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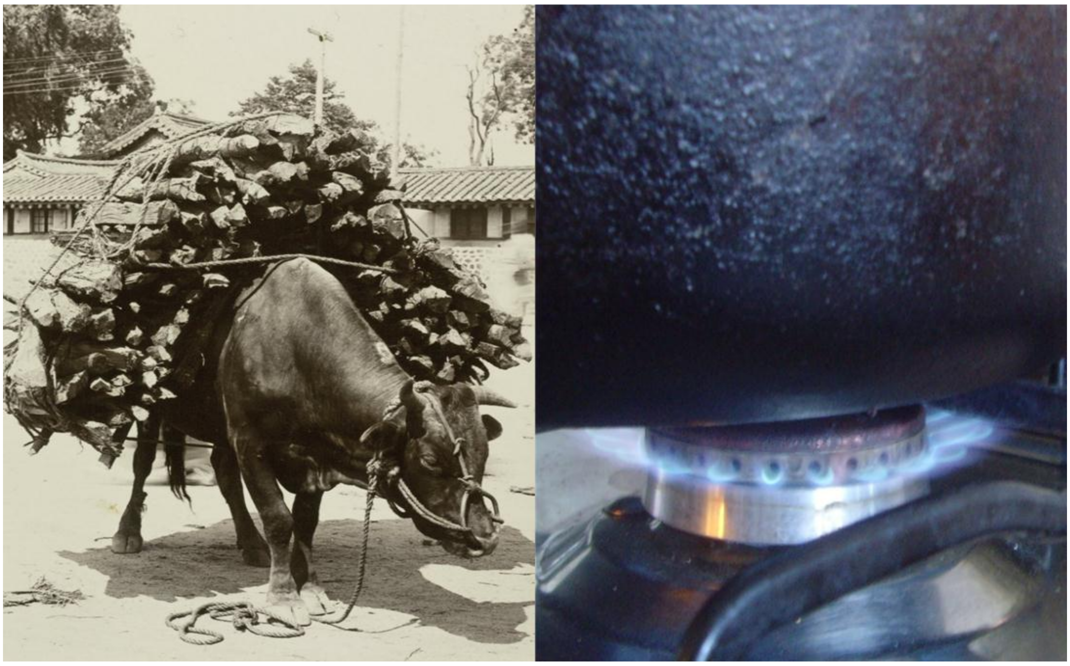

Trade-offs between Black Carbon and CO_2

Building a model to analyze the importance of black carbon abatement for cumulative emissions of CO_2 compatible with a 2 °C climate target

Thesis for the Degree of Master of Science in Complex Adaptive Systems

ERIK STERNER

Department of Energy and Environment
Division of Physical Resource Theory
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cooking on a modern gas stove (Sweden, 2011).

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Abstract

In addition to the greenhouse gases that cause radiative forcing (RF), the global climate is also affected by particles that absorb or reflect light.

Black carbon aerosols (BC) are the most important anthropogenic aerosols that enhance global warming. However, the contribution to RF from BC is considerably more uncertain than the RF of the well-mixed greenhouse gases that are present in the international climate policy discussions. The atmospheric lifetime of BC is only a few days, which suggests that reductions in emissions of BC would give a fast climatic response although BC also has indirect effects when it is deposited. It changes the albedo of snow or ice when deposited on for example Himalayan glaciers.

The magnitude of the RF from BC is considerable, central estimates of the current black carbon global average radiative forcing lie in the range 0.1-0.8 W/m^2. For this reason and the sizeable costs of reducing CO_2 emissions there is a policy interest in reducing BC emissions. However, comparing benefits of reducing BC to reducing CO_2 is a difficult task since there are many different types of aspects to the trade-off.

In this thesis a reduced complexity coupled carbon cycle climate model, constructed primarily for studying the climatic impact of BC and such possible trade-offs, is presented. The model, which is called Physical Prediction Model for Future Radiative forcing and Temperature (PPM-FRT), includes virtually all of the anthropogenic climate forcers and the subsequent global annual average temperature change. In order to find policy relevant questions to ask and experiments to conduct, a series of different rounds of experiments were conducted.

The final set of experiments investigate the effect on CO_2 emissions pathways compatible with a certain climate target of the timing of black carbon emissions reductions start as well as the rate of decline of these emissions. The aspects of the pathway studied are the cumulative CO_2 emissions up to 2100 and the rate of CO_2 emissions reductions from a certain peak year. The climate target used is defined as a maximal increase of the global average surface temperature to 2°C above the pre-industrial level, a target acknowledged in the Copenhagen Accord signed by 138 countries in January 2010.

For mean values of climate sensitivity and BC RF we find that the difference between zero and rapid reductions of BC emissions (red. of 4% per year) corresponds to a difference of between 60 and 140 GtC emitted during the 21st century. The variation in this result depends on the level of coupling between reductions in black carbon and reductions in a frequently co-emitted cooling carbonaceous aerosol called organic carbon (OC). This difference of between 60 and 130 GtC corresponds to a delay of the start year of CO_2 emissions reductions by a few years (for a given CO_2 emissions decline rate of 2.3% per year), illustrating the tradeoff between BC emission pathways and maximum cumulative CO_2 emissions.

A few years delay of CO_2 emissions reductions represents an opportunity for the world to start taking measures against the single most important driver of the climate change: use of fossil fuels (without carbon capture and storage) and unsustainable land use changes, the two main reasons behind our emissions of carbon dioxide.

Preface and Acknowledgements

This is a master thesis in the physics master's program Complex adaptive systems at the department of Energy and Environment, Chalmers University of Technology. The project supervisor was Daniel Johansson and the examiner was Christian Azar. I am greatly thankful to both of you, offering an interesting topic and a continuous support throughout the project. Daniel has mastered the challenge of balancing the amount of help which is instructive, for a student to develop his/her own skills, in a very nice way.

I would also like to thank Niklas Schräder, Thomas Sterner and Viktor Jonsson for helping hands in different issues regarding the project.

This work developed into an abstract that was accepted for a poster presentation on NCGG-6, a conference on non-CO_2 greenhouse gases (see Appendix 1).

The intended audience for this thesis is Master's students and researchers in physics, climate science or related fields.

The source code for the model is available, for academic purposes, on request.

Contents

Appendix: (1) Poster, (2) Recommended Reading, (3) PPM-FRT User Manual,
(4) PPM-FRT Models Key Governing Equations, (5) Standard Simulation Results.

1. Introduction

Global warming is possibly the greatest challenge humanity will face in the conceivable future. Along with higher temperature of the oceans and atmosphere there is likely an increase in the frequencies of extreme weather and melting of snow and ice (Solomon 2007). The expected costs of the damages and lost land areas, due to rising sea water levels, are substantial (Stern 2007).

The main force behind the global warming is the anthropogenic emissions of CO_2. In addition to the well-known greenhouse gases there are other atmospheric species affecting the global climate by either enhancing or masking the ongoing warming.

The most important atmospheric aerosol, caused by anthropogenic activities, that enhance global warming are Black carbon (BC) aerosols (Ramanathan et al. 2008). The contribution to radiative forcing from the current emissions of BC lie in the range of 0.1-0.8 W/m^2. The central estimate used in this study is 0.4 W/m^2 and is assumed to include the indirect effect of BC on snow and ice albedo (Bond et al. 2004; Ramanathan et al. 2008; Fuglestvedt et al. 2009; Kopp et al. 2010). This can be compared to the contribution (as of 2005) from carbon dioxide of about 1.66 W/m^2 (Solomon 2007). As the variation in the central estimates displays, there is a large amount of uncertainty regarding the influence of black carbon.

The atmospheric life time of BC is only a few days or weeks (Rodhe et al. 1972), which suggests that removing the sources of BC would give a fast response on the climate. This can be compared to the most important anthropogenic greenhouse gas, carbon dioxide, which stays in the atmosphere for hundreds of years, and small fractions even more than 10 000 years (Rodhe et al. 1972). Yet another difficulty in assessing the impact of black carbon is that it is commonly emitted together with a cooling aerosol called organic carbon.

There is currently an enhanced interest from policymakers to include short-lived climate forcers, such as black carbon, in policy discussions (Arctic Council 2011; The Swedish Government Offices 2010). Two additional reasons for this are that the majority of pollution is emitted in the developing world (Bond et al. 2004; Kopp et al. 2010) and that these particular emissions have severe health consequences resulting in hundreds of thousands, perhaps millions, of premature deaths (UNEP 2008). The combination of these two paves way for an alternative climate mitigation option for regions which may be unwilling to reduce their CO_2 emissions.

To start the process, the climate impact of different atmospheric species, contributing to global warming, operating on a wide range of time and geographical scales have to be put on a common unit in order to be comparable.
Worries have also started to appear regarding the risk to forget the long term impacts on the reductions of CO_2 when shifting the discussion on to shorter time spans and other climate forcers, such as BC (Quinn et al. 2008; Tanaka et al. 2010).

The advantages of black carbon mitigation on global climate and health are considerable, but it is important that suggestions on how to deal with BC are formed as an integrated part of an overall effort to reduce the anthropogenic global warming. This sets the scene for this master-thesis.

Aim

The aim of this thesis is to build a model and use it to examine trade-offs between abatement in emissions of carbon dioxide and black carbon. More specifically we will estimate how the maximal cumulative emissions of CO_2 by 2100 that is compatible with a two degree temperature target is affected by different rates of black carbon abatement (see Chapter 3).

Limitations

The main limitations of this thesis is that it only accounts for a physical based metric and it only allows for a limited category of emission scenarios. It does not examine what the temperature response is after the year 2100. Further, it only investigates the cases with no or full correlation between emission reductions of BC and OC.

Structure of thesis

This thesis is structured in a way that allows a reader, who is new to the subject, to gradually become acquainted with the terms and concepts needed to understand the constructed model and the experiments performed. The first chapter gives an introduction to the subject of the thesis. Chapter two presents the background of the study. Chapter three develops the purpose or objective of the thesis work. In chapter 4 the model and the method used is presented. Chapter 5 presents and analyses the simulation experiments performed. Chapter 6 lists some sketches of ideas on potential future work and chapter 7 offers a final discussion and conclusions.

2. Background

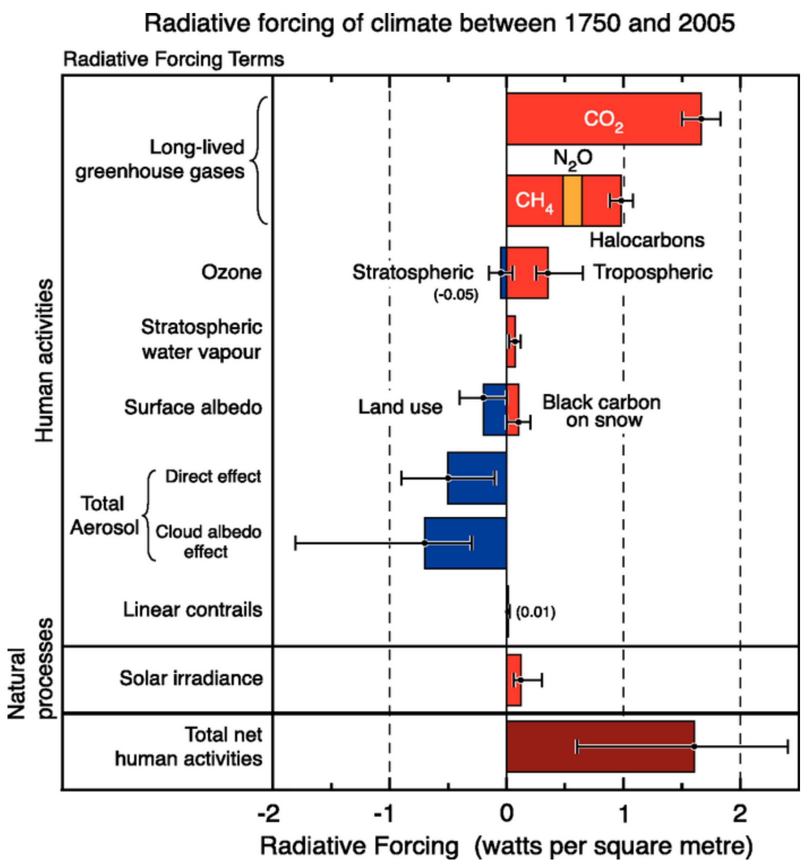
This chapter deals with brief descriptions of the most fundamental concepts needed to study trade-offs between CO_2 and black carbon: global warming, radiative forcing, climate sensitivity, aerosols, feedbacks, metrics, emissions scenarios and global climate models.

2.1 Global Warming, Radiative Forcing and Climate Sensitivity

Earth's atmosphere has the last couple of hundred years been subject to anthropogenic induced increasing levels of carbon dioxide and other atmospheric species affecting the radiative balance of incoming and outgoing radiation. The greenhouse gases absorb outgoing infrared radiation, while the aerosols impact the incoming solar radiation. Some of the aerosols decrease and some increase Earth's albedo (or reflection coefficient) which leads to an increase/decrease of solar radiation absorbed by the climate system.

Summing up the effects of all forcers affecting the incoming and outgoing radiation there is currently a small imbalance which the climate system is continuously trying to counteract by warming up. This imbalance is mainly caused by the steadily increasing level of carbon dioxide in the atmosphere. If the temperature would not have changed during the last couple of hundred years, then the value of the imbalance would have been around 1.6 W/m^2 (see Figure 1) (Solomon 2007). This energy imbalance is called radiative forcing (RF). The following figure from IPCC 4th assessment report presents their estimates of the magnitude and uncertainties of the climate forcers (as of 2005).

Figure 1. *Radiative forcing between 1750 and 2005 (Solomon 2007)*



The overall radiation from an object increases when the temperature increases. Radiative forcing is hence a measure of the heating needed by the system to restore radiative balance.

The total incoming solar radiation that is not reflected by the surface or the atmosphere is about 240 W/m^2 (see Equation 1) (Solomon 2007). The solar radiation changes on at least two different timescales. In cycles of about 11 years and on a greater time-perspective, of billions of years. On the long time horizon, billions of years, solar radiation has increased quite substantially (Harvey 2000) and it's still increasing to a small but not negligible extent.

Since there is no large source of energy within the Earth system the magnitude of the outgoing thermal radiation depends primarily on the absorbed solar radiation. In case of a temporary change of the abundance of molecules that interfere with the radiation (see 2.1.1) the Earth's energy budget can temporarily become unbalanced.

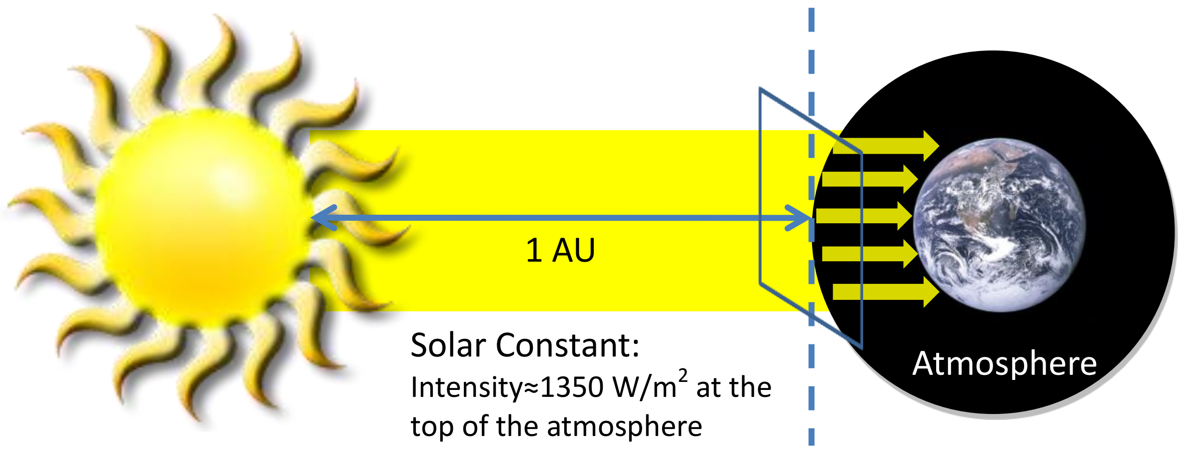
If we wouldn't have an atmosphere and a greenhouse effect the Earth would have been considerably much colder than it is today. The temperature would then approximately be described by Stefan-Boltzmann's law (see Equation 2).
For the Earth's climate system to regain radiative balance, this equation states that Earth needs to warm up. As the planet warms up, the outgoing thermal radiation increases.

$$Incoming\ solar\ radiation = (1 - albedo) * \frac{Solar\ constant}{4} \approx 240 \qquad \text{(Equation 1)}$$

$$Outgoing\ thermal\ radiation \approx \sigma T_{eff}^4 \qquad \text{(Equation 2)}$$

σ is the Stefan-Boltzmann constant and T_{eff} is the "effective radiating temperature" which is the temperature with which a black body would radiate as much as Earth does (Hottel et al. 1932). Note that T_{eff} can be calculated by setting Eq.1=Eq.2. A black body is an idealized object that absorbs electromagnetic radiation of all incoming wavelengths and reemits it in a continuous spectrum. The solar constant is a measure of the energy per square meter coming from the solar radiation that would hit a plane perpendicular to the direction of the sunrays placed at the top of the atmosphere at a distance that corresponds to the average distance between the sun and Earth (figure 2).

***Figure* 2.** *Solar Constant*

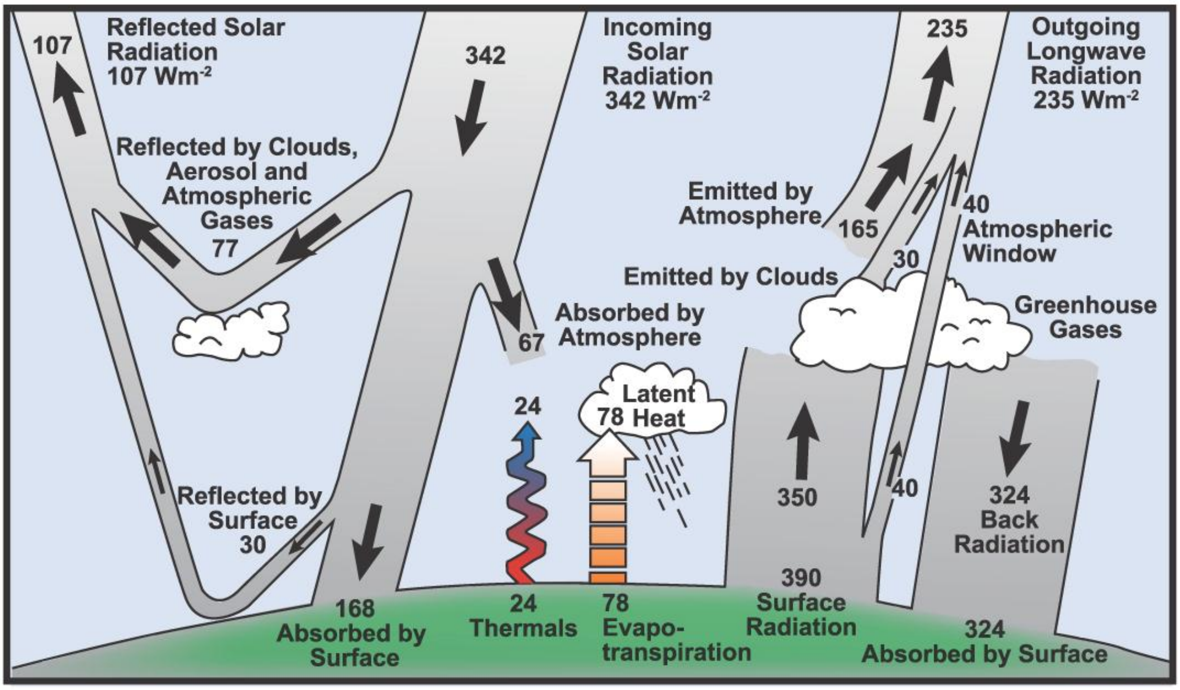


Climate Sensitivity (ΔT_{2xCO2})
Climate sensitivity is a term which states the expected equilibrium temperature change given a certain constant level of radiative forcing. It is commonly expressed in terms of a change in °C given a doubling of the atmospheric CO_2. The size of the ΔT_{2xCO2} is considerably uncertain. In the summary for policymakers IPCC has estimated the climate sensitivity to likely be in the range 2 to 4.5 °C with a best estimate at about 3°C (Solomon 2007). The explanation of the uncertainty lie partly in the fact that the climate sensitivity cannot be measured directly and partly in the uncertainties of which feedbacks (see 2.1.3) that will be operating and the magnitude of these.

See Appendix 2 Recommended Reading, for further reading on these topics.

2.1.1 Greenhouse Gases
CO_2 together with methane (CH_4), nitrous oxide (N_2O), ozone, halocarbons and water vapor are called greenhouse gases since they absorb and emit outgoing thermal radiation. For a technical but still illustrative description of how the greenhouse gases give rise to global warming see the article called Infrared radiation and planetary temperature by R. T. Pierrehumbert (Pierrehumbert 2011). The IPCC presents the quantitative effect of the greenhouse gases on the atmospheric radiation budget as in figure 3.

Figure 3. *The greenhouse effect and the atmospheric radiation budget (Solomon 2007)*



Note that the part of the outgoing long wave radiation (in the figure referred to as "Surface Radiation") that reaches space without getting absorbed is only a small fraction (40/390).

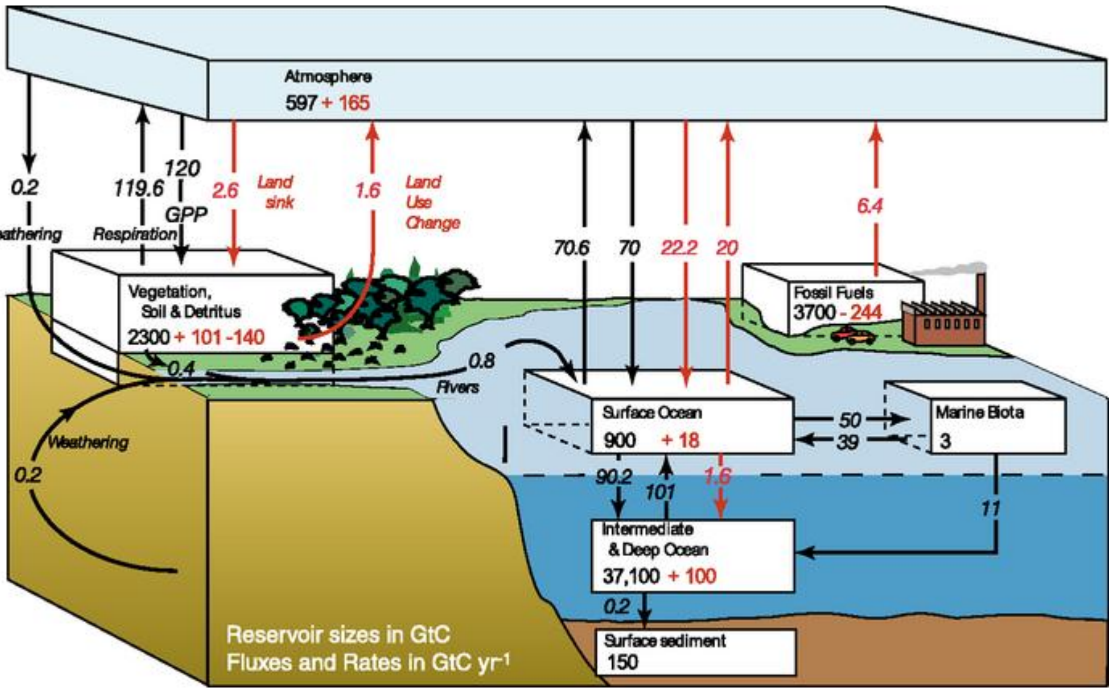
Carbon Dioxide and the Carbon Cycle

CO_2 is responsible for somewhat more than half of the positive radiative forcing from all of the long lived greenhouse gases.

The carbon on Earth is located in a large number of different places and chemical configurations. The different "forms" can, from a global perspective, be viewed as a limited number of reservoirs, which in different ways and on different timescales interact with the atmospheric CO_2 reservoir. Figure 4 by IPCC presents the most important carbon reservoirs and the annual fluxes between them (as of 1990). It is these fluxes that become perturbed when carbon dioxide is emitted into the atmosphere and it is this perturbation of the carbon cycle that results in higher atmospheric concentrations of CO_2 for centuries to come.

Section 4.1.1 contains short descriptions of the parts of the carbon cycle that the developed model explicitly takes into account.

Figure 4. *The different reservoirs and annual fluxes in the Carbon cycle (Solomon 2007)*



2.1.2 Aerosols

Alongside the greenhouse gases, anthropogenic aerosols play an important role in global warming. Aerosols are "a collection of airborne solid or liquid particles, with a typical size between 0.01 and 10 µm that reside in the atmosphere for at least several hours" (IPCC working group 1 glossary) (Solomon 2007).

Most aerosols, like sulfate aerosols (SO_x) have a negative radiative forcing and hence counteract the effect of the greenhouse gases while some, primarily black carbon aerosols, have the opposite effect (see Table 1). In common terms the cooling aerosols "mask the effect of global warming". This refers to the fact that SO_x based aerosols and other cooling agents hide a substantial amount of the global warming awaiting. The masking will most likely be reduced since the SO_x emissions are expected to decrease during the century as an effect of cleaner technologies and expected regulations.

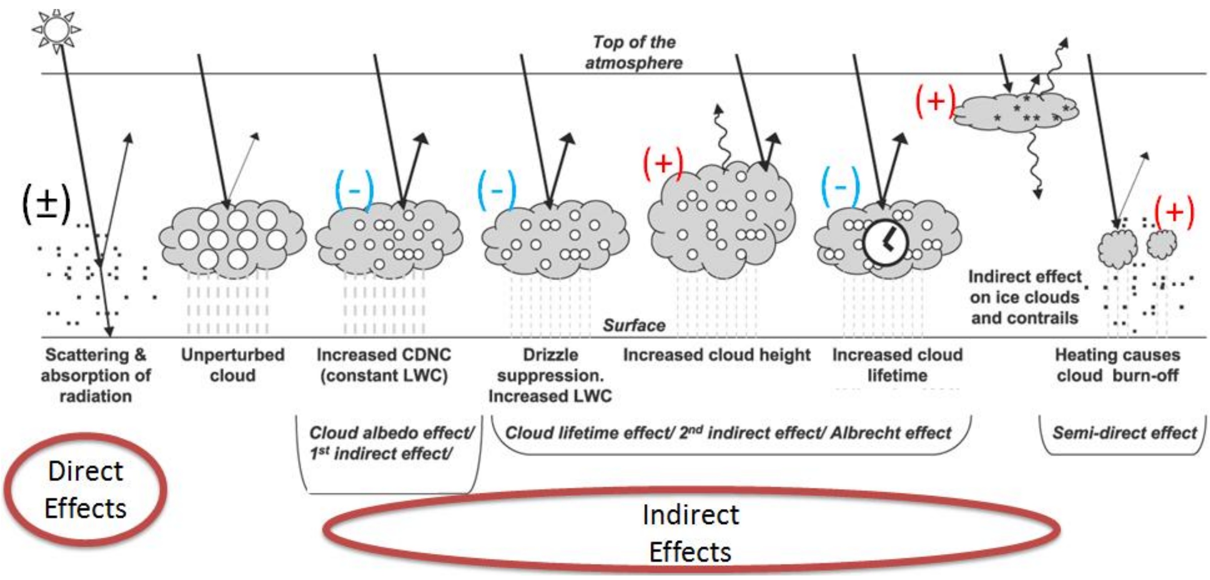
There are several mechanisms involved in the radiative forcing effects caused by aerosols. The aggregated effect of the radiative forcing imposed by these particles (labeled Total Aerosol[1]) can be found in figure 1. The primary, or so called direct, effect is through the absorption or reflection of the incoming solar radiation (see Table 1 and Figure 5). In this study the radiative forcing from the direct effect is estimated to be about 0.3 W/m^2 and the indirect effect on snow and ice albedo is of about 0.1 W/m^2.

Table 1. *Aerosols direct radiative forcing (as of 2005) (Meinshausen et al. 2011)*

Warming	**Radiative forcing 2005 [W/m^2]**	**Cooling**	**Radiative forcing 2005 [W/m^2]**
Black carbon	0.2	Sulfate	- 0.4
		Nitrate	- 0.1
		Organic carbon	- 0.2
		Mineral dust	- 0.1

The other effects, which alter the properties and abundance of clouds, are categorized as indirect effects. Figure 5 (modified from (Solomon 2007)) gives a schematic overview of the processes by which aerosols interfere with incoming radiation. As stated in figure 1, the central estimates of the radiative forcing from the direct- and indirect effects are -0.5 and -0.7 W/m^2 respectively (as of 2005).

Figure 5. *The direct and indirect effects on climate by aerosols[2]*



[1] Black carbon's effect on snow is however not included in this category.
[2] Modified from IPCC AR4 (Solomon 2007).

The anthropogenic sources of aerosols, excluding mineral dust, are to the vast majority different forms of combustion of fossil fuel, biomass and biofuel. NO_x based aerosols is partly an exception since it is also caused by the agricultural practice of nitrogen fertilization (Solomon 2007). Black and organic carbons' sources are described further in section 2.3.2.

2.1.3 Feedback Mechanisms

The concept of a feedback mechanism is that given a forcing of a system, a feedback mechanism either reinforces (positive feedback) or suppresses (negative feedback) the initial forcing as a result of the changes in the system that the initial forcing caused. An example of a positive feedback is the melting of glaciers and sea ice as a result of the increase of global mean surface air temperature: when the ice-covered surface area decrease the albedo also decreases since the surface under the ice and snow is darker and thus does not reflect as much of the solar radiation as the glacier does. A larger absorption of incoming solar radiation results in an even higher temperature and thereby reinforces the original forcing.

The most important positive feedback is that of water vapor which more or less doubles the warming effect of CO_2 (Solomon 2007) by increasing the atmospheric content of water vapor when the temperature is increased. The increase of water vapor in the atmosphere could itself cause a negative or positive feedback through changing the characteristics and abundance of clouds. How clouds will react to future climate is the greatest uncertainty amongst the feedbacks.

2.2 Metrics

The term metric is here defined as a method, scheme or in general any procedure which aims to put the effects of the different climate forcers on a comparable scale or unit. The purpose of doing so is to support decisions of policies which need a comparison of the effects of the forcing agents on the climate system.

Global Warming Potential (GWP)

GWP is a measure of the potential for global warming that an atmospheric species has in comparison to carbon dioxide over a specified time period. The value for carbon dioxide itself is hence by definition equal to 1, regardless of the time horizon. The GWP of a certain climate forcer for the time horizon X is calculated by integrating the radiative forcing caused by a pulse emission of the climate forcer and dividing that by the corresponding expression for carbon dioxide. The same mass is used for each species. It is the most widely used metric for climate forcers in global warming, used for example in the Kyoto Protocol.

Global Temperature Change Potential (GTP)

GTP is like GWP a measure of the climate impact by a climate forcer in relation to that of CO_2. However, it is not a measure of what happens during a certain time period in the same sense as GWP. Instead it expresses what temperature change, at the end of the specified time period, which can be inferred from the studied pulse emission.

Table 2 presents typical results of GTP and GWP respectively for BC and OC on different time horizons (Fuglestvedt et al. 2009) . The values are based on a pulse emission of one year of aerosol emissions and a climate sensitivity of 3.9 °C.

Table 2. *Metrics; GTP and GWP values for BC and OC (direct effect only) (Fuglestvedt et al. 2009)*

Metric	**GWP**			**GTP**	
Time horizon [year]	20	100	500	20	100
BC [C basis]	1600	460	140	470	64
OC [OC basis][3]	-240	-69	-21	-71	-10

The rapid decline of the values with increasing time horizon is a direct effect of the limited atmospheric lifetime of these aerosols in comparison to that of carbon dioxide. For GWP, the difference between the value produced by the metric on the two time horizons 20 and 100 years, indicate that the significance of BC is regarded to be about 70% lower on the longer time horizon. The corresponding feature is true for GTP, which gives an 85% lower value for BC on the time horizon of 100 years. The same trend is true for OC.

2.3 Black and Organic Carbon

Carbon aerosols[4] fall into two, for this study relevant, categories: light-scattering organic carbon, and light-absorbing black carbon. Both of these aerosol types are formed through incomplete combustion of organic materials[5] (more on this in 2.3.2).
Absorption of light contributes to a direct positive radiative forcing and BC is thus the name for the category of carbon aerosols that contributes with direct positive RF. In contrast to BC the OC aerosols have a direct negative radiative forcing due to their light-scattering properties (Kopp et al. 2010). Some of the radiative properties of the different carbon aerosols depend on the degree of mixing with other aerosols (Kopp et al. 2010). Besides these direct effects on the incoming solar radiation, the aerosols are involved in a number of indirect mechanisms that have considerably large and uncertain contributions to the Earth's overall radiative forcing (see Figure 1 and Figure 5). The emissions of different aerosols with their different effects on radiative forcing (direct and indirect), makes the question of aerosols impact on the climate utterly complex.

2.3.1 Black Carbon's Radiative Forcing Characteristics

Black carbon aerosols affect the total radiative balance in many ways, of which some are more certain than others. BC affects the global RF by the following mechanisms: Absorbing solar radiation, changing ice and snow albedo, changing cloud albedo, as cloud condensation nuclei (affecting cloud formation and cover). The absorption of solar radiation affects the climate in at least two ways; by warming the air that

[3] A ratio of particulate organic matter to organic carbon was assumed to be 1.4 (Fuglestvedt et al 2009)
[4] Also referred to as carbonaceous aerosols. These particles typically have complex structures and contain other elements besides carbon as well.
[5] Organic carbon is hence in no sense "more organic" than black carbon. It can be argued that a more suiting name for organic carbon would be "white carbon" or "reflective carbon".

surrounds the particle and by dimming the ground (i.e. reduce the amount of solar radiation that reaches the surface) (Fuglestvedt et al. 2009).

Table 2 above provides a per unit (on carbon basis) mass comparison of the strength of the influence on climate that BC particles has to that of carbon dioxide. From here on black carbon's RF will refer to a summation of both the direct effect and the effect BC has on snow and ice.

2.3.2 Sources of Black and Organic Carbon

Black carbon and organic carbon have several sources in common and are thus frequently emitted simultaneously (Bond et al. 2004). The ratio of the two pollutants varies between sources. For forest fires for example the OC/BC ratio is high while for diesel combustion the ratio is low. This results in a likely net negative RF for open biomass burning (Kopp et al. 2010).

Bond et al. (2004) found the following distribution among sources for the BC emissions of 1996: 38% fossil fuel, 20% bio fuel and 42% open biomass burning. The corresponding values for OC were 7%, 19% and 74% for the same sources. Although the values are not up-to-date, they represent the best estimates (to our knowledge) of the sources behind the about 8 Mt BC emitted. "The total uncertainties are about a factor of 2" (Bond et al. 2004).

It should be noted that bio fuel includes wood, agricultural waste, animal waste, and Charcoal. For an illustrative example of source for each category see figure 6.

Figure 6. *Examples of Black carbon sources*

Examples of BC and OC sources: Diesel vehicles, slash and burn and dried cow dung cakes.

The distribution of BC and OC pollution per capita is not far from even, however Africa has a substantially higher average pollution than the rest of the world (Bond et al. 2004). The geographical distribution of BC emissions is of importance for its deposition on snow and ice as well as its exposure to solar radiation.

2.3.3 Uncertainties about Black Carbon

The uncertainties are widespread. They range from the size of past and current emissions, to the geographical distribution of emissions, to BC atmospheric lifetime, to BC lifetime when deposited on snow or ice and to the details and the characteristics of the different mechanisms by which BC contribute to radiative forcing.

As for the size of the emissions: A range of 4.3–22 Mt BC/year was estimated by Bond et al. (2004). The geographical distribution varies to a similar extent, so that the estimated emissions of, for example, India lie within a range of 0.36-1.26 Mt BC/year (Bond et al. 2004). Black carbon's atmospheric lifetime is considered to be somewhere between a couple of days and a few weeks (Rodhe et al. 1972), while its lifetime on snow and ice, although largely unknown, is typically assumed to be in the order of half a year (Randerson et al. 2006).

An example of a source of uncertainty, when it comes to the radiative forcing of BC, is its role as a cloud condensation nuclei which affects how cloud droplets form and evolve. This is a key feature of black carbon's effect on clouds. All in all the uncertainty of the radiative forcing from BC is greater than a factor of 2 with best guesses typically falling in the range 0.1-0.8 W/m^2.

2.3.4 Reduction of Black Carbon as an Alternative to CO_2 Mitigation

Reducing black carbon emissions gives a decrease in radiative forcing and so does reducing the CO_2 content of the atmosphere. This section lists some key issues related to the difference between reducing CO_2 and BC in despite of the fact that the same reduction in radiative forcing might be obtained at a certain point in time.

The following aspects play an important role: (1) CO_2 in the atmosphere has a long lifetime while BC has a much shorter life time, (2) time horizons, (3) metrics, (4) inertia of the socio-technological system, (5) the global means versus regional variation, (6) the carbon cycle, (7) political factors, (8) health co-benefits of reducing BC.

(1) Black carbon is removed virtually immediately from the atmosphere when the emissions are cut, while for CO_2 this is not true. Instead a substantial amount of the previously emitted CO_2 (as explained in the introduction) stays in the atmosphere producing an increased radiative forcing for decades, even centuries to come. Perhaps more importantly: constant emissions of BC give a constant RF while constant emissions of CO_2 gives an increasing RF, since the CO_2 concentration builds up while BC does not.

(2) This naturally brings up the aspect of the different time horizons. There are several time horizons or aspects of time that are of importance when it comes to the trade-off between BC and CO_2: the lifetimes of the two radiative forcers, the time it takes the climate system to respond to a forcing and the time horizon chosen for climate targets.

(3) The choice of metric is intimately connected to these time horizons and the goal of the targets. For example GWP will take into account the radiative forcing during the

entire time period up until its chosen end (time horizon), while GTP will only look at the temperature change at the end time.

(4) It takes time to change the energy system, stop deforestation, change social habits and in general reduce our net CO_2 emissions. If the majority of measures taken, in order to reach a certain climate target, are focused on short lived climate-forcers, then the technologies in use, the habits of society and contemporary emission levels will likely be in line with a path for the future with more difficulties in keeping the temperature down.

(5) Since carbon dioxide is a well-mixed gas with a long life time it does not really matter where it is emitted. Black carbon, on the other hand, has a short life time and has a definite regional impact because it does not reach certain areas before it is removed from the atmosphere by wet- or dry deposited (Ramanathan et al. 2008). The precipitation patterns, as well as the occurrence of ice and snow (in particular glaciers), of the areas in which BC is emitted will also affect the actual radiative forcing per unit of mass emitted. In areas with large precipitation the particles will reside in the atmosphere for a shorter period of time. I.e. the radiative forcing due to black carbon emissions depend on where it's emitted while that is not the case for CO_2.

(6) Since a trade-off between BC and CO_2 emission reductions may influence the cumulative amount of CO_2 emitted, as well as the CO_2 concentration in the atmosphere, it will affect the carbon cycle. The "CO_2-saturation" of the oceans, and thereby the degree by which future emissions will be absorbed by the ocean, will be affected.

(7) It is easier to reduce an emission that is not in a "strong" sense connected to the profit of certain stakeholders. In the Economist (Feb 17, 2011) the following could be read: "doing something about these short-lived forcings is easier than tackling carbon dioxide. Since carbon dioxide is an essential by-product of burning fossil fuels, controlling it is a big economic issue". This is true since BC emissions is to a larger extent an avoidable waste product. This along with the health-issues associated with black carbon makes it easier for politicians to undertake measures to reduce emissions of BC rather than CO_2.

(8) When dealing with real world issues, they are often intertwined with other issues. Reducing black carbon emissions is a good example. It can hence be argued that the health-issues of BC emissions, in some way, should be accounted for when calculating and comparing the benefits of reducing BC emissions to CO_2 emissions. On the other hand, current CO_2 emissions lead to a seemingly unprecedented acidification of the oceans, which in the long-run may threaten marine ecosystems (Raven et al. 2005).

2.4 Historical Emissions & Emissions Scenarios

The historical concentrations as well as the emissions scenarios used in this study are taken from the RCP series. There are 4 RCP scenarios: RCP3PD, RCP4.5, RCP6 and RCP8.5. RCP3PD is short for Representative Concentration Pathways, giving rise to a radiative forcing of 3 W/m^2, Peak and Decline (Meinshausen et al. 2011) . The peak in this case occurs at the year 2045.

The Task Group 'RCP Concentrations Calculation and Data' concludes that it has "harmonised and consolidated greenhouse gas concentration and emission datasets for the pre-industrial control runs, 20th century, and the Representative Concentration Pathways (RCPs)".

2.5 Global Climate Models

Climate models are built on varying levels of abstraction with varying complexity and varying detailed accounting for the mechanisms governing the global climate. The simplest one is a 0-dimensional model excluding feedbacks corresponding to setting the energy of the absorbed incoming solar radiation equal to the energy of the emitted outgoing thermal radiation (i.e. setting Equation 1 equal Equation 2 in Section 2.1). While a fully equipped climate model, such as the HadCM3 used by the IPCC, is an Atmospheric-Oceans General Circulation Model (AOGCM) "representing physical processes of the atmosphere, oceans, cryosphere and land surface" (IPCC 2009).

Different categories of models serve different purposes, ranging from merely pedagogical illustrations of the Earth's climate system to models aiming at describing and or predicting the climate on global and regional scales for our history, today and the future. Within the category of models simulating the future climate there are also a vast variety of models, besides the simplest and the most advanced models there is a series of models trying to capture certain aspects of the climate system and put them in a simpler or more convenient framework. Examples are MAGICC (Wigley et al. 1997), an Upwelling Diffusion Energy Balance Model (UDEBM) that capture dynamics of advanced 3D OAGCMs, and the Chalmers Climate Calculator (Azar and Johansson, 2011) that in turn is even simpler than MAGICC.

The aim of the models, that do not go into detailed calculations of the different parts of the climate system or its interactions with different of the Earth's subsystems, can vary but is typically to offer a model which is less computationally heavy and/or intuitive to use. A model that is less computationally heavy and thereby possibly much faster offers the possibility to manage large numbers of simulations. This makes it possible to test many different hypotheses and to perform sensitivity analyses.

3. Objective

The main objective of this study is to build a model and use it to examine trade-offs between mitigation of carbon dioxide and black carbon.

For this thesis we limit the attention to physical based indicators (see Section 2.2) and leave economics based metrics aside. The indicator that will be of primary focus is the maximal cumulative emissions of CO_2 by 2100, compatible with a 2 °C climate target[6]. Its dependence on the emission pathways and radiative forcing characteristics of black carbon will be examined.

Problem Formulation

Main question:
To what extent is it possible to affect the cumulative emissions of CO_2 compatible with a specific climate target by reducing black carbon emissions?

A question which develops the main question further is: How should the timing of CO_2 peak emissions and the rate of CO_2 emissions reductions be chosen, for a given BC scenario, in order to maximize the amount of emitted CO_2 up to 2100 for the specified climate goal (a limit of the global average surface temperature increase by 2 °C above the pre-industrial level). The emissions scenarios follow a RCP scenario. For CO_2 emissions follow the same RCP scenario but they are modified to turn into a scenario with an annual percentage wise decrease of emissions from a chosen peak year.

As mentioned in the introduction (Chapter 1) there is currently an enhanced interest from policy makers and others in utilizing reductions of short lived climate forcers, such as black carbon, in order to reduce anthropogenic climate impact.

Meanwhile several recent research papers have shown that there is a strong correlation between cumulative emissions of CO_2 and global average surface temperature change (Allen et al. 2009; Meinshausen et al. 2009). This correlation is due to the long lifetime of CO_2 in the atmosphere and the inertia of the climate system (caused mainly by the large heat capacity of the world's oceans). With these two perspectives we want to investigate to what extent substituting CO_2 abatement with abatement of BC could lead to increased cumulative emissions of CO_2 (given that a two degree climate target should be met).

[6] A limit of the global average surface temperature increase by 2 °C above the pre-industrial level.

4. Method

A reduced complexity coupled carbon cycle climate model is developed and by using it the global mean surface temperature is calculated. The input the model has is the history followed by scenarios of yearly emissions for the major atmospheric climate forcers along with black and organic carbon (see Figure 7).

We take the carbon cycle and the heat capacity of the oceans into explicit account. Further integrated components of the model calculate the atmospheric levels of CH_4 and N_2O and the subsequent radiative forcing of these gases. The radiative forcing of carbon dioxide and the selection of climate forcers specified by the user are then calculated and used to derive the temperature response. The temperature which is defined as the maximum temperature for a simulation is the average temperature over a period defined by the year which had the highest temperature ±5 years[7] up until 2100. We stop the model simulation at 2105 in order to be able to attain an average around 2100.

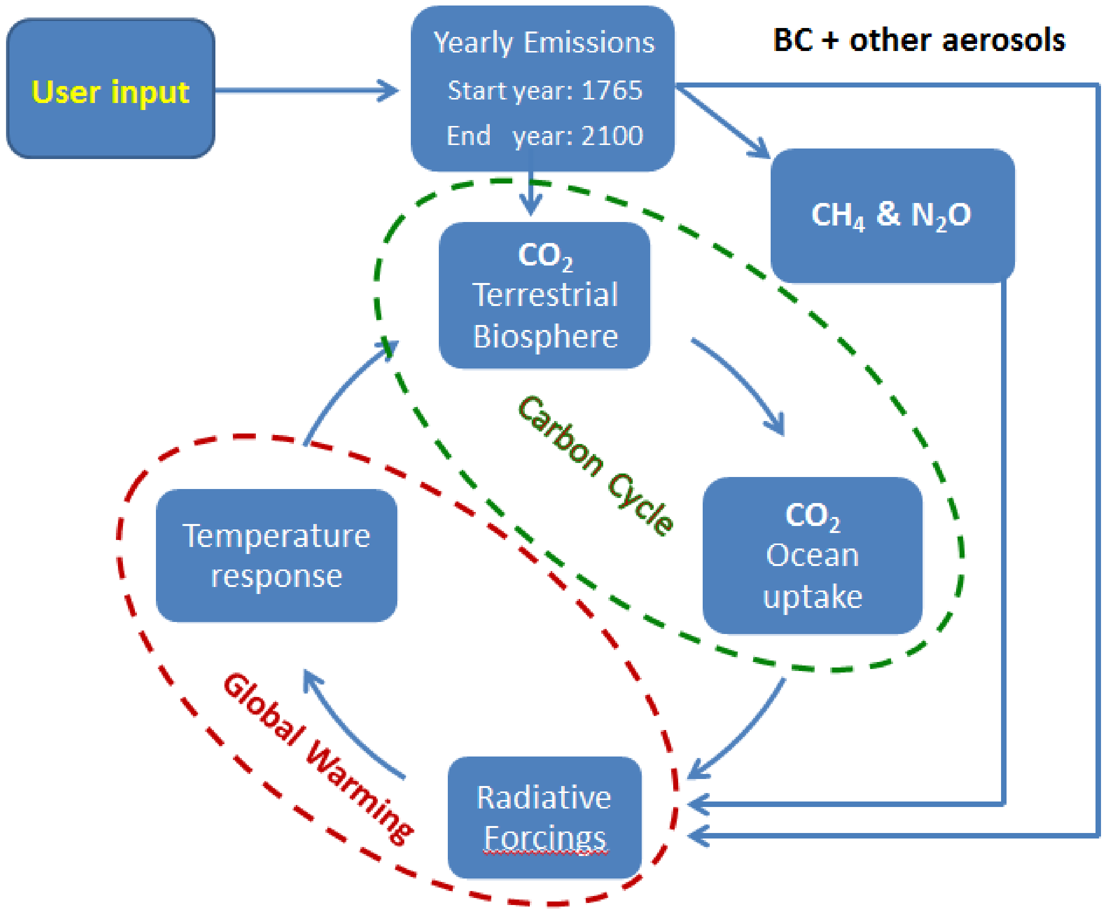
The model produced is called: Physical Prediction Model for Future Radiative forcing and Temperature (PPM-FRT). For a schematic description of the model see figure 7 in section 4.1.

[7] By this we get a maximum temperature value that is independent of variations in incoming solar radiation.

4.1 PPM-FRT: "Physical Prediction Model for Future Radiative Forcing and Temperature"

The basic outline of this model is illustrated in figure 7 below. A majority of the components of PPM-FRT are new and modified implementations of models described by D. Harvey (Harvey 2011). The components allowing for customized black and organic carbon emission scenarios as well as the coupling of the models and the graphical user interface are, however, novel (a user manual is presented in Appendix 3).

Figure 7. *Schematic representation of the PPM-FRT model*



This model outline illustrates the connectivity of the core parts of the model. The end year 2100 displayed here is only an example, it can be chosen from 2005 to 2500.

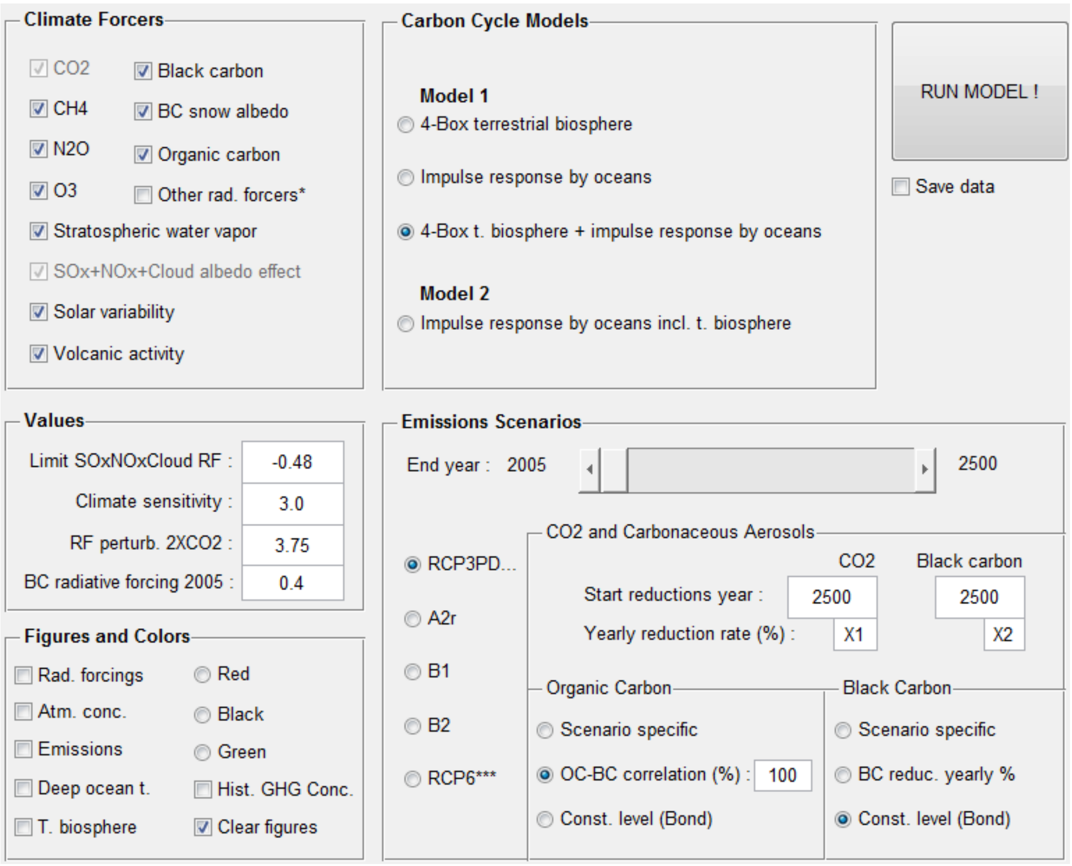
4.1.1 The Components of PPM-FRT

PPM-FRT consists of the following set of coupled components or modules: a graphical user interface, yearly emissions, a model of the atmospheric levels of CH_4 and N_2O, a terrestrial biosphere model, a model of the oceans' absorption of CO_2, a model to calculate the radiative forcing and at last a model of the temperature response. The modules will now be presented one by one (followed by some concluding remarks on their couplings). For the models' key governing equations see Appendix 4.

User Interface

The user interface (figure 8) allows the user to specify the time horizon, choose which of the implemented carbon cycle models and which of the climate forcers to include. In addition, it offers a series of emission scenarios[8] to choose from, possibilities to manually construct scenarios focusing on BC, OC and CO_2, some certain characteristics of the climate system to set and ways to illustrate the simulation results.

Figure 8. *The user interface with the default settings.*



Yearly Emissions

Given input from the user interface this model produces series of yearly emission data for the climate forcers included. The data sources for the emissions are from the representative concentration pathways (RCPs) presented in section 2.4 (Meinshausen et al. 2011) and from (IIASA, 2011) for the A2r, B1 and B2 scenario (see footnote 8). Historical (1765-2005) emissions are always the same, taken from the RCP series.

The yearly emissions, when simulating the future climate, can be chosen to follow one of five emission scenarios which in turn, for BC and CO_2, can be modified to have a specific peak year followed by a percentage wise decrease. A chosen decrease of BC emissions can be specified to produce a correlated decrease in OC emissions (from 0 to 100% correlation). The organic carbon emissions can also be set to be constant or to follow the current scenario.

---

[8] For A2r, B1 and B2 emissions of CO_2, N_2O, CH_4 and BC are employed. Complementary data for these scenarios is taken from RCP3PD.

Imposing a decrease on the CO_2 emissions is, however, assumed to always equally affect the radiative forcing from direct and indirect effects of SO_x and NO_x based aerosols[9] (the indirect effect is also referred to as the cloud albedo effect, see Figure 5). This equal reduction follows the falling CO_2 emissions until a limit value on their summed RF is reached. The user specifies this value in the user interface (see values in Figure 8). For simplicity, there has not been any lower bound set on the proportion of emissions from BC, CO_2 and OC that can be reduced in the model.

Some other climate forcers, such as the CFCs, are optional to include in simulations (via the user interface). Those included are those specified in the RCPs. They are included by adding their mid-year radiative forcing from RCP3PD to the RF produced by the individually modeled climate forcers mentioned above.

Methane (CH_4) and Nitrous Oxide (N_2O)

This component estimates the evolution of the atmospheric concentrations of CH_4 and N_2O given the yearly emissions paths of the greenhouse gases. Their stocks in the atmosphere are modeled with exponential decay functions. The atmospheric lifetime of nitrous oxide used is 114 years (Solomon 2007) while the atmospheric lifetime of methane depends on the contemporary atmospheric level of methane. Methane's lifetime is calculated for each year as a function of the last year's CH_4 concentration and the resulting average lifetime varies from 6.5 to about 8 years. The abundance of stratospheric water vapor and ozone (O_3) are, as an approximation, modeled in direct proportion to the atmospheric concentrations of methane (Solomon 2007).

Terrestrial Biosphere Model

In the default mode of PPM-FRT the terrestrial biosphere is modeled as a so called four-box model. The different boxes, or carbon-reservoirs, are: soil carbon, detritus, woody biomass and leafy biomass. The model simulates the annual flows between the boxes dependent on the current CO_2 concentration, the temperature and the quantities of carbon in the different reservoirs (i.e. the different boxes). This model was implemented in direct accordance to a model described by D. Harvey (Harvey 2011).

Oceans Absorption of CO_2

For each annual emission the absorption by the oceans of the emitted CO_2 is modeled by the use of impulse response functions and convolution (Maier-Reimer et al. 1987). As a numerical approximation the emissions are regarded as if they were split into five fractions with different lifetime. The model treats the different fractions as exponential decay functions with different time-constants. How much of the marginal emissions that goes into each fraction depend on the amount of CO_2 that has been added to the atmosphere through anthropogenic activities.

Determining the portion of CO_2 left in the atmosphere a certain year is done by adding the responses from the preceding years' "pulses of emissions". The oceans have a tendency to become saturated with CO_2 as the cumulative emissions increase. This is the reason for the dependency, mentioned above, which results in the oceans absorbing proportionally less and less of the emitted CO_2.

[9] These forcing agents are treated as a sum. The RCP3PD data of their RF is used consistently.

Radiative Forcing

The radiative forcing is calculated based on the different atmospheric concentrations of the greenhouse gases and the yearly amounts of emitted aerosols. For example an increase in CO_2 is assumed to give a logarithmically increasing radiative forcing (see Equation 3), with a doubling of CO_2 giving rise to a best guess of 3.75 W/m^2.

$$RF\ CO_2 = 5.35 * \ln\left(\frac{pCO_2}{p_0CO_2}\right) \quad \text{(Equation 3)}$$

The radiative forcing from a doubling of CO_2 (3.75 W/M^2), as well as the value of BC RF by the year 2005, can be simulated to be of different sizes, set by the user (in the user interface).

The so called indirect effects, produced by aerosols, are for simplicity assumed to be caused only by the SO_x and NO_x based aerosols and not by black and organic carbon.

Radiative forcing is, in line with IPCC's findings, assumed to be additive (Ramaswamy et al. 2001; Solomon 2007). The formulas for the radiative forcing produced by the other climate forcers can be found in Appendix 4. See figure 1.c in Appendix 5 for an example view of the radiative forcing levels produced by the model in a default simulation.

Temperature

The model in use for the global temperature is a so called two-box, energy balance model. It has two boxes in the sense that the atmosphere and the surface water are considered as having one global mean temperature and the deep oceans having another. The temperature change for a given amount of RF at a specific moment in time is a function of the climate sensitivity, the heat capacity of the two boxes and the flow of heat between them.

The flow of heat between the surface and the deep water is modeled as dependent on the difference between the temperature in the two boxes and a given amount of mass exchange. The heat flux becomes larger when the temperature gradient is larger. See figure 1.b in Appendix 5 for an illustration of how the temperature in the two boxes develops under an example scenario[10].

[10] The deep ocean temperature is an optional setting in the user interface.

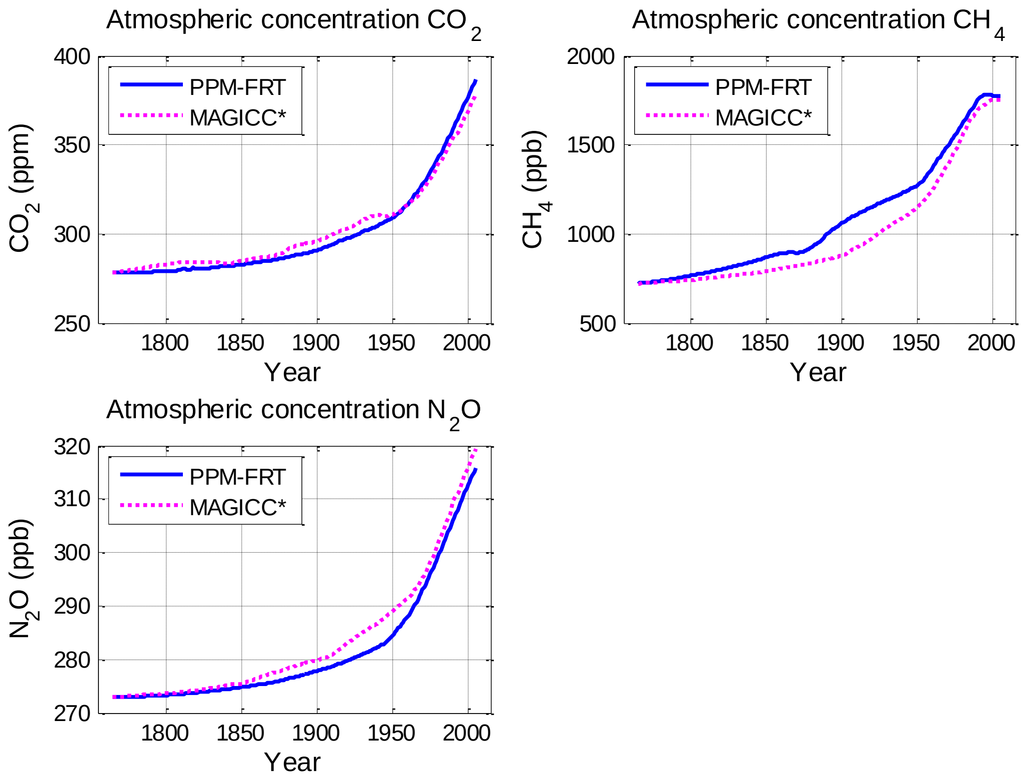
4.1.2 Testing, Calibrating and Validating PPM-FRT

Calibration and validation of the model is performed through a series of tests and comparisons. The first category of tests is of an intra-model character, in which the different parts or modules of the PPM-FRT have been unit-tested. The unit tests controls if the module performs as intended and as expected. For example: perturbations of the different parameters yield simulation outcomes that are affected in an expected way, or at least in a way that can be understood. The components[11], which are implemented according to Harvey's descriptions (Harvey 2011), reproduce the outcome of example simulations performed by him.

Calibration is performed by running PPM-FRT and adjusting some of the "model parameters" to make the results fit historic data. These parameters deal with the overall radiative forcing from aerosols. The fit to historic data is made with regards to the different atmospheric concentrations of the most important GHGs and the global average temperature.

Validation of the model is performed by studying the performance of the model in comparisons with other models and also by comparing its results with historical data. The comparison with historical data is done by studying both long term trends and short term swings caused for example by a volcano erupting. See figure 9 for an example comparison between models, of the three GHGs: CO_2, CH_4 and N_2O.

Figure 9. *Comparing simulated GHG conc. in PPM-FRT and MAGICC*[12]



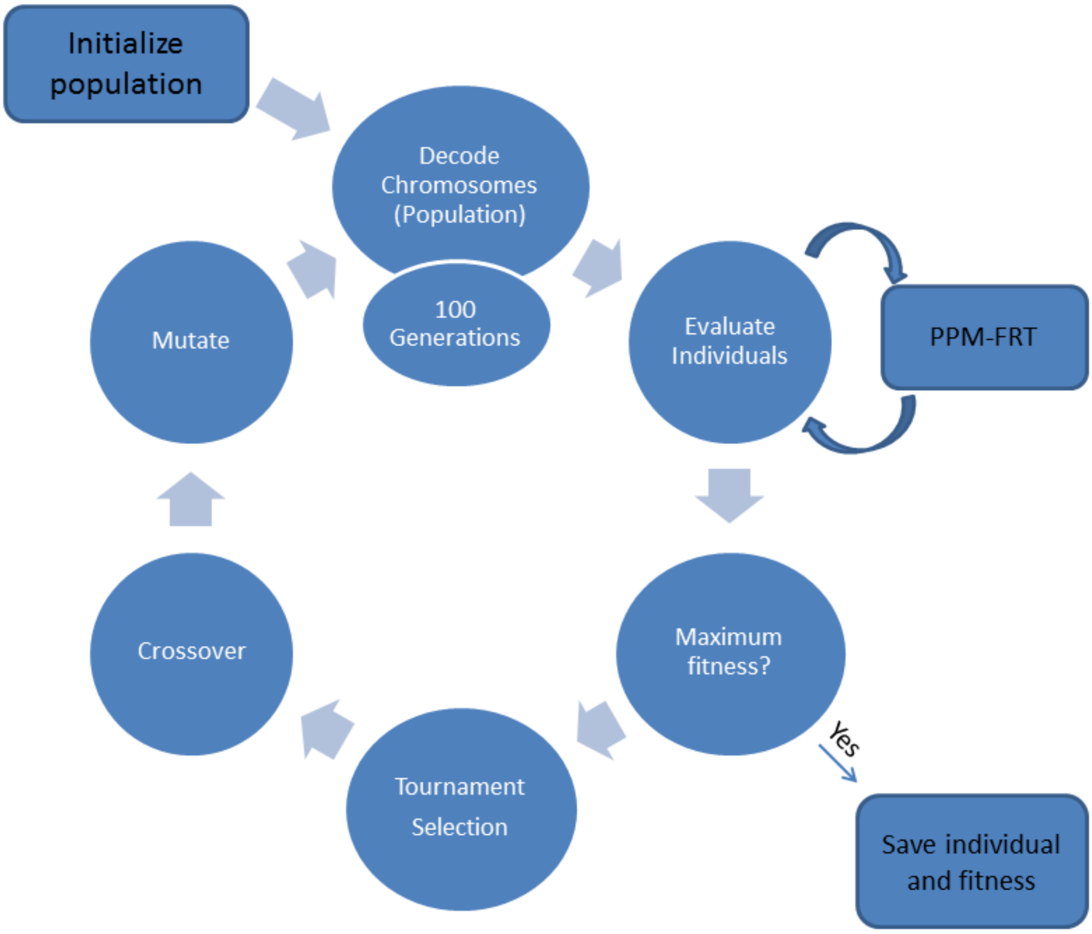
Comparing PPM-FRT's simulated historical atmospheric concentrations of three main GHGs with that of MAGICC for the RCP3PD emissions (Meinshausen et al. 2011).

[11] The carbon cycle, the model for CH_4 and N_2O, the radiative forcing of some climate forcers and the temperature model.
[12] MAGICC-VERSION: 6.3.09, 25 November 2009

4.2 Maximization through a Genetic Algorithm

A genetic algorithm (Wahde 2008) (see Figure 10) is deployed in order to address the main question of the thesis: “How should the timing of CO_2 peak emissions and the rate of CO_2 emissions reductions be chosen, for a given BC scenario, in order to maximize the amount of emitted CO_2 up to 2100 for the specified climate goal”. A genetic optimization algorithm is a biologically inspired stochastic algorithm that uses the concepts of selection, inheritance and mutations in order to find optimal values of a chosen fitness function.

Figure 10. *A schematic illustration of the genetic algorithm*



The theory behind the genetic algorithm is that it is possible to simulate the way organisms develop over time by mixing and perturbing characteristics, which enables it to fulfill specific goals. The characteristics are passed on in the form of “genetic code” (i.e. a specific combination of parameter settings). This simulation which offers a way to automatically chose favored characteristics, for example of a solution to a problem, mimics the natural selection process which has been going on for billions of years. A thorough description of the model can be found in the book Biologically Inspired Optimization Methods by M. Wahde (Wahde 2008).

5. Results and Analysis

In this chapter the simulations performed, the results and a first analysis of them will be presented.

The purpose of the experimental simulations in this thesis is to optimize the timing of start- and rate of emissions reductions to meet a certain temperature target, under varying climate and emission settings. The target studied is a limit of the global average surface temperature increase by 2 °C above the pre-industrial level. The settings that are varied, in looking at effect of the trade-off between CO_2 and BC on cumulative carbon dioxide are:

- Climate sensitivity
- BC radiative forcing
- Correlation between BC and OC emissions[13]
- BC start of emissions reductions and emissions reduction rate
- CO_2 start of emissions reductions and emissions reduction rate

The experiments are performed in four series of simulations:

1. Effects of black carbon on the temperature
2. Temperature response as a function of different climate characteristics
3. Maximizing the cumulative emissions of CO_2
4. Policy relevant emission scenarios

The first round of experiments covers two series of simulations in which the effect of black carbon on the temperature was studied alone. The second round of experiments consists of systematically testing different variable values by varying the corresponding parameters systematically in a wide range. By this we try to identify the ranges of parameter values which produce temperature changes close to the target. In the third round the timing of peak emissions and the rate of emissions reductions, of CO_2 and BC, are optimized.

The maximization is performed using a genetic algorithm, given a constraint on the global average surface temperature to 2°C above the pre-industrial level. In the final set of experiments the start of emissions reductions and the rate of emissions reduction for BC is viewed as interesting policy options and thereby studied specifically. These simulations basically investigate the effect of not doing anything (no reductions) about black carbon, or initiating BC mitigation work now (starting 2020) or later (starting 2060).

In the sections 5.1 and 5.2 we will now present the results and a first analysis of them. The temperature response and the cumulative CO_2 emissions up to the year 2100 will be

[13] The correlation between the two aerosols is for simplicity modeled as complete or non-existing. For the case of no correlation, the emissions of organic carbon is assumed to be constant.

used as indicators throughout. Results from a standard simulation are found in Appendix 5.

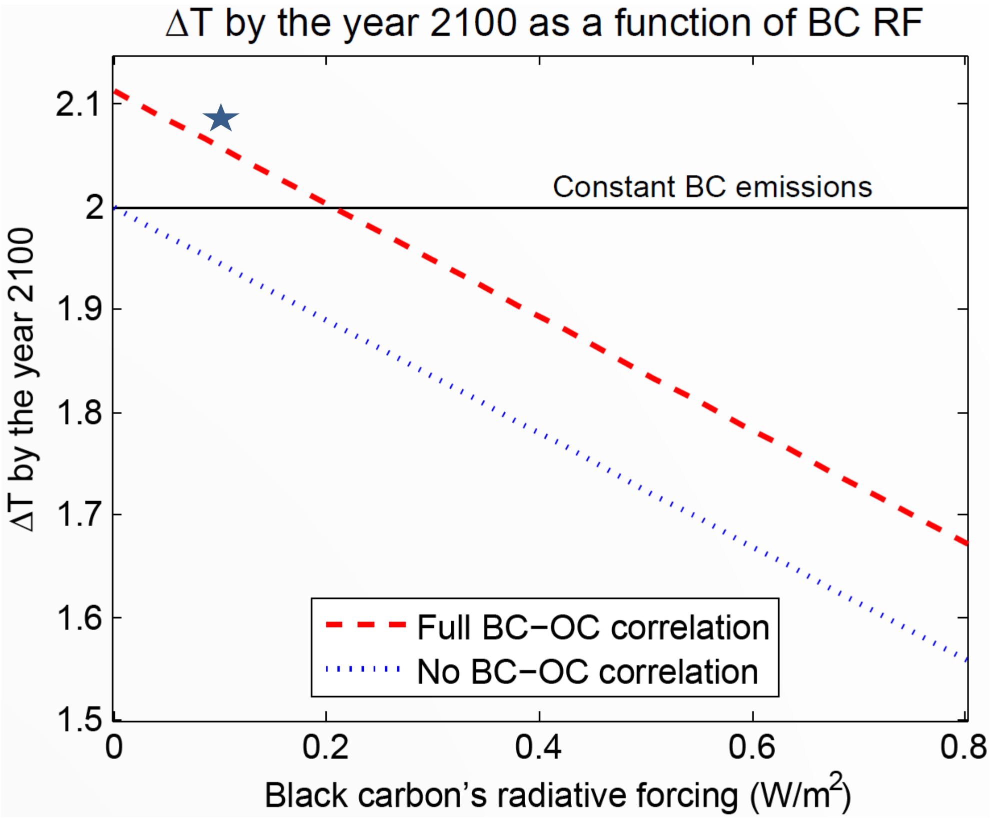
First we present two series of simulations in which the effect of black carbon on the temperature was studied alone. These simulations were followed by a large number of simulations conducted to find the combinations of variable values which gave maximum temperature responses in proximity to 2 °C up until 2100. The relevant intervals of the variables' values were then studied further using an optimization algorithm and by investigating selected plausible policy options.

5.1 Effects of Black Carbon on the Climate System

This section will present the results from two sets of simulations. The two experiments aim to estimate the impact BC could have on the temperature response by the year 2100[14]. A climate sensitivity of 3 degrees has been used in both experiments.

The first experiment[15], in which ambitious mitigation of black carbon is introduced (ambitious mitigation is defined as 4% yearly reduction from 2020), the effect of BC abatement is determined to be in the range of +0.03 to -0.43 °C. The range depends on the strength of BC radiative forcing[16] and the correlation between reduced emissions of black and organic carbon (in the case of no correlation, the OC emissions are assumed to remain constant). Figure 11 demonstrates this linear relationship for the case with and without a full correlation between BC and OC emissions reductions.

Figure 11. *Effects BC radiative forcing on a modified RCP3PD (see footnote 15)*



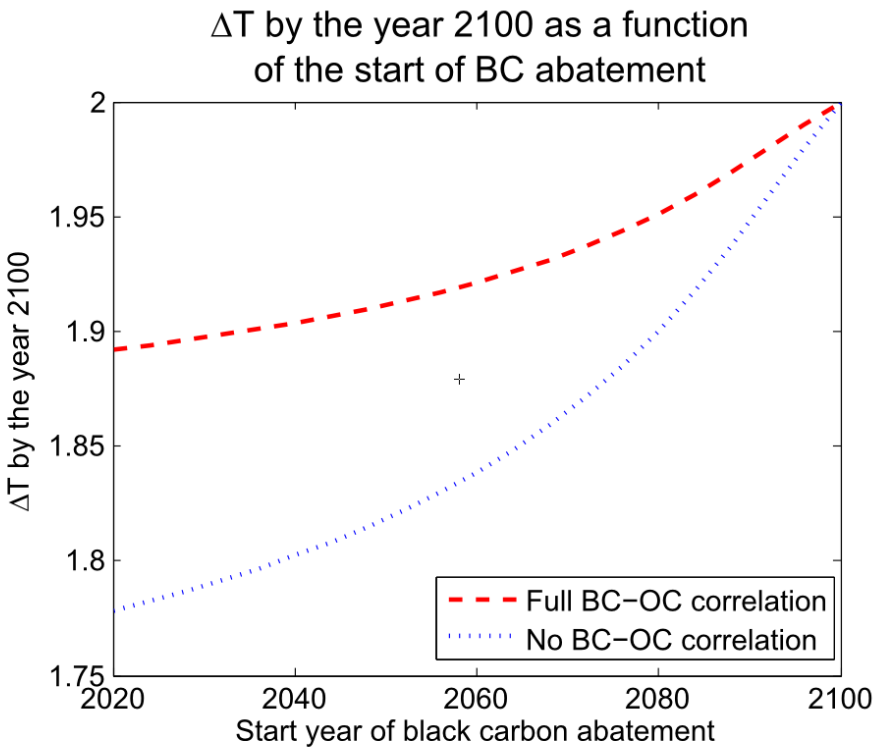
[14] The temperature which is presented in Section 5.1 is always taken as an average around the year 2100.
[15] The background emission scenario is chosen so that it would meet a 2 °C climate target 2100. The scenario is RCP3 except for CO_2 which is from RCP45 until 2025 followed by a 3.0% annual reduction.
[16] BC RF 2005, incl. both the direct effect and the indirect effect BC has (lowering snow and ice albedo).

The reason that the value of ΔT can become larger than in the case of constant BC emissions (see★ in Figure 11) is due to a combination of two assumptions. The first is that the radiative forcing of black carbon in that region is assumed to be lower than the absolute value of the cooling RF from organic carbon and the second is that reduction of BC emissions is assumed to be followed by an equal reduction in emissions of organic carbon. Together these two result in a reduction of a combination of aerosols that was in total masking the global warming. This leads to a small warming.

An increase of the total radiative forcing of BC should lead to a warming of the climate. There is however a central assumption that strongly affects what happens in the model when BC RF is increased, which needs to be emphasized. In order for the modeled historic temperatures to fit historic data, when the estimate of BC RF is changed, a counteracting force needs to be introduced. This counteracting force is modeled by adjusting the direct and indirect RF from SO_x and NO_x based aerosols. I.e. when BC is modeled to have a higher radiative forcing, the SO_x and NO_x aerosols are modeled to contribute with a larger negative RF which compensates for this and puts the overall radiative forcing from aerosols intact.

The second experiment which has a similar background scenario (see footnote 15), but in which the radiative forcing is kept fixed at the central value with varying start of reduction of BC, produces resulting ΔT by 2100 lying within the range of 0.0 to - 0.22 °C (see Figure 12).

Figure 12. *Effects of the start of BC emissions reductions on a modified RCP3PD*



The two curves meet since the emissions scenarios become equivalent in the year 2100, where no reductions has been taking place in none of the cases. The analysis of the magnitude resulting temperature responses (ΔT) partly differs from that of the previous experiment (figure 11) since the assumption of BC RF being 0.4 W/m^2 (as of 2005) is used throughout. The comment, on the magnitude of the cooling potential of reducing BC when it comes to the assumption of having a background scenario with a constant level of BC, is still relevant. The reasons for why the curves are not flat for the earlier starts of reductions (in the leftmost part of figure 12), even though the atmospheric lifetime of the aerosols is very short, are that the BC emissions have not been entirely eliminated by 2100 and that the climate system has inertia.

5.2 Trade-Off between Cumulative CO_2 and BC

In this section the results from the remaining experiments will be presented.

Temperature response as a function of different climate characteristics

In about 20,000 simulations seven parameters, identified to be of crucial importance to the trade-off between BC and CO_2 mitigation options, were varied. The parameters and the intervals studied are summarized in table 4. The "BC-OC correlation" is a proxy for the connection between black and organic carbon. A 100% BC-OC correlation gives equal cuts in OC emissions when BC emissions are reduced.

Table 4. *Simulation parameter ranges and resolution*

Parameter	**Lower limit**	**Upper limit**	**Step size**
Peak year BC	2020	2090	10
Peak year CO_2	2020	2035	5
Reduction rate BC [%]	0	4	1
Reduction rate CO_2[17] [%]	1	4	0.5
Climate sensitivity [°C]	1.5	4.5	1.5
BC RF 2005 [W/m^2]	0.1	0.8	0.3 & 0.4[18]
BC-OC correlation [%]	0	100	

The choices of lower and upper limits as well as the step size were based on arguments about the possible paths ahead of us, and the literature on black carbon (Bond et al. 2004; Solomon 2007; Ramanathan et al. 2008; Kopp et al. 2010).

The simulation results, when the correlation between BC and OC was 100%, displayed a maximum temperature response[19] during the time period 1765-2100 that varied from 1.1 to 3.0 °C. The different value of the climate sensitivity was the major determinant of the temperature response (see Table 5). The emission scenario is that of RCP3PD, except for CO_2. Carbon dioxide emissions in this scenario follow RCP45 until reductions of carbon dioxide start.

[17] Reduction rates of CO_2 used, 1%/4% emissions reductions from 2035/2020 corresponds to having cumulative CO_2 emissions of 1322.3/855.1 GtC during 1765-2100.
[18] The values studied were 0.1, 0.4 and 0.8 W/m^2.
[19] The maximum temperature response is in this section considered to be an average around the maximum temperature reached during the time period simulated, regardless of its timing (see Chapter 4).

Table 5. *Temperature response up to 2100 with full BC-OC emissions correlation*

Climate sensitivity ΔT_{2xCO2} [°C]	Lowest temperature response [°C]	Uppermost temperature response [°C]
1.5	1.1	1.7
3.0	1.5	2.5
4.5	1.6	3.0

In order to narrow the scope of the thesis and the number of cases to investigate a single value on the climate sensitivity was chosen for the following experiments. The choice was based on the results in table 5 and IPCC's position on the climate sensitivity (Alley et al. 2007). The reason of not choosing ΔT_{2xCO2} =1.5 °C to study further is that the emissions need seemingly not to be cut during the 21st century in order to reach the climate target in focus[20]. For a ΔT_{2xCO2} = 4.5 °C there is most likely a need for more drastic measures than a 4% reduction of CO_2 emissions per year which, in this study, is considered an upper feasible limit on how fast the energy system could adapt.

Maximizing the Cumulative Emissions of CO_2

Future applications of the model may expand the analysis to integrate economic aspects of the trade-off between carbon dioxide and black carbon, but in this thesis we are simply maximizing the cumulative emissions of CO_2. With these potential future applications in mind, the maximization model was implemented so that the rates of emissions reductions and the timing of the start of emissions reductions for both CO_2 and BC were allowed to vary.

The maximization experiment was conducted, using a genetic algorithm (see Section 4.2), in six different cases in order to capture the range of different possible outcomes. Three cases with varying strength of black carbon's radiative forcing: low (0.1 W/m^2), medium (0.4 W/m^2) and high (0.8 W/m^2) was investigated either with or without a full correlation between reductions of emissions in BC and OC. In order for modeled historic temperatures to fit historic data when varying the estimate of BC RF the direct and indirect RF from SO_x, NO_x based aerosols is adjusted.
The parameters optimized were the peak year and the rate of reductions for BC and CO_2 respectively. Table 6 summarizes the result of the experiments.

The general results obtained were that the peak year of CO_2 would be in the latter part of the allowed period while the peak year for BC would be as early as possible. This is basically a corner solution and thus in this case, the genetic algorithm would not have been needed. See the chapter on future work for some thoughts on expanding the model (expansions that would likely produce interior solutions for which the genetic algorithm would be more useful).

[20] An example with 1.5 climate sensitivity: Following the RCP45PD scenario for CO_2 until 2040 and then keeping CO_2 emissions constant at 11.5 GtC per year after 2040 results in temperature increase of 1.7 °C.

Table 6. *Maximizing the cumulative CO_2[21] emissions using a genetic-algorithm*
a) With BC-OC correlation

BC RF[22]	**Cumulative CO_2 [GtC]**	**Peak CO_2 [year]**	**Reduction Rate [%]**	**BC Reduction start [year]**	**Reduction Rate [%]**
0.1	364	2029	3.7	2021	0.0
0.4	428	2035	3.8	2020	4.0
0.8	562	2027	1.4	2020	4.0

b) Without BC-OC correlation

BC RF	**Cumulative CO_2 [GtC]**	**Peak CO_2 [year]**	**Reduction Rate [%]**	**BC Reduction start [year]**	**Reduction Rate [%]**
0.1	397	2033	4.0	2022	4.0
0.4	495	2033	2.6	2020	4.0
0.8	645	2028	1.0	2020	4.0

Notable is that the when a full correlation between the emissions of BC and OC is assumed (Table 6a), and BC RF is believed to be low, reductions of BC are avoided in the maximum. The reason being that the cooling provided by the organic carbon that is also reduced is greater than the warming avoided by the BC reduced. Since the optimum is found for an annual reduction rate of 0% in this occasion the "BC reduction start" becomes redundant (which explains why it can end up at 2021 instead of 2020). However, in the case of no correlation between BC and OC and a BC RF of 0.1 W/m^2 there is no such reason for why the start of reduction obtained was 2022 (i.e. the algorithm did not find the optimum this time).

In the other extreme, when there is no assumed coupling between OC and BC (Table 6b) and BC is believed to have a high RF, the simulation with 4% annual reduction of BC allows for 636 GtC to be emitted. The difference between the two extreme cases is 272 GtC. The reason for the large difference is the combination of the studied case of high BC RF (which we assume is possible to remove) and the assumed compensating negative RF from SO_x, NO_x based aerosols (which we have assume in order for modeled historic temperatures to fit historic data) discussed earlier.

Policy Relevant Emission Scenarios

There are plausibly a couple of alternative ways to deal with short lived climate forcers such as black carbon. These alternatives in coarse terms are: not to do anything or to initiate, medium or full, mitigation work as soon as possible or later[23]. For simplicity there is assumed to be no upper bound on the reductions of emissions possible.

[21] Values are given for 2020-2100; add 619.4 GtC to obtain the cumulative CO_2 emissions for 1765-2100.
[22] The radiative forcing (RF) referred to is the level at 2005.
[23] The studied timings of peak emissions are 2020 and 2060.

The study was conducted for two different CO_2 emission peak years (2020 and 2030) but the results were seemingly invariant to this. The emission scenario is that of RCP3PD, except for CO_2. Carbon dioxide's emissions in this scenario follow RCP45 modified not to exceed two °C temperature increases. The modification consist of a steady rate of CO_2 emissions reductions from 2020 according to table 7. A central estimate on black carbons radiative forcing of 0.4 W/m^2 was used.

Table 7. *Simulation results for varying BC emissions reduction scenarios*
a) Maximizing CO_2 emissions during 2020-2100 with full BC-OC correlation

BC Reductions Start	**BC Rate of Reduction [%]**	**Cumulative CO_2 emissions [GtC]**	**CO_2 Rate of Reduction [%]**
No reductions	0	366	2.3
Year 2020	2	414	1.9
	4	427	1.8
Year 2060	2	389	2.1
	4	414	1.9

b) Maximizing CO_2 emissions during 2020-2100 with no BC-OC correlation

BC Reductions Start	**BC Rate of Reduction [%]**	**Cumulative CO_2 emissions [GtC]**	**CO_2 Rate of Reduction [%]**
No reductions	0	366	2.3
Year 2020	2	470	1.5
	4	503	1.3
Year 2060	2	427	1.8
	4	455	1.6

For best guess values of climate sensitivity and BC RF we find that the difference between zero and full reductions of BC emissions, from 2020, corresponds to a difference of between 61 and 137 GtC emitted for 2020-2100. The variation in this result depends on the level of correlation between the reductions of black carbon and reductions of the frequently co-emitted cooling carbonaceous aerosol called organic carbon (OC).

The difference of between 61 and 137 GtC found in the experiments (see Table 7) corresponds to a delay[24] of the start year of CO_2 emissions reductions by 5 to 11 years, assuming that the same rate of emissions reductions is used independent of the peak year. This illustrates a reason for a possible trade-off between BC and CO_2 emissions reductions.

[24] The emissions are assumed to follow the RCP45 scenario during the delay.

6. Future Work

There are a couple of primary areas in which further work would be helpful and hopefully fruitful. These areas are: development and further validation of the model (1), further research into the radiative forcing effects of aerosols (2) and expand the categories experiments performed (3).

Firstly: develop and further validate the model to improve its accuracy and increase its areas of application.

- Include all acknowledged climate forcers
- Compare results to similar acknowledged models further
- Do statistical analysis of the model results to historic data
- Implement efficacies[25]
- Couple the model to an economic model to produce an integrated assessment model for a wider perspective on what could/should be done
    i. Assess the potential economic benefits of reducing BC on different timescales and with different pace
    ii. Evaluate or further investigate the cost-effectiveness issues when it comes to BC emissions reductions (looking at different alt. ways to cut emissions etc.)

Secondly: Deepen the study of the different ways in which the aerosols have direct and in-direct effect on the radiative budget. For example, investigate the potential effect of reducing BC/OC aerosol emissions on the indirect effects the aerosols has on the cloud albedo.

Finally: Further investigations of parameters only partially covered, changing boundary conditions and new examinations of additional variables or indicators not deployed in this thesis. An example of another indicator to examine is integrated temperature change, a measure that would put equal focus on all times. Future work could also focus on more complex optimizations that include costs of adjustment, discount rates, assumptions on technology advances etc.

[25] "The efficacy is the global temperature response per unit forcing relative to the response to CO_2 forcing" (Hansen et al. 2005).

7. Discussion and Conclusions

Global climate policy faces a serious dilemma. It seems that action is urgent but it is also costly and the distribution of costs is a very controversial issue. It is therefore important to explore what measures can be undertaken that might be relatively fast, effective and cheap. One such option may be to reduce emissions of short lived climate forcers such as black carbon. The purpose of this thesis has been to build a model to explore the trade-offs between reductions in black carbon and carbon dioxide.

There is considerable uncertainty in several of the parameters but using central estimates we find that mitigating black carbon emissions completely corresponds to increasing the emissions space of about 60 -140 GtC carbon dioxide emissions over the 21st century (given that the 2 °C target should be met). This corresponds to a five to eleven years delay of the start of CO_2 emissions reductions. The 80 GtC range in this result is due to the unknown extent of the correlation between reductions of BC emissions and reductions in emissions of the cooling aerosol organic carbon.

In the larger picture black carbon abatement is not a single solution to global warming. It can however potentially provide an opportunity to buy some time, especially if the radiative forcing from BC turns out to be high and the correlation to emissions of organic carbon low. If the RF from BC is as high as 0.8 W/m^2 (as of 2005), and if BC can be reduced without affecting OC, the effect of BC just described (the cumulative CO_2 emissions an ambitious mitigation of BC would allow) is doubled to 280 GtC.

These results are all based on simulations focusing on keeping the mean global average surface temperature below two degree climate target up to 2100. There is a risk that a focus on a particular target and on the time period up to year 2100 misses some key issues, for example it allows for “solutions” in which the temperature has not peaked by 2100. In fact, several of the solutions found in this study are of such a character. On the other hand, this effect is to a certain extent introduced by the artificial limitation on the emission scenarios to have fixed percentage annual decreases. In future work with this model, one may explore more general constraints than that of meeting a given temperature target for a given year and more flexible emission reductions scenarios, particularly in the distant future when new technologies may be assumed.

The uncertain magnitude of the correlation between emissions of black and organic carbon contributes with an uncertainty term of about ± 40 GtC for the best guess case simulations described in the beginning of this section. The key question is if BC can be reduced independently from the cooling OC emissions. By modeling BC abatement independently for each different source of black carbon (open biomass burning, fossil fuel and biofuel), a first approximation of the cuts in co-emitted organic carbon could be made, which could reduce the level of uncertainty.

The timing of when the potential mitigation work starts also has an effect. Comparing 2020 and 2060 as start years for BC abatement (assuming an annual reduction rate of 4%) shows that the effect could correspond to 10/50 GtC (with/without full correlation between BC and OC emissions).

The greatest uncertainty however concerns the magnitude of the radiative forcing caused by black carbon. Its effect on the cumulative CO_2 emissions compatible with the two degree climate target for scenarios with full black carbon mitigation is found to range from around zero to 200/270 GtC with/without a full coupling between BC and OC, respectively. The negative value highlights that if, the correlation between emissions of BC and OC is high and black carbon turns out to have a lower absolute radiative forcing than organic carbon, then the effect on the climate of reducing BC will be a net warming (since the OC will also be reduced and have a greater effect). This is also an area for future research.

Our conclusion is that the trade-off between black carbon and carbon dioxide can be important but that it is also limited. The future climate is driven mainly by cumulative CO_2 emissions over time. The temperature response up to the year 2100 is probably an inferior indicator compared to the level of emissions and rate of emissions reductions for the main climate forcers. The average rate of emissions reductions over the century is what decides the "long term" rate of change towards a world with a reasonably stable climate. If no radical changes start occurring within the next few decades, then we will most likely be committed to a temperature hike of several degrees.

Black Carbon abatement has a smaller but still important effect. It might buy us something like a few years of time. Considering how difficult international climate negotiations are, the World might just need an option like this. It might be a good way to start climate agreements with a tangible and relatively easy goal to delay warming. Hopefully this creates time for the more difficult negotiations, while at the same time saves many lives.

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Appendix 1. Poster

This is a preview of the poster which will be presented at NCGG-6 Autumn 2011.

CHALMERS

Aggregating and Valuing the Climate Impact of Black Carbon Aerosols

Erik Sterner
Physical Resource Theory

Background & Aim

The global climate is affected by aerosols that absorb or reflect light.
Black carbon (BC) is the most important anthropogenic aerosol that enhances global warming by absorbing light.
Current BC radiative forcing (RF) lies in the range 0.2-0.8 W/m^2. Most black carbon sources also emit organic carbon (OC) which partly offsets the warming effect of BC by reflecting light. Since CO_2 abatement is difficult there is a policy interest in reducing BC emissions.

The aim of this study is to examine the effect on the climate of reducing black carbon emissions within the context of a two degree climate target 2100.

Method

A reduced complexity coupled carbon cycle climate model is built to study the impact of BC on the climate.
The study has temperature response by 2100 and cumulative CO_2 emissions by 2100 as its primary indicators.
In the main case a 2 °C constraint on the global average surface temperature and a climate sensitivity of 3 °C is used. In order for modeled historic temperatures to fit historic data when varying the estimate of BC RF the direct and indirect RF from SO_x, NO_x based aerosols is adjusted.
In the background scenario we assume constant emissions of BC and OC.
The two cases of full or no correlation between emissions reductions in black and organic carbon are studied.

Results

- Assuming 4% yearly abatement of black carbon from 2020 and varying strengths of BC RF, the effect of BC abatement is estimated to be as much as -0.4 °C by 2100 compared to a case with no abatement. (See Figure 1)
- For central values of BC RF (0.4 W/m^2), the effect on the temperature by 2100 of BC abatement, in case of no BC-OC correlation, is estimated to approach -0.2 °C (given that the mitigation starts at the latest 2035). (See Figure 2)
- For the central estimate of BC RF we find that the difference between full and no reductions of BC emissions, from 2020, gives the same cooling as reduction of between 60 and 140 Gt C during the period 2020-2100. (See Table 1)

Conclusions

◆ Central estimates suggest that reducing black carbon emissions rapidly increase the emissions space by about 60 -130 Gt C of carbon dioxide emissions. This corresponds to about five to ten years delay of the start of CO_2 emissions reductions assuming the reductions would have started 2020.

◆ The variation in the results depends on the size of the BC radiative forcing, as well as the level of correlation between the RF reductions of black carbon and RF reductions of organic carbon.

Figure 1

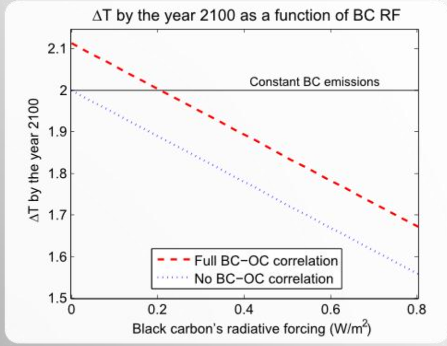


Figure 2

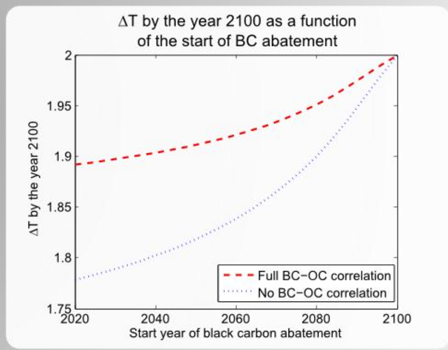
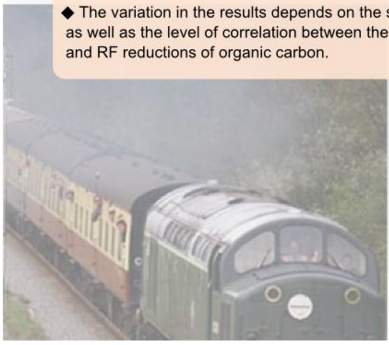
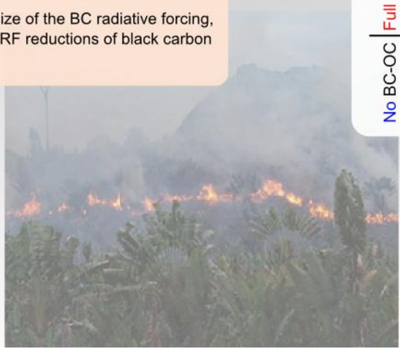


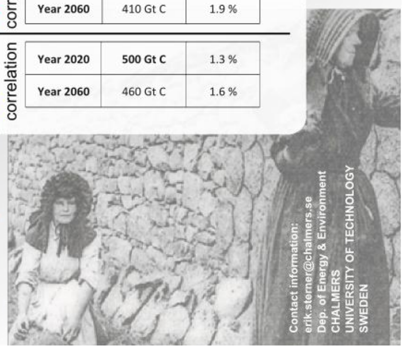
Table 1

Maximizing CO_2 emissions during 2020-2100 with Full/No BC-OC correlation

	Start of BC Reductions (4%/year)	Cumulative CO_2 emissions	CO_2 Rate of emissions Reduction
Full BC-OC correlation	*No reductions*	370 Gt C	2.3 %
Full BC-OC correlation	Year 2020	430 Gt C	1.8 %
Full BC-OC correlation	Year 2060	410 Gt C	1.9 %
No BC-OC correlation	Year 2020	500 Gt C	1.3 %
No BC-OC correlation	Year 2060	460 Gt C	1.6 %







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Appendix 2. Recommended reading

A comprehensive and accessible introduction to global warming can be found in Global Warming (David Archer, 2008) or Atmospheric chemistry and physics: From Air Pollution to Climate Change (Seinfeld et al. 1998) for a thorough description of the subject. For further reading, D. Harvey's Global Warming: The Hard Science also provides an important contribution to the overall understanding of the science underlying climate change, including the topics climate sensitivity, radiative forcing and climate models. IPCC also has a very good and comprehensive presentation of their assessment reports and much more on their webpage: http://www.ipcc.ch/.

Appendix 3. PPM-FRT User Manual

The model can be run through a user interface or coupled to other models. In this thesis the model has been used in both ways. An example of the latter is when the model is coupled to a genetic optimization algorithm (see Section 4.2). This user manual describes how the user interface can be used.

Using the model with the user interface

The boxes labeled “Climate Forcers”, “Carbon Cycle Models” etc. contains sets of different options or values to set which affect the actual combination of models to use, the characteristics of the simulation to run and how the results should be presented. Outside the boxes there is one button called “RUN MODEL !” which executes the MATLAB code and a checkbox which lets the user save the data produced during the simulation. The data is saved in a folder called “SavedData” located in the model’s folder.

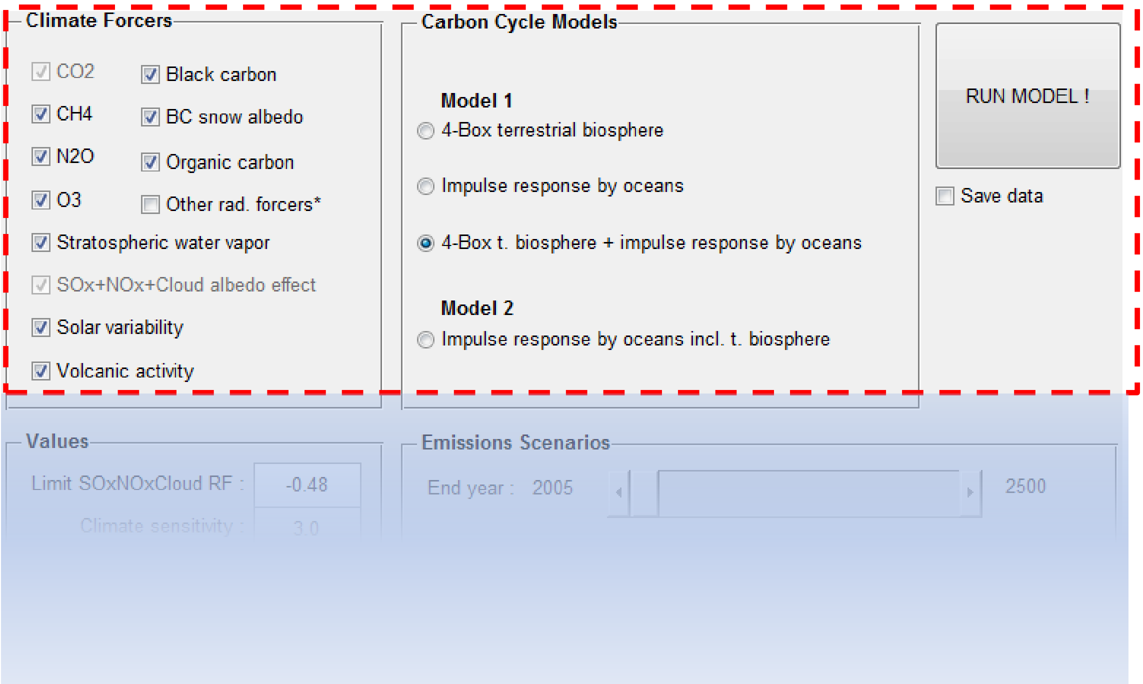
Climate Forcers

Out of the main climate forcers CO_2, SO_x and NO_x based aerosols and the cloud albedo effect is automatically included. Besides these the rest of the main climate forcers can be chosen to be included or excluded from simulations[26]. The default is that a large part of the forcers are included.

Carbon Cycle Models

Two basic Carbon Cycle models are available. For “Model 1” there is an alternative to choose not to include the terrestrial biosphere or the ocean in simulations.

Figure 1.a. *User Interface: Climate Forcers and Carbon Cycle Models*



[26] The setting under ”Climate Forcers” labeled “Other RF agents” is a summation over all of the climate forcers included in RCP3PD by Meinhausen et al.

Values

This set of values offer the opportunity to test some different characteristics of the climate system. The majority of the characteristics can be categorized as uncertain. The parameter which may not be intuitive is the so called "Limit SO_xNO_xCloud RF" which is a value that sets an upper bound to the negative RF from SO_x, NO_x and the Cloud Albedo Effect due to aerosols. The reason behind this is that while some part of it is likely to be reduced with reductions of CO_2 emissions (for example burning less coal) not all of it is.

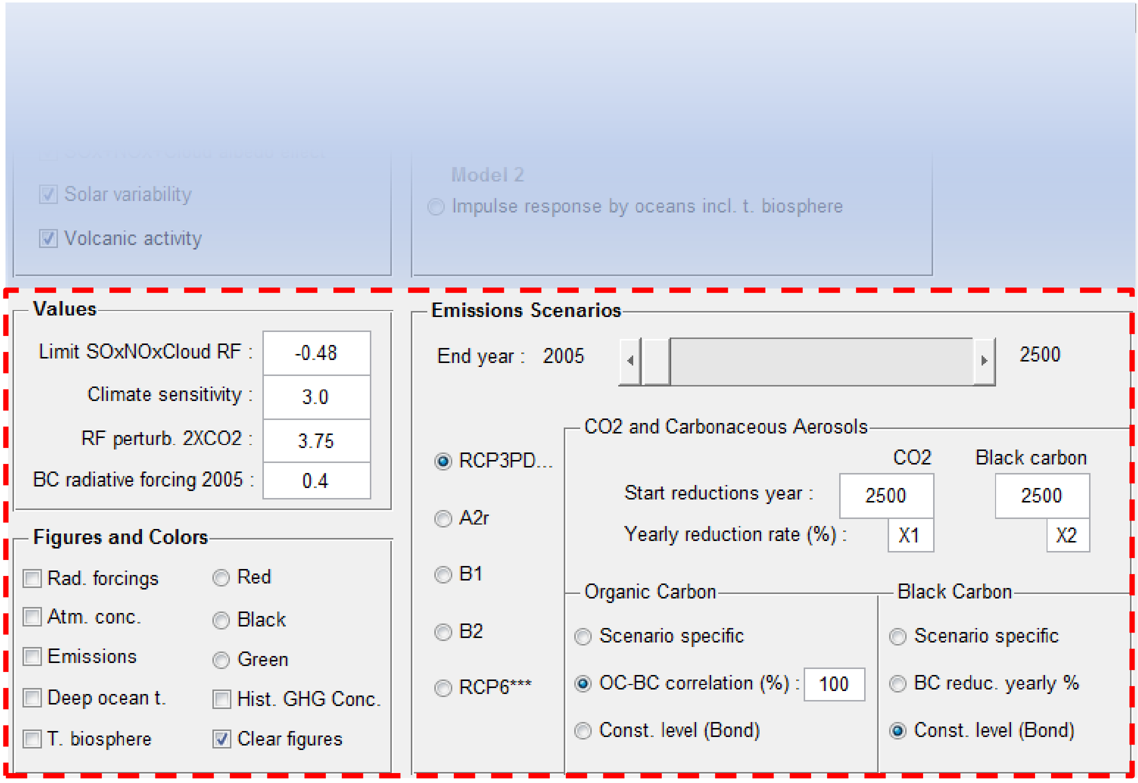
Emissions Scenarios

These options are described in the subsection of 4.1.1 called Yearly Emissions.

Figures and Colors

The settings in this box offers choices of what to illustrate and ways to do that. For example: un-ticking the "clear figures box" allows the user to easily draw several graphs from multiple simulations in the same graphics windows (hint: combine this with changes of color to make the visual analysis of the results easier).

Figure 1.b. *User Interface: Values, Emissions Scenarios and Figures and Colors*

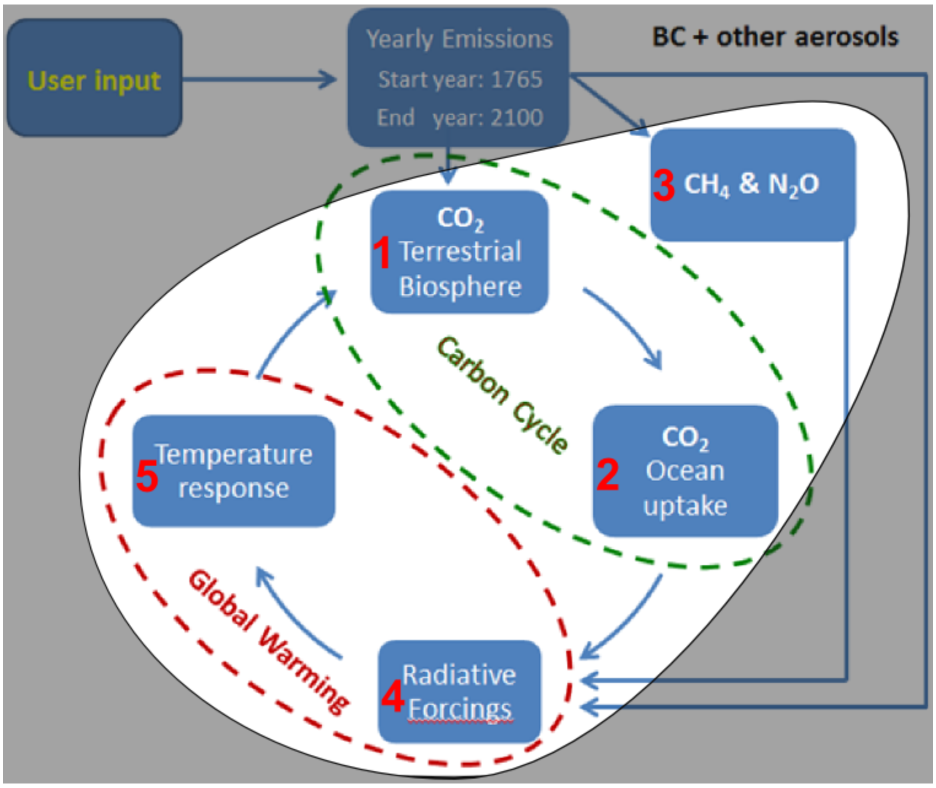


Appendix 4. PPM-FRT Models Key Governing Equations

This appendix will present the governing equations in PPM-FRT for the following models: (1) Terrestrial Biosphere, (2) Oceans Absorption of CO_2, (3) Methane (CH_4) and Nitrous Oxide (N_2O), (4) Radiative Forcing and (5) Temperature Response (see Figure 1).

The model source code is available, for academic purposes, on request.

Figure 1. *PPM-FRT highlighting the parts described in Appendix 4.*



(1) Terrestrial Biosphere

Net primary production (NPP) represented as a logistic function, where crowding is assumed to be the main limiting factor:

$$NPP = \nu B_1 - \rho B_1^2 \qquad \text{(Equation 1)}$$

Where B_1 is the carbon reservoir called "leafy biomass". The biomass in box 1 is hence governed by equation 2:

$$\frac{dB_1}{dt} = (\nu - \alpha_{12} - \alpha_{13})B_1 - \rho B_1^2 \qquad \text{(Equation 2)}$$

Whilst the carbon in the other reservoirs (or boxes) is governed by simpler equations of the form:

$$\frac{dB_1}{dt} = B_{i,flux\ in} - B_{i,flux\ out} \qquad \text{(Equation 3)}$$

(2) Oceans Absorption of CO_2

The so called impulse response function gives an approximation of the proportion of CO_2 still left in the atmosphere at time t after the CO_2 was emitted. The approximation assumes that the amount emitted can be regarded to consist of a few different fractions $a_{i,j}$. These fractions are modeled as decay functions with different time constants τ_i. The amount of the emitted CO_2 that is modeled to go into each fraction depends on the cumulative CO_2 emissions by that time (see Section 4.1.1 for more on this). This dependency is the reason for the j in the $G_j(t)$ which states how much of a pulse emission that is left in the atmosphere after t years (see Equation 4). In this model we have five fractions (i:s) and four cumulative emission levels (j:s) for which these fractions and their respective time constants change.

$$G_j(t) = \sum_{i=1}^{n} a_{i,j} \cdot e^{-t/\tau_i} \qquad \text{(Equation 4)}$$

The so called convolution integral added to the initial atmospheric carbon dioxide concentration gives us the atmospheric CO_2 concentration at time t (see Equation 5).

$$C(t) = C(0) + \int_0^t G_j(t-t')E(t')dt' * 0.469 \qquad \text{(Equation 5)}$$

This integral is discretized in the model on a year by year basis with $C(t_i)$ being the CO_2 level at the end of year i, $E(t_i)$ the total emissions during year i, 0.469 the conversion factor from GtC to ppm and $G_j(t_i\text{-}t_x)$ the amount of the CO_2 emitted in year x that is left in the atmosphere at the end of year i.

(3) Methane (CH_4) and Nitrous Oxide (N_2O)

The atmospheric concentrations of methane and nitrous oxide are governed by:

$$\frac{dC}{dt} = aE - \tau C \qquad \text{(Equation 6)}$$

E is the total emission that year, a is a conversion factor from Mt to ppbv and C is the current atmospheric concentration. The lifespan of nitrous oxide is constant whilst the lifespan of methane is dependent on the current atmospheric CH_4 concentration (see Equation 7).

$$\tau = \tau_0 \left(\frac{C}{C_0}\right)^{0.238} \qquad \text{(Equation 7)}$$

For the pre-industrial CH_4 concentration, an average lifespan of 6.5 years and the CH_4 concentration of today this relationship give a current average lifespan for methane of about 8 years.

(4) Radiative Forcing

The magnitude of the radiative forcing exerted by the different climate forcers are modeled to be related to the atmospheric concentration levels for the well mixed greenhouse gases but for the short lived climate forcers to their emission rates. The radiative forcing from CO_2 and BC as examples:

$$RF\ CO_2 = 5.35 * \ln\left(\frac{pCO_2}{p_0CO_2}\right) \qquad \text{(Equation 8)}$$

$$RF\ BC = E * BC_{Spec.F.} * BC_{lifetime} \qquad \text{(Equation 9)}$$

(5) Temperature Response

The temperature is modeled using a time dependent temperature model with two-boxes. T_1 and T_2 are the temperature of the boxes corresponding to a mixed atmosphere and surface water in the first box and the deep ocean in the other.

$$\begin{cases} C_1 \frac{dT_1}{dt} = \Delta R - \frac{T_1}{\lambda} - \kappa(T_1 - T_2) & \text{(Equation 10)} \\ C_2 \frac{dT_2}{dt} = \kappa(T_1 - T_2) & \text{(Equation 11)} \end{cases}$$

Where:

$\lambda = \frac{Climate\ sensitivity}{RF_{2xCO_2}}$ and $\kappa = \rho_{H_20} * C_{H_2O} * \frac{Exchange\ layer\ thickness\ per\ year}{seconds\ in\ a\ year}$

Where C_i is the heat capacity of layer (or box) 1 or 2, t is time, ΔR is the radiative forcing, ρ_{H_20} is the density of water, and C_{H_2O} is the heat capacity of water. $\kappa(T_1 - T_2)$ is thus the flux of heat from the surface layer to the deep ocean (box 1 → box 2). Note that λ is commonly used for the climate sensitivity. The "exchange layer thickness per year" is the part of the deep ocean that is mixed between the deep ocean and the surface ocean each year.

Appendix 5. Standard simulation results by PPM-FRT

Standard simulation with default settings except for the scenario which is RCP6.

Figure 1.a. *Example simulation using RCP6*

Standard model output

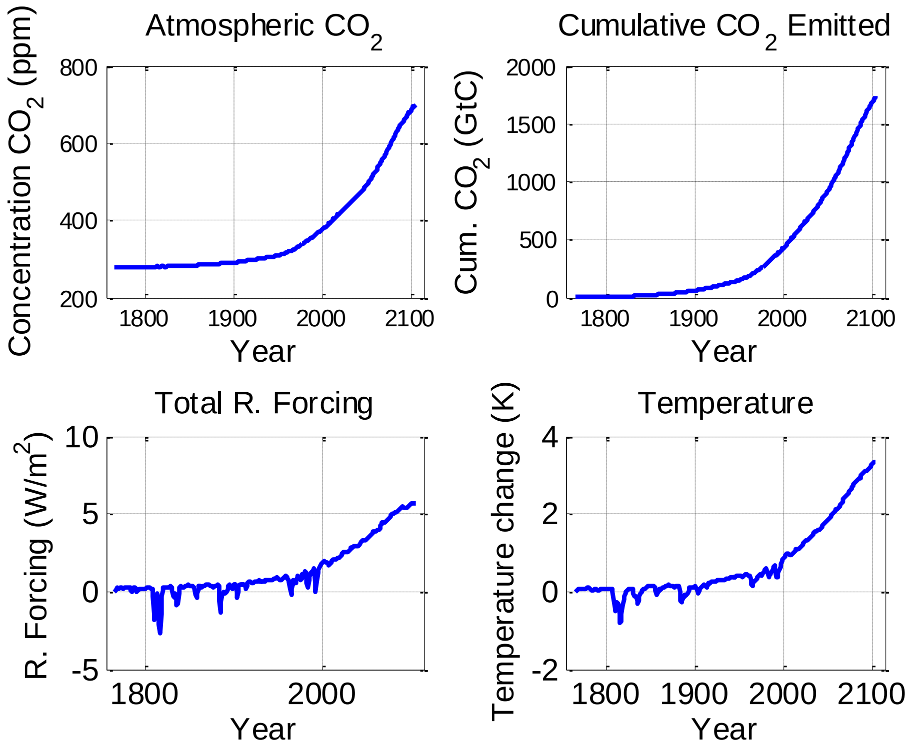
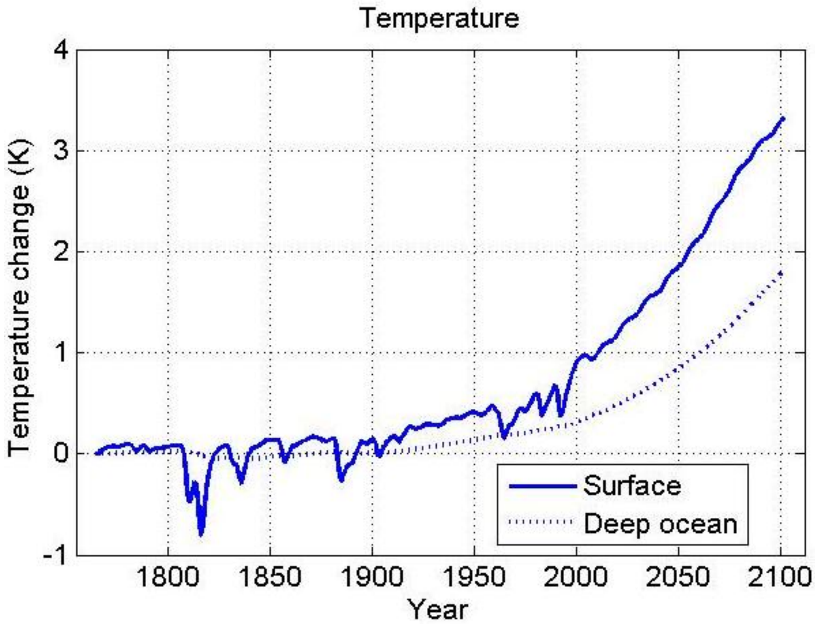


Figure 1.b. *Temperature response in the surface*[27] *and the deep ocean*



The time lag between the deep ocean and the temperature becomes evident in figure 1.b as the dotted line (Deep Ocean) is slower to react to changes than the solid. The large dips in temperature are results of large volcanoes spewing reflective aerosols into the atmosphere.

[27] The surface temperature is in this model an average of the atmospheric and the surface water.

Figure 1.c. *Radiative forcing for most of the major climate forcers.*

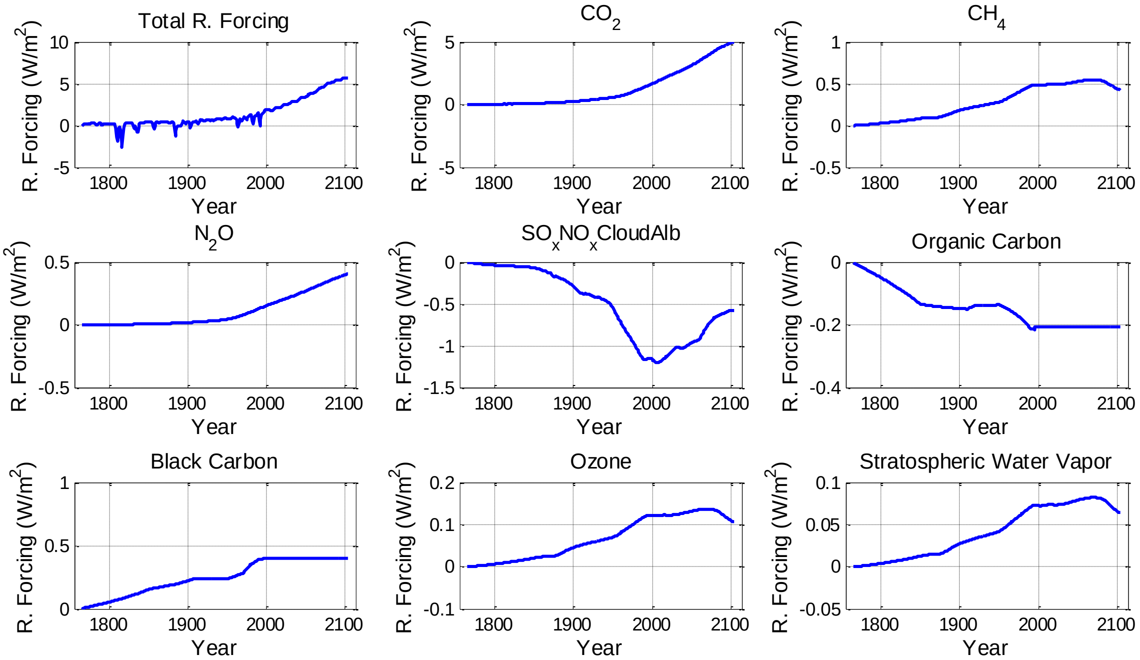


Figure 1.d. *Comparing RCP6 to RCP3PD.*

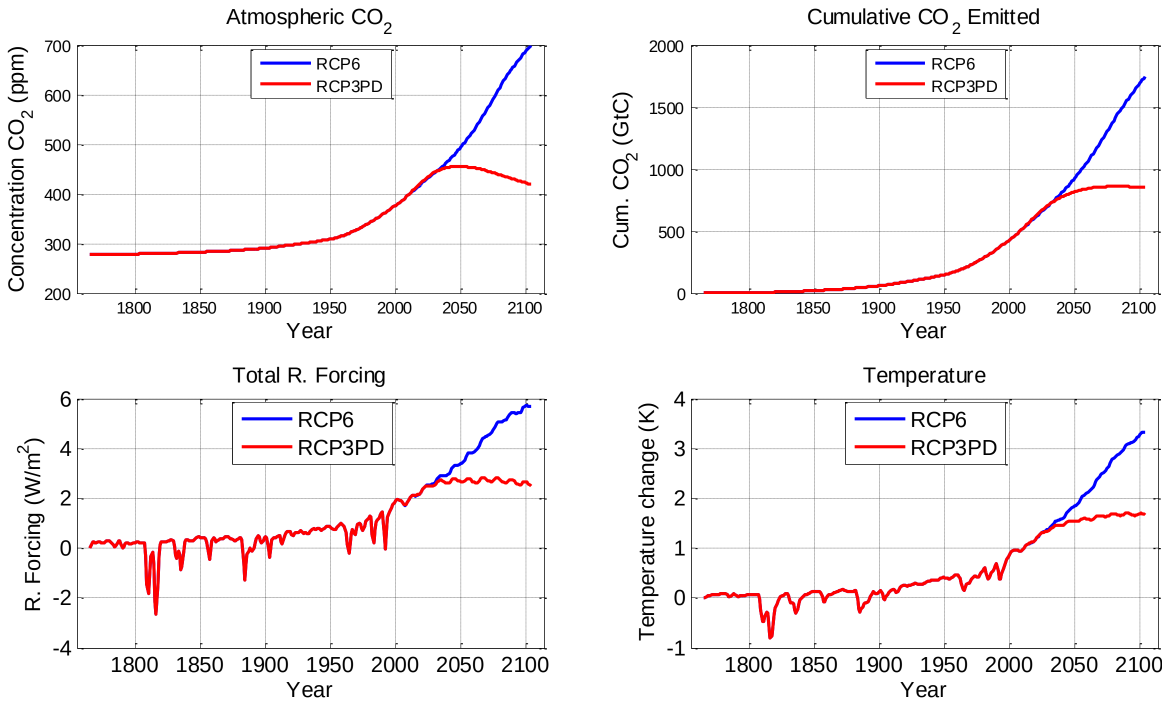


Figure 1.d is an example of the dramatically different futures ahead depending on which emissions scenario we follow is here visualized.