delay the onset of the 1.5 °C target is narrow; of the SLCF mitigation scenarios evaluated, only mitigation beginning in 2015 at the highest rate will delay the onset of the target by more than 10 years. Halving the rate of SLCF mitigation (or doubling the mitigation period to a 40-year period) results in a 0.02 °C loss in the magnitude of peak temperature reduction whereas delaying mitigation by 20 years results in a loss of 0.11 °C. Starting in 2015 with an SLCF mitigation spanning 60 years results in approximately the same peak temperature reduction as beginning in 2035 with a 20-year mitigation; therefore, beginning SLCF mitigation sooner, even at a slow rate, is more beneficial than postponing mitigation. As shown in Figure 3.5, the rate of reduction makes a bigger difference during early mitigation start years than later start years as the peak temperature approaches. With respect to peak temperature under RCP-2.6 CO_2 conditions, the largest difference in peak temperature reduction between the fast and medium SLCF mitigation rates is 0.06 K when mitigation begins in 2035; there is little difference in peak temperature for these mitigation rates when mitigation begins in 2015 or 2055.

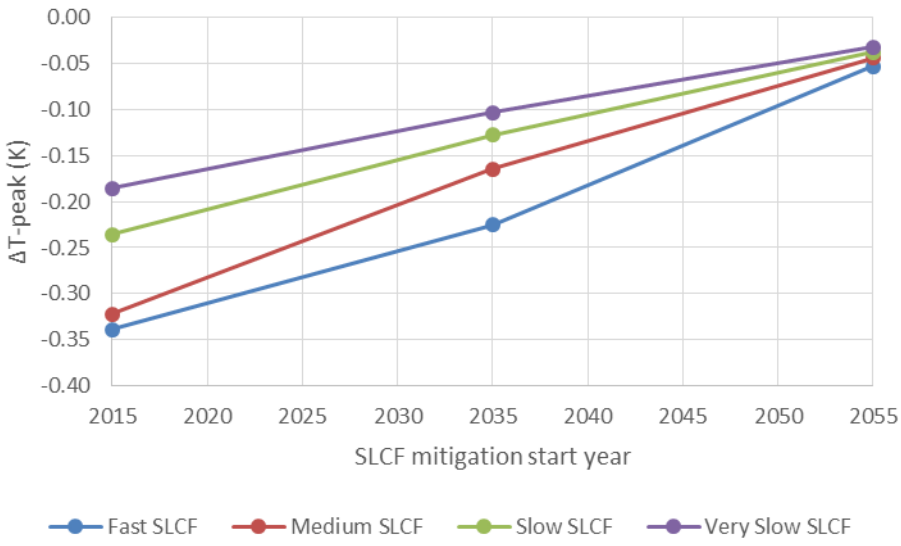

Figure 3.5. Change in peak temperature from SLCF mitigation in different years at different rates under RCP-2.6 CO_2 conditions.

Similar trends are seen with an RCP-4.5 CO_2 trajectory. Delays in reaching the 2 °C target are greatest when beginning SLCF mitigation early. The delays in reaching 3 °C in an RCP-6 CO_2 trajectory are close to the maximum possible delays from Table 3.1, and the range of delays is small. The small range is observed because the target temperature occurs well after most of the SLCF mitigation scenarios evaluated here have finished. In the RCP-2.6 and RCP-4.5 cases, the target temperatures are reached during mitigation or shortly after mitigation has finished.

3.4 Implications for infrastructure and policy

Yan et al. [54] projected global emissions for on-road vehicles using a dynamic vehicle fleet model . The analysis took into account socioeconomic variables, fuel consumption, technological changes, and vehicle distributions to project fuel consumption and emission factors for four of the IPCC Special Report on Emission Scenarios (SRES) emission projections. The SRES emission projections are illustrative economic growth and climate policy scenarios from IPCC's Third and Fourth Assessment Reports (TAR and AR4). Although the SRES scenarios used by Yan et al. are not the same as the RCPs evaluated in Section 3.2, they provide a means of comparing the mitigation rates found above to feasible policy and infrastructure initiatives. The estimated 2100 warming in SRES B1 and B2 are closest to RCP-4.5 and RCP-6 respectively [55]. SRES A1B and A2 both fall between RCP-6 and RCP-8.5 [55]. There is no comparable SRES to RCP-2.6 [55].

Yan et al. [54] project that global particulate matter (PM) emissions from the on-road sector will decrease by 0.3-1.3%/year (for the SRES scenarios listed above) over the 40 year period 2010-2050. This results in a total reduction of 12-53% of PM emissions. Assuming that BC emissions decrease in the same proportion as PM emissions, this means that it is possible to achieve BC reductions of ~50% over a 40 year period (or -1.25%/year). If this rate of mitigation were attainable for all BC sources (or a combination of BC sources and other SLCF sources), then this type of reduction would be similar to reducing 0.5 W/m^2 at the medium SLCF mitigation pace presented in Sections 3.2-3.3. Therefore, beginning SLCF mitigation in 2015 could result in reductions of approximately 1.4, 5.9, and 8.3 K-years in the first three generations, respectively, or 86%, 74%, and 56% of the CTP difference of switching CO2 between RCP-8.5 and RCP-6. This could also delay the onset of the 2 °C warming target by approximately 14 years under RCP-4.5 CO_2 conditions or the 3 °C target by approximately 18 years under RCP-6.5 conditions. Under an RCP-2.6 CO_2 trajectory, no significant delays would be achieved with this rate of SLCF mitigation, especially if mitigation is delayed.

The aforementioned PM emission projections are rates for the entire globe; however, the rates of mitigation vary depending on different economic and policy factors in different regions of the world. For example, PM emissions in regions such as North America, Latin America, and Europe are expected to decrease by 1-2%/year, closer to 2%/year in the A2, B1, and B2 scenarios; however, emissions in Asia are projected to decrease by 0.5-1%/year, and emissions in Africa are expected to grow by 1-2%/year. Because SLCFs cause regional temperature impacts [15] and other climate impacts, one might expect regions with higher mitigation rates to experience greater regional reductions in temperature and feel the benefits in the first two generations, whereas if Africa does begin SLCF mitigation late, it might not see any benefit from these reductions until the third or fourth generation.

Chapter 4 – Conclusion

Although carbon dioxide (CO_2) emissions are the largest contributor to anthropogenic warming, pollutants with much shorter lifetimes called short lived climate forcers (SLCF) also contribute substantially to radiative forcing, sparking interest in mitigating them as a way of slowing global warming [31], [41], [27]. Recent publications [35], [36], [34] have questioned the importance of mitigating short lived climate forcers (SLCF) such as black carbon, tropospheric ozone, or methane in the near term because of their limited impact on peak temperature compared to CO_2. However, these studies did not acknowledge the path dependence of cumulative climate impacts and ignore potential welfare gains that could result from reducing SLCF in the near term. In this work I evaluated the impact of SLCF mitigation on cumulative warming in addition to target temperatures. I varied the rate and timing SLCF mitigation and calculated the resulting global mean temperature change and integrated temperature response (referred to as a cumulative temperature perturbation, or CTP) for future emissions.

I found that the rate and timing of SLCF mitigation matter especially to the first three generations (2015-2090). In these generations 50-100% or more of the CTP difference between the RCP-8.5 CO_2 pathway and the RCP-6 CO_2 pathway can be achieved by beginning SLCF mitigation before 2035 and mitigating over 40 years or less. These mitigation rates are consistent with projections for global on-road transportation emissions.

With respect to peak temperatures, I found that SLCF mitigation needs to occur in the near term at medium to fast rates to achieve a significant delay in reaching the 2 °C target under CO_2 trajectories similar to RCP-2.6 or RCP-4.5. However, in agreement with recent studies, under higher CO_2 concentration pathways, the rate is less important and mitigation can be delayed because the peak temperature is farther in the future and CO_2 emissions drive the rate of temperature increase more than SLCF. Looking at achievable mitigation rates from the on-road transportation sector, I found that significant delays to reaching target temperatures under low CO_2 pathways could not be achieved, especially if mitigation is delayed.

Although mitigating SLCF might not result in significant temperature delays or reductions of peak temperature depending on the CO_2 trajectory, mitigating SLCF can increase

welfare by reducing cumulative warming impacts in the near future. This benefit can be especially important in countries in Asia and the Pacific where SLCF have a higher impact on regional warming [15] or faster mitigation rates are possible [54] and cost effective [41].

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Appendix A – MATLAB Code

```
%Dimensions

%i = time, j = pollutant (BC, CO2)

%Load RCP CO2 Emissions in g/yr
% rownum = 1; %RCP-2.6
 rownum = 2; %RCP-4.5
% rownum = 3; %RCP-6
% rownum = 4; %RCP-8.5
load('RCPEmissions.mat','RCPCO2','t');
E_CO2 = RCPCO2(rownum,:);
%E_CO2 = zeros(1,length(t)); %to run SLCF only wiht no CO2

%Load SLCF RF
load('SLCF_11.mat','t','RF_SLCF');
t=t;
RF_SLCF = RF_SLCF;
%RF_SLCF = zeros(1, length(t)); %to run CO2 only with no SLCF


%Define an array for dt. Diff(t) calcualtes the difference between adjacent
elements of t along the t array
dt = [t(2)-t(1) diff(t)]; %cannot start at 0 b/c then will divide by 0 later,
so start with t(2)-t(1)


%Calculate CO2 mass in the atmosphere (grams)
MCO2 = zeros(1, length(t));
for i=1:length(t)
    tpidx = find(t<=t(i)); %creates an array of positions/indicies where t is
less than or equal to t(i)
    tpassed = t(i) - t(tpidx); %subtracts tpidx from t to determine the
amount of time passed since emission
    CO2frac = IRF3(tpassed); % same as above but uses constants from AR5
    MCO2(i) = sum(E_CO2(1,tpidx) .* CO2frac .* dt(tpidx));  %the CO2
concentration in the atmosphere at a time t from an emission profile E(t)
(see Boucher and Reddy 2008)
end

%Calculate the concentration of CO2 in the atmosphere (ppm)
%1.2819e-16 ppm/gCO2 - See IPCC AR5 Chapter 8 Supplemental Material and
Boucher and Reddy 2008 for calculation method
CO2Conc = (MCO2 * 1.2819e-16); %CO2 concentration in ppm

%Calculate the CO2 Forcing based on concentration (see IPCC AR5 Ch 8
Supplemental Material)
alpha = 5.35; %W/m2
C0 = 401; %reference concentration in ppm (in 2015)
for i = 1:length(CO2Conc)
    CO2RF(i) = alpha * (log( (C0 + CO2Conc(i))/C0));
end
```

```
%F is Forcing
F = [RF_SLCF; CO2RF]; %combine forcing into one matrix
%Sum Forcing
SumFrc = sum(F); %sum of the forcing from BC and CO2


%Temperature Response
dtemp = zeros(1,length(t));
for i=1:length(t)
    tpidx = find(t<=t(i)); %creates an array of positions/indicies where t is
less than or equal to t(i)
    tpassed = t(i) - t(tpidx); %subtracts tidx from t to determine the amount
of time passed since emission?
    tresp = CRF(tpassed); % temp response based on amount of time passed. See
CRF.m file for function, from Boucher and Reddy 2008
    %tresp = CRF3(tpassed); % temp response based on amount of time passed.
IRF to fit CMIP3. See CRF3.m file for function,
    dtemp(i) = sum(SumFrc(tpidx) .* tresp .* dt(tpidx));%integrate
temperature response times pollutant concentration times dt
end
```

```
% Impulse Response Function for carbon dioxide: The fraction of carbon
emitted at time t=0 that is left in the atmosphere at time t (see Boucher and
Reddy 2008, Joos et al, 2013)
%THis version uses the constants from IPCC AR5
function IRF3 = IRF3(t)
    a0 = 0.2173;
    a = [0.2240  0.2824  0.2763];
    b = [394.4  36.54  4.304];

   IRF3 = a0;
   for i=1:length(a)
      IRF3 = IRF3 + (a(i) * exp(-t / b(i)));
   end

return
```

```
% climate impulse response function from boucher and reddy 2008. t can be a
vector
function delT = CRF(t)
   c = [0.631 0.429];
   d = [8.4 409.5];

   delT = 0;
   for i=1:length(c)
      delT = delT + (c(i) /d(i) * exp(-t / d(i)));
   end

return
```

```
% climate impulse response function. t can be a vector. Constants to fit
% CMIP3, see Olivie and Peters (2013) Variation in Emission Metrics
function delT = CRF3(t)
   c = [0.48 0.20];
   d = [7.15 105.55];

   delT = 0;
   for i=1:length(c)
      delT = delT + (c(i) /d(i) * exp(-t / d(i)));
   end

return
```

```
%CTP Calculations
%Cumulative Temperature Perterbation (CTP) for emission trajectory

baseline = 1; %baseline temp in reference yr (2015)

%Define indices for integration
%integration start year
refyr = 2015; %reference yr on which calculations are based
%integration end years
tstart = 2015 - refyr; %initial year for integral
tend1 = 2040 - refyr; %final year for integral, 25 yrs from start yr
tend2 = 2065 - refyr; %final year for integral, 50 yrs from start yr
tend3 = 2090 - refyr; %final year for integral, 75 yrs from start yr
tend4 = 2115 - refyr; %final year for integral, 100 yrs from start yr

%This will read all the .mat file in a folder
folder_name='C:\Users\Kevin\Documents\UIUC School\Research\CTPcalculation\';
all_m_filenames=dir([folder_name,'*.mat']);
filenames = {all_m_filenames.name}'; %creates a nx1 cell with all filenames


CTP = zeros(size(all_m_filenames,1),3); %initialize a matrix with the number
of rows equal to number of files and 3 columns for CTP1, CTP2, and CTP3

for i = 1:numel(filenames)
    fname(i,:)=[folder_name,all_m_filenames(i).name];
    load(fname(i,:),'t', 'dt', 'dtemp');
    t = t; %read in t
    dt = dt; %read in dt
    dtemp_a = dtemp; %read in dtemp
    dtemp_b = dtemp + baseline; %add baseline temp to dtemp

    %find integration intervals
    gen1 = find(t>=tstart & t<tend1); %index for 1st 25 yrs (1 generation)
    gen2 = find(t>=tend1 & t<tend2); %index for 2nd 25 yrs (2 generations)
    gen3 = find(t>=tend2 & t<tend3); %index for 3rd 25 yrs (3 generations)
    gen4 = find(t>=tend3 & t<tend4); %index for 4th 25 yrs (4th generration)

    %Integrate a temeprature response trajectory over a set period of time
```

```
    CTP(i,1) = sum(dtemp_a(gen1).*dt(gen1)); %cumulative temperature
perturbation for gen1 (25 yrs)
    CTP(i,2) = sum(dtemp_a(gen2).*dt(gen2)); %cumulative temp. perturbation
for gen2 (50 yrs)
    CTP(i,3) = sum(dtemp_a(gen3).*dt(gen3)); %cumulative temperature
pertyrbation for gen3 (75 yrs)
    CTP(i,4) = sum(dtemp_a(gen4).*dt(gen4)); %cum temp perturb for gen4
end

CTPcell = num2cell(CTP); %creates a nx3 cell with all CTP
result = [filenames CTPcell]; %concatenates filenames with CTP calcualtions
```

```
%Calculate years delay to target temperatures

baseline = 1; %baseline temp in reference yr (2015)
refyr = 2015;

%Define targets
targ1 = 1.5;
targ2 = 2;
targ3 = 2.5;
targ4 = 3;

% targindex1 = find(dtemp < targ1); %finds number of values in dtemp leading
up to the target temp
% targindex2 = find(dtemp < targ2);
% targindex3 = find(dtemp < targ3);
% targindex4 = find(dtemp < targ4);
%
% targyr1 = t(length(targindex1));
% targyr2 = t(length(targindex2));
% targyr3 = t(length(targindex3));
% targyr4 = t(length(targindex4));


%This will read all the .mat file in a folder
folder_name='C:\Users\Kevin\Documents\UIUC School\Research\CTPcalculation\';
all_m_filenames=dir([folder_name,'*.mat']);
filenames = {all_m_filenames.name}'; %creates a nx1 cell with all filenames


targyr = zeros(size(all_m_filenames,1),3); %initialize a matrix with the
number of rows equal to number of files and 3 columns for CTP1, CTP2, and
CTP3

for i = 1:numel(filenames)
    fname(i,:)=[folder_name,all_m_filenames(i).name];
    load(fname(i,:),'t','dtemp');
    t = t+refyr; %read in t and add ref yr
    dtemp_a = dtemp; %read in dtemp
    dtemp_b = dtemp + baseline; %add baseline temp to dtemp

    %find targets intervals
```

```
    [M I] = max(dtemp_b); %finds a maximum and tells us the index
    targindex1 = find((dtemp_b(1:I)) < targ1); %finds number of values in
dtemp leading up to the target temp
    targindex2 = find(dtemp_b < targ2);
    targindex3 = find(dtemp_b < targ3);
    targindex4 = find(dtemp_b < targ4);


    targyr(i,1) = t(length(targindex1)); %yrs to trgt1
    targyr(i,2) = t(length(targindex2)); %yrs to trgt2
    targyr(i,3) = t(length(targindex3)); %yrs to trgt3
    targyr(i,4) = t(length(targindex4)); %yrs to trgt4
    targyr(i,5) = t(I); %yrs to peak

end

targyr = num2cell(targyr); %creates a nx5 cell with all targs
result = [filenames targyr]; %concatenates filenames with CTP calculations
```

Appendix B – Table of Target Temperature Delays

Table B1. Target temperature delays due to SLCF mitigation at different rates and start years. Delays are measured relative to case with constant, unmitigated 0.5 W/m^2 SLCF for the entire modelled period.

SLCF mitigation start year	SLCF mitigation rate (W/m^2/yr)	RCP-2.6 CO_2		RCP-4.5 CO_2		RCP-6 CO_2			
		Delay to 1.5 °C (years)	Peak temperature reduction (°C)	Delay to 1.5 °C (years)	Delay to 2 °C (years)	Delay to 1.5 °C (years)	Delay to 2 °C (years)	Delay to 2.5 °C (years)	Delay to 3 °C (years)
2015	0.0250	15	-0.339	8	16	10	13	13	19
	0.0125	4	-0.323	3	14	0	11	13	18
	0.0083	2	-0.236	2	8	2	8	12	18
	0.0063	1	-0.186	1	5	1	5	9	17
2035	0.0250	0	-0.225	0	12	0	11	13	18
	0.0125	0	-0.165	0	3	0	4	11	18
	0.0083	0	-0.128	0	2	0	2	7	17
	0.0063	0	-0.104	0	1	0	2	5	12
2055	0.0250	0	-0.053	0	0	0	0	10	17
	0.0125	0	-0.044	0	0	0	0	3	16
	0.0083	0	-0.038	0	0	0	0	2	10
	0.0063	0	-0.032	0	0	0	0	1	6