INVESTIGATING GEOENGINEERING SOLUTIONS TO MEET THE 2ºC TARGET

Climate Change; Geoengineering; MAGICC; CDR; SRM

Abstract

The international community have adopted a global warming limit of 2ºC or below relative pre-industrial levels as a goal for mitigation efforts to avoid dangerous climate risks. Attempts of deliberate large-scale intervention of the environment to moderate global warming, the so-called geoengineering, have been proposed as complementary solution due to the significant probabilities of exceeding the target. Furthermore, the warming relative to a specified greenhouse gas emissions are not well constraint currently owing to uncertainties in the climate response and the carbon cycle. This research uses a simple climate model to quantify the degree of geoengineering intervention that might be required to meet the 2ºC target under the 'representative concentration pathways' (RCP) emission scenarios, and to probabilistically assess the different combined strategies resulted. The results show that deploying carbon dioxide removal options to neutralise the cumulative emissions under RCP3-PD (~400 PgC), global surface temperature could be restored to pre-industrial levels by approximately 2500. Removing 1200, 800, 400, and 0 PgC from the atmosphere might require a reduction in the solar constant from 0.7% to 0.99% for RCP45, and from 1.55% to 2.23% for RCP6. The different strategies leave from 56.6% to 78.8% of probability (90% probability interval) to avoid exceeding the 2ºC limit. Substantial amounts of research is needed into geoengineering, particularly the climate response to those activities that counteract the radiative forcing imbalance by reducing the solar constant.

1. Introduction

Climate change is recognised as one of the greatest challenges that humankind faces (IPPC 2007). The international commitment at the Copenhagen Accord have adopted a global warming limit of 2ºC or below (relative to pre-industrial levels) as a target for mitigation efforts to reduce climate change risks. However, it has been showed that significant efforts will be required (Meinshausen et al. 2009). This situation has been anticipated (Crutzen 2006; Shepherd et al. 2009) by looking for alternative solutions. As a result, geoengineering, defined as deliberate large-scale intervention of the environment (Keith 2000), offers a possible means to offset greenhouse gases' (GHG) current radiative imbalance (Lenton and Vaughan 2009).

This paper proposes a research focused on quantifying the degree of geoengineering intervention that may be required to meet the 2ºC target under different future emission scenarios. Firstly, a critical review of the most relevant published scientific papers is given. Then, the text sets in detail the research: objectives; data and methods; potential problems; and schedule. Finally, the potential value of the results are described.

2. Meeting the 2ºC target

Geoengineering options have already been analysed in a number of studies. The papers reviewed in this text answer in somewhat several key issues of these solutions. Those that suggest geoengineering options may be required to avoid dangerous climate. Studies that describe what these solutions are in terms of technology development and their constrains. Papers that have analysed their risks of side effect. Finally, those which argue the conditions that geoengineering solutions might be deployed.

2.1 Avoiding dangerous climate risks

Some studies based on probabilistic assessment using a simple climate model, MAGICC, show that under the current scenarios the chances to limit the temperature rise below the 2ºC goal is likely to become less feasible (Wigley and Raper 2001; Hare and Meinshausen 2006; Meinshausen et al. 2006; Van Vuuren et al. 2008; Meinshausen et al. 2009; Macintosh 2010; Rogelj et al. 2010).

As a result, renewed interest in direct climate intervention has arisen (Fleming 2010), which can be divided in two main categories (Keith 2000): solar radiation management (SRM) options that attempt to rectify the radiative imbalance caused by anthropogenic GHGs by reducing the solar radiation absorbed; and carbon dioxide removal (CDR) options which are based on the subtraction of atmospheric carbon dioxide (CO_2) by enhancing the existing natural carbon sinks or creating new ones.

A set of SRM solutions have been proposed. A fraction of incoming solar radiation could be reflected away before entering the Earth system, by objects placed either in a solar (Angel 2006), and in an Earth orbit (NAS 1992; Pearson et al. 2006). Crutzen (2006) has proposed the injection of sulphate aerosols into the lower stratosphere to cool the climate based on the natural analogy of large volcanic eruptions. Finally, there are a set of options for enhancing the albedo effect. Increasing the reflectivity of low level marine stratiform clouds by mechanical (Latham 1990; Latham et al. 2008; Salter et al. 2008) or biological (Wingenter et al. 2007) generation of cloud condensation nuclei (CCN). Other studies have suggested modification of grasslands, croplands, human settlements and deserts (Hamwey 2007; Akbari et al. 2009; Ridgwell et al. 2009).

There have been suggested some CDR options. Lenton and Vaughan (2009) have estimated the long-term potential of “land carbon sink enhancement” for increasing conventional vegetation and soil carbon storage (~165 Pg C). Several geoengineering proposals have been made to enhance the existing ocean carbon sink. Two studies suggest the enhance of the solubility pump, increasing the sinking of CO_2-rich waters (Zhou and Flynn 2005), or by manipulating surface ocean chemistry (Harvey 2008)). Other studies propose enhance the biological pump, adding limiting nutrients (NAS 1992; Boyd 2008; Lampitt et al. 2008), or by mechanically enhancing the upwelling of nutrient (Lovelock and Rapley 2007; Karl and Letelier 2008). Finally, air capture storage or removing atmospheric CO_2 by wholly artificial means with subsequent storage in the lithosphere, sediments or the deep ocean has been proposed (Elliott et al. 2001; Keith et al. 2006; Zeman 2007).

2.2 Evaluating geoengineering options

Often the above geoengineering options have been evaluated somewhat in terms of “climatic effectiveness”. Air capture and storage has considerable century-timescale potential to reduce atmospheric CO_2, although the main limitation is the storage capacity (Lenton and Vaughan 2009). Nutrient addition options for enhancing the ocean carbon sink are less effective on the century timescale (Lenton and Vaughan 2009). Proposals to enhance the albedo over the Southern Ocean (biologically), or in urban areas could provide useful regional cooling (Lenton and Vaughan 2009). Options to enhance ocean upwelling or downwelling are wholly ineffective, and carbonate addition to the ocean only becomes effective if sustained for many centuries (Harvey 2008; Lenton and Vaughan 2009). Sunshades in space or stratospheric aerosols have the greatest potential to uniformly decrease radiative forcing in a short term (Govindasamy et al. 2003; Angel 2006; Crutzen 2006; Wigley 2006; Matthews and Caldeira 2007). Mechanical enhancement of cloud and land surface albedo modifications with could provide a partial offsetting (Bower et al. 2006; Latham et al. 2008).

The potential side effects and related risks of geoengineering interventions are substantial. Land carbon sink solutions would be likely to come into conflict with food production (Rajagopal et al. 2007; Goldemberg and Guardabassi 2009). Attempts to enhance the biological pump component may result in (Cullen and Boyd 2008; Lampitt et al. 2008; Law 2008): eutrophication, loss of biodiversity, algal bloom effect, and potential redistribution of the global macronutrient balance. Furthermore, the temperature response in the case of an abrupt termination of SRM leads to much higher rates of warming (Matthews and Caldeira 2007; Ross and Matthews 2009). Modelling studies show that sun shade solutions although would counteract a known forcing from increased CO2 (Govindasamy et al. 2002; Matthews and Caldeira 2007), often drive to a residual global cooling or warming (Govindasamy and Caldeira 2000; Govindasamy et al. 2002; Govindasamy et al. 2003; Lunt et al. 2008). Other papers present several possible side effects when sulphate aerosols are injected into the lower stratosphere: ozone depletion (Tilmes et al. 2008); disruption to the monsoons (Robock et al. 2008); stronger positive phase of the Arctic Oscillation (Stenchikov et al. 2002; Stenchikov et al. 2006); decreases on precipitation over land (Trenberth and Dai 2007); and potential acid rain (Crutzen 2006). Moreover, SRM solutions does not face the CO2 atmospheric concentration. Hence, the ocean acidity issue (Kleypas et al. 1999; Caldeira and Wickett 2003; Caldeira and Wickett 2005; Orr et al. 2005; Cao and Caldeira 2008) is not tackled.

2.3 Emission scenarios

Over time, a broader range of emission scenarios has been developed, which let address different components of climate change. Emission scenarios, defined as a plausible representation of the future discharges to the atmosphere of the potentially radiatively active gases (e.g. GHG and aerosols), based on a range of assumptions about driving forces and their main relationships (Meehl et al. 2007), are used as input to a climate model to compute climate projections.

The IPCC developed long-term emissions scenarios, such as the so-called IS92 scenarios in 1992, and the IPCC Special Report on Emission Scenarios (SRES) (Nakicenovic et al. 2000), classified in four storylines or 'families' representing alternative demographic, social, economic, technological, and environmental pathways until 2100 (A1, subdivided in A1FI, A1T, and A1B; A2; B1; and B2).

However, there are new information needs, such as the interest of exploring different approaches to mitigation in addition to the 'no climate policy' scenarios (e.g. SRES), or the interest in modelling the oceans or the ice sheets needs emissions scenarios to extend well beyond the conventional 2100 end-point (Hibbard et al. 2007), which in turn brings the opportunity to a better exploration of the geoengineering solutions. Those needs and the improvements in the climate change understanding for nearly a decade (e.g. inherent climate system's variability, socio-economic, environmental and technological factors) are being reflected in a new set of emission scenarios, the 'representative concentration pathways' (RCP) (Moss et al. 2010). The RCP (RCP3-PD, RCP4.5, RCP6 and RCP8.5), rather than beginning with detailed driving forces storylines to generate emissions and then climate scenarios, starts identifying the characteristics for scenarios of radiative forcings for climate modelling until 2500 (Meinshausen et al. in prep.), due to these might result from a number of different combinations of socioeconomic and technological factors. RCP3-PD represents very low GHG atmospheric concentration, where radiative forcing reaches a value around 3.1 W m-2 mid-century, reducing to 2.6 W m-2 by 2100) (van Vuuren et al. 2007). For RCP4.5 (Clarke et al. 2007), the total radiative forcing is stabilized before 2100, whereas for RCP6 (Fujino et al. 2006; Hijioka et al. 2008), the total radiative forcing is stabilized after 2100, by employment of a range of technologies and strategies. The RCP8.5 characterises an increase of GHG emissions over time representative for scenarios in the literature leading to high greenhouse gas concentration levels (e.g. A2 storyline) (Riahi et al. 2007). Finally, it is important to recognise some limitations, that above emission scenarios (e.g. SRES, RCP) are neither forecasts nor policy recommendations (Nakicenovic et al. 2000; Moss et al. 2010).

2.4 MAGICC model

MAGICC (Model for the Assessment of Greenhouse-gas-Induced Climate Change) is a reduced complexity coupled carbon cycle climate model, that was developed by Wigley and Raper (1987; 1992), and that has been improved continuously (Raper et al. 1996; Wigley and Raper 2001; Meinshausen et al. 2009; Wigley et al. 2009). MAGICC provides a mean to estimate the joint responses of the more comprehensive atmosphere-ocean general circulation models (AOGCM) by extrapolating their key characteristics to a range of other scenarios, and thus to extend the understanding achieved on the climate system (Meinshausen et al. 2009).

There are some tasks that make simple models valuable for better understanding of the climate system. First, emulations. AOGCM usually demand high computational resources (e.g. for running large ensembles), and simple models can emulate these for the global or large-scale averaged results in a set of different emission scenarios (Meinshausen et al. 2011). A central condition for a simple model reliability is that the results of the emulation are accurate with the AOGCM on the emission scenarios performed (Osborn et al. 2006) (e.g. MAGICC model). Second, parametrization of structural uncertainties. The way some processes and components are "parameterized" or implemented in AOGCM (e.g. clouds) brings structural uncertainties, and simple models might be used to confine these (Meinshausen et al. 2011). For example, the aggregated response of two models could differ because these have different structures, or within common structures, owing to these set different parameter values. Third, factor separation analysis. A main limitation when interpreting the AOGCM projections is that the different radiative forcings considered in each modeling group (e.g. interpretations of the projections in the IPCC AR4) (Meehl et al. 2007; Knutti and Hegerl 2008). Simple models, by applying factor separation analysis, may help to harmonize the results from AOGCM, thus making these more comparable (Meinshausen et al. 2011). Finally, joint response and feedback analysis. Simple models might contribute estimating the joint response of the more comprehensive models. In the IPCC AR4, the CO2 concentrations were implemented in the CMIP3 AOGCM without regarding to the climate sensitivity, though a higher sensitivity is likely to lead to both, more CO2 atmospheric concentration and higher GMST owing to the climate feedbacks of the carbon cycle (Meinshausen et al. 2011). For example, due to the climate feedbacks on the carbon cycle are driven by the climate model response, MAGICC is consistent in its CO2 concentrations (Meinshausen et al. 2009).

3. Overall objective and specific aims

The above studies show significant probabilities of raising global mean surface temperature above 2ºC relative to pre-industrial levels, therefore geoengineering has been suggested though it might carry substantial side effects and potential risks. Climatic intervention in the absence of deep emissions cuts could arguably constitute increased risk of dangerous anthropogenic interference in the climate system. This concern have led the scientists to call for a widely shared research and an international governance of the geoengineering options (NAS 1992; Robock 2008; Shepherd et al. 2009; Blackstock and Long 2010; Keith et al. 2010), which might help to avoid rushed actions, improve our knowledge and make wiser decisions. Rather than as an alternative, geoengineering is considered by some as a potential complement to mitigation of global greenhouse gas emissions. The overall objective of this research is to quantify the degree of geoengineering intervention that may be required to meet the 2ºC target under different future emission scenarios. This objective involves three specific aims:

- first, to build custom scenarios for the above solutions suggested which attempt to increase the amount of radiation emitted by the Earth (note that different solutions have specific requirements in term of deployment, potential effects, maintenance, and so forth);
- second, to develop a methodology within MAGICC 6 to implement the geoengineering solutions:
  - representing the carbon dioxide removal custom scenarios;
  - deploying the solar radiation management (by reducing the amount of solar radiation absorbed) focused on a specific target;
- third, to probabilistically assess the different combined strategies resulted that might be required to meet the 2ºC target.

4. Methodology

4.1 The MAGICC model

This research uses the MAGICC (Model for the Assessment of Greenhouse-gas-Induced Climate Change) climate model, version 6, to quantify the degree of geoengineering intervention that might be required to meet the 2ºC target since pre-industrial periods under different future emission scenarios. MAGICC is a reduced complexity coupled carbon cycle climate model. Hemispheric emissions of greenhouse gases, aerosols, and tropospheric ozone precursors are its main inputs, whereas atmospheric concentrations, radiative forcings, surface air temperatures, sea level rise, and ocean heat uptake are the outputs. The MAGICC model is described in detail in Wigley (2008) and has been used extensively in past IPCC Assessment reports to emulate higher complexity models.

4.1.1 Climate sensitivity

Climate sensitivity is defined as the equilibrium response of global mean surface temperature after a doubling of CO2 atmospheric concentrations (Meehl et al. 2007). For MAGICC, this is a primary model parameter. The range of the climate sensitivity is likely to lie between 2-4.5ºC, with a best estimation of 3ºC according to the IPCC AR4. Though the most likely value diagnosed for the AOGM emulated under MAGICC is on average 2.88ºC (Meinshausen et al. 2011), estimation which is taken as a central value on this paper for solar constant reduction calculus.

4.1.2 Carbon cycle

MAGICC presents a globally integrated box model for the terrestrial carbon cycle. It is built with three sub-boxes, one for living plant box, and two for dead biomass, detritus and organic matters in soils. The terrestrial carbon cycle accounts for the decay issue of the biomass (Meinshausen et al. 2011), thus any further rectification is applied carbon dioxide removal solutions suggested as Lenton and Vaughan (2009) did for taking it into consideration.

4.1.3 Emission scenarios

Along the emission scenarios considered to be used (see Section 2.4), this paper works with RCP3PD, RCP45, and RCP6 as a baseline for implementing CDR solutions, which in turn poses three custom emission scenarios for each of these (see Section 4.2 and Table 5.1).

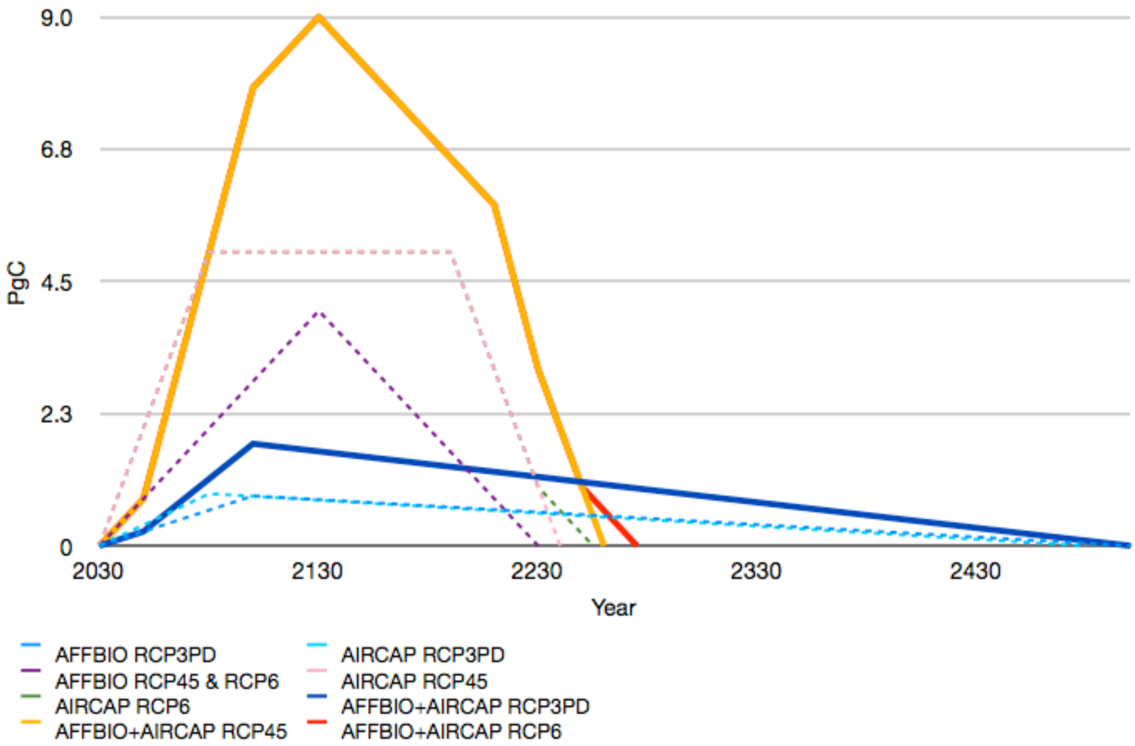
4.2 Carbon dioxide removal scenarios

Among all the CDR options suggested on the literature, this work represents afforestation and reforestation, bio-char, and air capture and storage due to their overall potential to remove CO2 from the atmosphere is fairly higher than the other solutions suggested (e.g. enhancing the ocean carbon sink or increasing the surface albedo) (Table 2.1), and these presents in somehow less questionable assumptions (e.g. land requirements) (Lenton and Vaughan 2009), thus helping to counteract the radiative forcing imbalance caused by anthropogenic GHGs.

Instead using the scenarios proposed (see Section 2.3), this paper builds its custom scenarios owing to some issues (Figure 1). First, to take into account the time of deployment and dismantling of all the infrastructure, thus avoiding the sharp end of the CDR when these are in their maximum potential, the solutions start rising until reach the maximum flux, approximately in a central year of their lifetime, and start decreasing afterwards. Note that the RCP have different shapes of deployment owing to these have different years as input values. Second, due to the amount of CO2 that could be removed from the atmosphere and the potential of the CDR options might not be accurate constrained (Lenton and Vaughan 2009; Shepherd et al. 2009; Lenton 2010; Vaughan and Lenton 2011), the best scenarios argued may be overestimated (e.g. economic and energetic constrains). Hence, the CDR solutions are halved, resulting in total storage capacities of: 150 PgC for afforestation and reforestation; bio-char accounts for a total of 250 PgC; and 800 PgC for air capture and storage. This 1200 PgC overcomes the cumulative CO2 emissions in the RCP3-PD (~400 PgC). Thus, the total storage capacities are halved again for afforestation-reforestation and bio-char, and the air capture and storage accounts only for the eighth of its capacity to neutralise the cumulative CO2 emissions under RCP3-PD. Third, these solutions start in different years to take into account the deployment time that each of these might require as a constrain issue (Lenton 2010; Vaughan and Lenton 2011). Afforestation-reforestation and bio-char begin in 2030, whereas air capture and storage starts in 2050.

To build these scenarios on MAGICC there are a couple of considerations that have to be done. Representing the CO2 emissions could be implemented both, globally or regionally. Due to the CO2 is a well mixed gas (IPCC 2007) and to simplify the task, the scenarios files are compiled globally. Afforestation-reforestation and bio-char solutions are affected by the terrestrial carbon cycle, whilst the air capture and storage is not affected. To take into account this particularity, the first is implemented on the emission file which considers the terrestrial carbon cycle and the decay issue (see Section 4.1.2), and the second is applied on the fossil CO2 emission file. The resultant emission files are the subtraction of the CDR solutions to the former emissions under the RCP.

a. Total storage capacities



b. CO_2 emission pathways

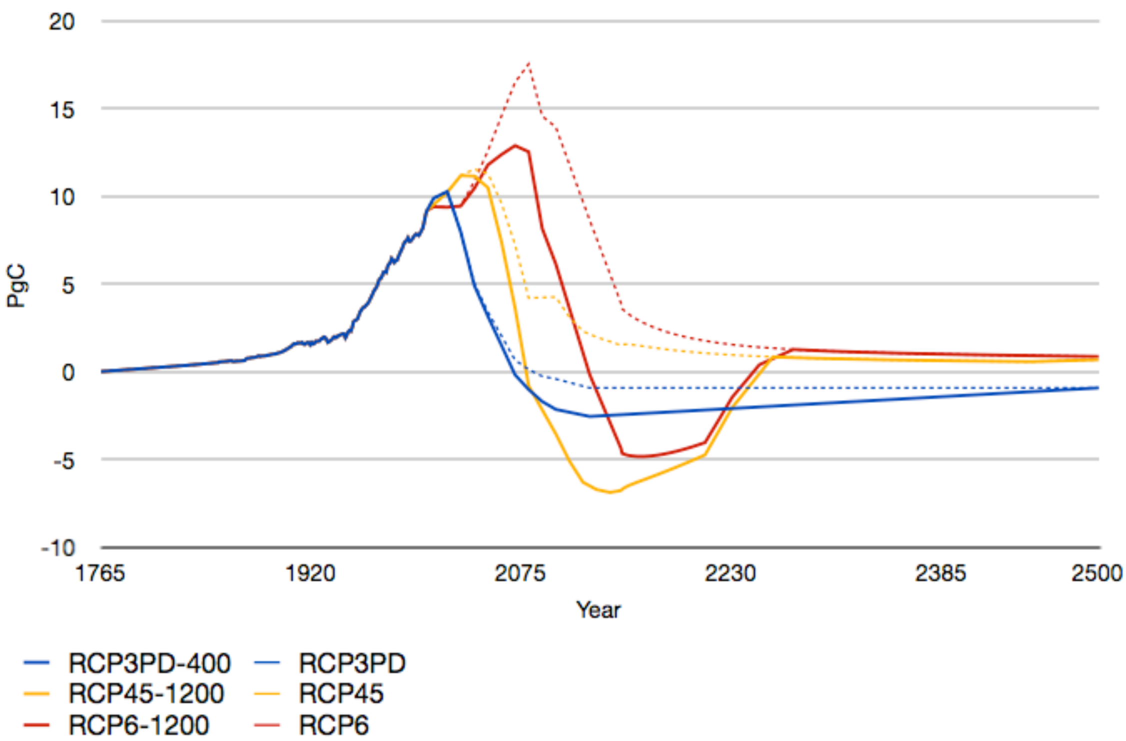


Figure 1 CDR scenarios. **a**. shows the total storage capacities; solid lines represents all carbon dioxide removal solutions, and dashed lines presents the shapes for each solution. **b**. shows the CO_2 emission pathways; solid lines represents the total CO_2 emissions for the RCP when all the CDR solutions are deployed, and dashed lines shows the total CO_2 emissions for the former RCP scenarios.

Figure 1 shows the CO2 emission scenarios for each of these CDR solutions under the RCP. The total storage capacity deployed is represented on Figure 1.a, whereas the CO2 emission pathways, after subtracting the CDR to the emissions on the RCP, are plotted on Figure 1.b.

4.3 Solar radiation management implementation

This research does not consider the technical or spatial complexities of solar radiation management solutions, thus it simulates these solutions by reducing the amount of incoming solar radiation that reaches the Earth system to explore global mean surface temperature changes.

Due to the risks involved on rectifying the anthropogenic radiative imbalance by reducing the solar radiation that reaches the Earth could be higher than those involved by enhancing the existing natural carbon sinks or creating new ones to remove CO2 from the atmosphere, this paper applies SRM after the above CDR solutions are deployed and the GMST is still higher than the 2ºC target since pre-industrial period for a climate sensitivity of 2.88ºC and the CCSM1 C4MIP. The climate sensitivity of 2.88ºC is the most likely value diagnosed on MAGICC (see Sections 4.1.1), and the CCSM1 C4MIP is the randomly related carbon cycle to that set of parameters which contains this climate sensitivity on MAGICC (see Section 4.4). The starting year is 2040 due to for some scenarios is needed to avoid exceeding the 2ºC.

To analyse the degree of SRM intervention, this research studies the Earth's annual global mean energy balance, due to similar pattern on GMST changes results from the same global magnitude of radiative forcing (Hansen 2005).

4.4 Probabilistic assessment

To relate the carbon dioxide removal and solar radiation management deployment under the default parameters chosen (e.g. climate sensitivity 2.88ºC and the CCSM1 C4MIP) to the climate system uncertainty reported in the literature (Meehl et al. 2007), thus obtaining a range of climate responses, this work uses the methodology of Meinshausen et al. (2009).

The methodology followed varies 9 climatic parameters related to the energy balance (e.g. climate sensitivity), 33 gas-cycle and global radiative forcing parameters, and 40 factors for scaling the regional 4 boxes pattern, though this research only studies the global mean surface temperature responses. To constrain these parameters, observational data of GMST was used from 1850 to 2006, the linear trend in ocean heat content from 1961 to 2003, the radiative forcing estimation for 18 forcing agents in 2005, and the diagnosis of the effective climate sensitivity on the 21st century from the AOGM CMIP3 emulations. The distribution of these parameters was obtained using a Metropolis-Hastings Markov chain Monte Carlo approach, and for the likelihoods observational uncertainty and climate variability from AOGM were taken into account. This generates 82 dimensional parameters space. Finally, these 82 historically constrained parameters are represented by 600 sets and randomly combined with nine of the C4MIP carbon cycles.

5 Results

This paper quantified the degree of geoengineering intervention that might be required to avoid exceeding the 2ºC target since pre-industrial levels under different future emission scenarios (Table 1). Even if the afforestation and reforestation, bio-char, and air capture and storage (CDR solutions considered on this research) were deployed removing a total amount of ~1200 PgC from the atmosphere (~400 PgC on RCP3-PD), leaves the probabilities (90% probability interval) of above one third on RCP3-PD, one fifth for RCP45, and no chance on RCP6 to meet the 2ºC target. This result suggests the need of SRM solutions on RCP45 and the RCP6 (the RCP3-PD without CDR falls 0.23ºC below the target, thus SRM was not applied on this scenario, note that the SRM required was calculate for a climate sensitivity of 2.88ºC and CCSM1 carbon cycle).

Removing those 1200 PgC from the atmosphere, global mean surface temperature on RCP45 overshoots the target almost a century around 2100 (maximum of 0.5ºC in 2080), which would require a decrease in the incoming solar radiation of a maximum of approximately 0.7% over the overshoot period. Whereas, global temperature on RCP6 exceeds the target around 2055 for not returning back again, which in average would require 1.1% of solar constant reduction until 2500.

Table 1 Summary of results

SCENARIOS	AFFBIO + AIRCAP Afforestation-reforestation Bio-Char Air Capture Storage		SRM Solar Radiation Management		AFFBIO + SRM Afforestation-reforestation and Bio-Char Solar Radiation Management		AIRCAP + SRM Air Capture Storage Solar Radiation Management		AFFBIO + AIRCAP + SRM Afforestation-reforestation and Bio-Char Air Capture Storage Solar Radiation Management	
RCP3PD										
CDR (GtC)	400									
SRM (W m^{-2})										
	600 Parameters	5th-95th percentile								
Probability <2ºC	85.6%	78.7%								
Probability <0ºC	20.8%	8.5%								
RCP45										
CDR (GtC)	1200				400		800		1200	
SRM (W m^{-2})			-2.37 average		-1.21 average		Min: 0 / Max: -1.6		Min: 0 / Max: -1.6	
	600 Parameters	5th-95th percentile	600 Parameters	5th-95th percentile	600 Parameters	5th-95th percentile	600 Parameters	5th-95th percentile	600 Parameters	5th-95th percentile
Probability <2ºC	20.8%	20.3%	66.3%	68.5%	57.3%	58.1%	55.6%	56.6%	66.6%	68.5%
Probability <0ºC	0.3%	0%	6.6%	1.6%	0.2%	0%	0.2%	0%	0.2%	0%
RCP6										
CDR (GtC)	1200				400		800		1200	
SRM (W m^{-2})			-5.34 average		-4.37 average		Min: -1.01 / Max: -4.35		Min: -0.99 / Max: -3.81	
	600 Parameters	5th-95th percentile	600 Parameters	5th-95th percentile	600 Parameters	5th-95th percentile	600 Parameters	5th-95th percentile	600 Parameters	5th-95th percentile
Probability <2ºC	0.5%	0%	73.5%	76.2%	73%	78.3%	73%	78.8%	75.6%	78.7%
Probability <0ºC	0.3%	0%	33.5%	31.6%	26.8%	8.5%	18.8%	8.5%	12.8%	8.5%

Further analysis were made considering or afforestation-reforestation and bio-char (400 PgC), or air capture and storage (800 PgC), which allowed to investigate the degree of SRM required to meet the target under a wider range of CDR deployments and plausible emission scenarios. Removing 800 PgC from the atmosphere leaves similar scenarios for both, RCP45 and RCP6. For RCP45, the overshoot (~130 years) could be avoid with a maximum of 0.73% on solar constant reduction; whilst for RCP6, an average of -1.4% in incoming solar radiation would be required. A total amount of 400 PgC removed from the atmosphere would required in average a reduction in the solar constant reduction of ~0.51% and ~1.83% for RCP45 and RCP6 respectively, from 2040 to 2500. The extreme case without CDR deployment would require an average decrease in the incoming solar radiation, from 2040 to 2500, of ~0.99% and ~2.23% for RCP45 and RCP6 respectively to meet the 2ºC target. Overall, the degree of CDR and SRM solutions required to avoid exceeding 2ºC since pre-industrial levels, leaves between 56.6%-78.8% of probability (90% probability interval) for the 600 emulations to meet the target.

These results suggest that under high or moderate mitigation measures, possibly complemented by carbon dioxide removal options, no solar radiation management might be required, and if so, at low levels and for limited period. Although, the incoming solar radiation that may need to be reduced to meet the 2ºC limit, not only increases in the required level, but also in the period that has to be deployed, under high emission schemes and/or low carbon removal activities, which may involves substantial risks (e.g.

disruptions of the hydrological cycle, ocean acidity), and challenges (e.g. development of appropriate technology, narrowing the current uncertainties of the climate system).

6. Discussion

The results of this work are difficult to analyse against previous studies which implemented geoengineering solutions, due to some used different emission scenarios (e.g. ‘Wigley, Richels and Edmonds’, WRE), other investigated different issues (e.g. the risk of rapid temperature change and impacts on the hydrological cycle), and other used alternative methodology and/or climate models (see Section 2.3 for further details).

It is usually discussed in the literature that to offset a doubling atmospheric CO2 concentration since pre-industrial levels requires 1.8% reduction in the solar constant (Govindasamy and Caldeira 2000). In this paper, RCP45 doubles atmospheric CO2 concentration by 2100 and it holds afterwards similar values (~568 ppm), which requires approximately 0.99% reduction in the solar constant to avoid exceeding 2ºC. Although, the latter reduction in the solar constant takes into account total radiative forcings, and it does not attempt to completely offset radiative forcing imbalance, but to keep global temperature below 2ºC.

To increase the probability to avoid exceeding 2ºC, it might be deployed higher solar constant reductions (e.g. taking a higher value of the climate sensitivity as default parameter), though some issues may appear. The uncertainty of global temperature response rises when does the SRM implemented. The temperature range for the 50% probability interval rises with increased SRM (for RCP6-SRM-1200 global temperature ranges within 0.57ºC, and within 2.37ºC for RCP6-SRM). In addition, it shows that the probability of falling below 0ºC relative to pre-industrial periods rises when does the deployed SRM (over 30% when the solar constant reduction is higher than 5 W m-2).

Ocean responses slower than the atmosphere to changes in the climate system (e.g. heat content change, sea level rise) (Meehl et al. 2007). The results here seems to be consistent, decreases in incoming solar radiation leads to relative high reductions in the ocean heat uptake (from 0.344 W m-2 to 0.985 W m-2) until a new equilibrium is reached, approximately within a century for low solar constant reductions (e.g. total amount blocked of 89.26 W m-2) or still converging 5 centuries later for high solar constant reductions (e.g total amount reduced of 2.456 W m-2).

6.1 Assumptions, limitations and uncertainties

This section discusses the assumptions, limitations and uncertainties involved on this work which constrain the results above presented and suggest future improvements and research.

The 2ºC target relative to pre-industrial levels to avoid dangerous disruptions in the climate system and its consequences adopted at the Copenhagen Accord might leave unaddressed several issues (UN FCCC 1992). In addition to the critique of global temperature change target of 2ºC (e.g. it might lead the Arctic sea-ice to disappear each summer, see Section 1) (Lenton and Schellnhuber 2007), it has been argue that there might be thresholds which are not fully linked to global surface temperature change. For example, rates of climate change may affect the ability of ecosystems to get adapted (e.g. migrations in altitude and latitude on rates of temperature rise, and coral reefs and mangroves on rates of sea level rise), or spatial gradient of forcing might disrupt the climate system (e.g. the monsoon phenomena and El Niño events) (Lenton 2011). Hence, the degree of geoengineering presented and discussed on this research may not be an accurate measure if the international commitment is revised (e.g. to more ambitious levels of 1.5ºC or 1ºC, and/or to a wider policy frame), or if risks that may lie outside the 2ºC target are taken into account for further discussions and research.

The results can be only as good as the data used, due to the assumptions, limitations and uncertainties involved on these. CDR options and their potential of removing CO2 from the atmosphere are surrounded by many assumptions and uncertainties. The best estimations of the total amount of CO2 that could be removed are ~300 PgC for afforestation and reforestation, ~500 PgC for bio-char, and a range between 453-3000 PgC of total storage capacity for air capture and storage (IPCC 2005; Lenton 2010), though substantial uncertainty involves these estimations (e.g. constraints, or issues of double-counting). The CO2 removal fluxes suggested may involve even higher uncertainty, ranging between 0.2-1.5 PgC yr-1 by 2050 and 0.3-3.3 PgC yr-1 by 2100 for afforestation and reforestation, approximately 1.74 PgC yr-1 by 2060 and 3.15 PgC yr-1 by 2100 for bio-char, and 10 PgC yr-1 by 2100 for air capture and storage, which leave an overall potential of 4-6 PgC yr-1 by 2050 and 6-14 PgC yr-1 by 2100 (Lenton and Vaughan 2009; Lenton 2010). In addition, these estimations do not account neither, the energy costs of the deployments that would reduce the net effectiveness of any solution if obtained from fossil fuels, and the economic constrains from the costs of implementing the geoengineering solutions (Lenton and Vaughan 2009). Hence, it seemed reasonable to halve the estimations on the fluxes and the total amounts of CO2 that could be removed from the atmosphere, and hold the deployment time, as data input for CDR solutions implemented on this research.

There are some limitations which affect the climate modelling realized on this work. First, those that arise when using MAGICC 6. The reduced complexity coupled carbon cycle climate model used emulates the original AOGCM and C4MIP models, thus it carries with the limitations involved on these former models. For example, there are substantial uncertainties on the original carbon cycle models related to fertilization, fire regimes or ocean circulation and chemistry (Meinshausen et al. 2011). Modelling is a simplification of the 'real world', and emulations can not simulate this any better than the original models. Furthermore, an incomplete knowledge of the forcings may lead, even in a perfect calibration (though limitations have been reported in Meinshausen et al. (2011)), to over- or under-estimate the climate response under a given forcing of an AOGCM. For instance, an AOGCM might include the first indirect aerosol effect of an effective radiative forcing of -0.4 W m-2 by 2005 since pre-industrial levels, though MAGICC attempts to emulate the AOGCM including the IPCC AR4 (2007) best estimation of -0.7 W m-2, therefore MAGICC will underestimate the temperature response of the AOGCM along the historical period (Meinshausen et al. 2011). There are a tested range of how AOGCM and carbon cycles models would behave, and uncertainties arise outside this range. Meinshausen et al. (2011) reports that the C4MIP were constrained only by a single emission scenario (SRES A2) until 2100, thus how the carbon cycle may behave under peaking scenarios (increasing and decreasing temperatures or concentrations), and beyond 2100 is not constrained. Note that this research does not use the RCP85 owing to an opposite behavior to that expected (Scott et al. 2011; Vaughan and Lenton 2011) on atmospheric CO2 concentration was found when applying SRM, which might be the result of the lack on C4MIP calibration procedure. MAGICC emulates only temperatures changes and some closely related variables (Meinshausen et al. 2011), such as ocean heat uptake (taken into account to calculate the SRM required), though precipitation changes are not modeled in MAGICC, and SRM options would likely lead to spatially inhomogeneous alterations on precipitation patterns (Govindasamy et al. 2008; Lunt et al. 2008). Finally, natural forcings (e.g.

volcanic and solar forcings) are not known beyond the present though these will be in the future, therefore, at this point assumptions should be made for future projections using climate models. MAGICC 6 emulating AOGCM assumes a constant negative forcing equal to the average over the 20th century for the volcanic forcing, setting this mean to zero (Meinshausen et al. 2011). For solar radiation forcing, this paper assumes the solar '11 years' cycle used in Meinshausen et al. (2011), which is close to the value in 2000.

Second, there are some limitations that should be held in mind when analyzing and/or using the above results related to the methodology applied. This work might be the first attempt of decreasing the incoming solar radiation to counteract the anthropogenic radiative forcing imbalance with an specific target (2ºC relative to pre-industrial levels), thus little is known about the methods. The research uses a climate sensitivity of 2.88ºC, due to this is the best estimation diagnosed on MAGICC after the AOGCM temperature responses were averaged (Meinshausen et al. 2011), although the best estimation of the IPCC AR4 is 3ºC, with a likely range of 2ºC-4.5ºC. Therefore, the results would be in somewhat different if other value of the climate sensitivity were applied. Furthermore, MAGICC uses 1765 as a starting year, though the AOGCM assume different years among them. Meinshausen et al. (2011) argue that this issue could lead to projections approximately 0.1ºC warmer relative to 1765 for the 21st century. Though this effect is minimised when a base period (e.g. 1980-1999) is taken for differences on future projections (Meinshausen et al. 2011), this work uses 1765 as a reference for changes on the global surface temperature. Furthermore, regarding to the deployment of geoengineering solutions some assumptions were made. This paper only implements three of CDR suggested in the literature, afforestation and reforestation, bio-char and air capture and storage, due to both, their overall potential to remove CO2 from the atmosphere lies substantially above than the potential suggested for the other solutions, and with simplification purposes. Although, the other solutions, even with less potential and/or higher constraints could contribute as well. Finally, assuming 2040 as a starting year for the SRM might be ambitious, although under the RCP45 and RCP6 scenarios it is required if there is the will to avoid exceeding 2ºC, even with the afforestation and reforestation, bio-char, and air capture and storage deployed.

Taken all together, the results presented here seem to be robust within the aims and the scope of this research, though it would be improved with a more comprehensive analysis.

7. Conclusion

There is high agreement that climate change is one of the greatest challenges that humankind faces, and current policies will likely lead to dangerous disruptions in the global climate system during the 21st century. The international commitment have adopted a global warming limit of 2ºC relative to pre-industrial levels as a target for mitigation efforts to reduce climate change risks. Although, it has been shown that significant efforts will be required to avoid exceeding this target. Geoengineering, looking for alternatively solutions, have been proposed as complement to mitigation measures. The objective of this work is to quantify the degree of geoengineering intervention that may be required to meet the 2ºC target under different future emission scenarios, which involves building custom carbon dioxide removal (CDR) scenarios, developing a methodology to implement the geoengineering solutions within MAGICC 6, especially for solar radiation management (SRM) to a specific target, and probabilistically assessing the different combined strategies resulted to avoid exceeding the 2ºC limit.

The carbon dioxide removal scenarios built are the result of the options suggested in the literature, taking into account both, their potential of removing carbon from the atmosphere, and their constraints (e.g. the flux and the total amount of carbon removed). This results roughly for RCP45 and RCP6 in ~200 years of carbon dioxide removal options, with 400 PgC removed due to afforestation-reforestation and bio-char activities (starting in 2030 and a maximum removal flux of 4 PgC yr-1 by 2130), and 800 PgC removed from air capture and storage measures (starting in 2050 and a maximum removal flux of 5 PgC yr-1 from 2100 to 2210). The carbon dioxide removal scenarios for RCP3-PD differs from the previous on the amount of total the carbon removed, due to 400 PgC are roughly its cumulative CO2 emissions (represented by 200 PgC on the above solutions respectively), and in the deployment period of ~450 years (peaking the removal carbon flux on ~1.74 PgC yr-1 in 2100 for decreasing afterwards). The methodology developed implements geoengineering solutions within MAGICC 6. Carbon dioxide removal options are represented in the emission scenarios as a subtraction of the former emissions (land changes emissions for afforestation-reforestation and bio-char, and fossil emissions for air capture storage). Whereas, solar radiation management options are implemented as a decrease in the solar constant to rectify the radiative forcing imbalance which exceeds

1.99ºC since pre-industrial levels, taking into account ocean heat uptake and the solar ‘11 years’ cycle. This research quantifies the degree of geoengineering solutions that might be required to meet the 2ºC target for different combined strategies and future emission scenarios. The RCP3-PD do not exceed the 2ºC limit, although applying the carbon dioxide removal solutions (~400 PgC), the global surface temperature could be restored to pre-industrial levels by approximately 2500. For RCP45 and RCP6 respectively to meet the target, deploying all carbon dioxide removal options (~1200 PgC) might require 0.7% and 1.55% of solar constant reduction, implementing air capture and storage (~800 PgC) may need a decrease in the incoming solar radiation of 0.73% and 1.82%, the deployment of the afforestation-reforestation and bio-char measures (~400 PgC) may require approximately 0.75% and 1.83% of solar constant reduction, and without implementing any carbon dioxide removal strategy may need a decrease in the solar constant of 0.99% and 2.23%. The probabilistic assessment of these combined strategies results in a range of 56.6%-78.8% of probability (90% probability interval) for the 600 emulations to avoid exceeding 2ºC since pre-industrial periods.

References

Akbari, H., Menon, S., & Rosenfeld, A. (2009). Global cooling: increasing world-wide urban albedos to offset CO2. *Climatic Change, 94*(3), 275-286.

Angel, R. (2006). Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proceedings of the National Academy of Sciences, 103*(46), 17184-17189.

Barrett, S. (2008). The Incredible Economics of Geoengineering. *Environmental and Resource Economics, 39*(1), 45-54.

Bazzaz, F. A. (1990). The Response of Natural Ecosystems to the Rising Global CO2 Levels. *Annual Review of Ecology and Systematics, 21*(1), 167-196.

Blackstock, J. J., & Long, J. C. S. (2010). The Politics of Geoengineering. *Science, 327*(5965), 527.

Bower, K., Choularton, T., Latham, J., Sahraei, J., & Salter, S. (2006). Computational assessment of a proposed technique for global warming mitigation via albedo-enhancement of marine stratocumulus clouds. *Atmospheric Research, 82*(1-2), 328-336.

Boyd, P. W. (2008). Implications of large-scale iron fertilization of the oceans. *Marine Ecology Progress Series, 364*, 213-218.

Caldeira, K., & Wickett, M. E. (2003). Oceanography: Anthropogenic carbon and ocean pH. *Nature, 425*(6956), 365.

Caldeira, K., & Wickett, M. E. (2005). Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. *J. Geophys. Res., 110*(C9), C09S04.

Cao, L., & Caldeira, K. (2008). Atmospheric CO2 stabilization and ocean acidification. *Geophys. Res. Lett., 35*(19), L19609.

Clarke, L., Edmonds, J., Jacoby, H., Pitcher, H., Reilly, J., & Richels, R. (2007). Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations. Sub-report 2.1A of Synthesis and Assessment Product 2.1 *US Climate Change Science Program and the Subcommittee on Global Change Research, Department of Energy, Office of Biological & Environmental Research* (pp. 154 pp.). Washington D.C., USA.

Crutzen, P. J. (2006). Albedo enhancement by stratospheric sulphur injections: A contribution to resolve a policy dilemma? *Climatic Change, 77*(3-4), 211–219.

Cullen, J. J., & Boyd, P. W. (2008). Predicting and verifying the intended and unintended consequences of large-scale ocean iron fertilization. *Marine Ecology Progress Series, 364*, 295-301.

Drake, B. G., González-Meler, M. A., & Long, S. P. (1997). MORE EFFICIENT PLANTS: A Consequence of Rising Atmospheric CO2? *Annual Review of Plant Physiology and Plant Molecular Biology, 48*(1), 609-639.

Elliott, S., Lackner, K. S., Ziock, H. J., Dubey, M. K., Hanson, H. P., Barr, S., . . . Blake, D. R. (2001). Compensation of atmospheric CO2 buildup through engineered chemical sinkage. *Geophys. Res. Lett., 28*(7), 1235-1238.

Falkowski, P., Scholes, R. J., Boyle, E., Canadell, J., Canfield, D., Elser, J., . . . Steffen, W. (2000). The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System. *Science, 290*(5490), 291-296.

Fleming, J. R. (2010). *Fixing the sky : the checkered history of weather and climate control*. New York: Columbia University Press.

Fujino, J., Nair, R., Kainuma, M., Masui, T., & Matsuoka, Y. (2006). Multi-gas Mitigation Analysis on Stabilization Scenarios Using AIM Global Model. *Energy J., 3*(Special Issue), 343-354.

Goldemberg, J., & Guardabassi, P. (2009). Are biofuels a feasible option? *Energy Policy, 37*(1), 10-14.

Govindasamy, B., & Caldeira, K. (2000). Geoengineering Earth's radiation balance to mitigate CO2-induced climate change. *Geophys. Res. Lett., 27*(14), 2141-2144.

Govindasamy, B., Caldeira, K., & Duffy, P. B. (2003). Geoengineering Earth's radiation balance to mitigate climate change from a quadrupling of CO2. *Global and Planetary Change, 37*(1-2), 157-168.

Govindasamy, B., Duffy, P. B., & Taylor, K. E. (2008). Impact of geoengineering schemes on the global hydrological cycle. *Proceedings of the National Academy of Sciences, 105*(22), 7664-7669.

Govindasamy, B., Thompson, S., Duffy, P. B., Caldeira, K., & Delire, C. (2002). Impact of geoengineering schemes on the terrestrial biosphere. *Geophys. Res. Lett., 29*(22), 2061.

Hamwey, R. (2007). Active Amplification of the Terrestrial Albedo to Mitigate Climate Change: An Exploratory Study. *Mitigation and Adaptation Strategies for Global Change, 12*(4), 419-439.

Hansen, J. E. (2005). A slippery slope: how much global warming constitutes 'dangerous anthropogenic interference'? *Climatic Change, 68*, 269-279.

Hare, B., & Meinshausen, M. (2006). How Much Warming are We Committed to and How Much can be Avoided? *Climatic Change, 75*(1), 111-149.

Harvey, L. D. D. (2008). Mitigating the atmospheric CO2 increase and ocean acidification by adding limestone powder to upwelling regions. *J. Geophys. Res., 113*(C4), C04028.

Hibbard, K. A., Meehl, G. A., Cox, P., & Friedlingstein, P. (2007). A strategy for climate change stabilization experiments. *Eos, 88*(20), 217, 219, 221.

Hijioka, Y., Matsuoka, Y., Nishimoto, H., Masui, M., & Kainuma, M. (2008). GlobalGHG emissions scenarios under GHG concentration stabilization targets. *J. Glob. Environ. Eng., 13*, 97-108.

IPCC. (2005). IPCC Special Report on Carbon Dioxide Capture and Storage *Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

IPCC. (2007). Climate Change 2007: Synthesis Report. In P. Core Writing Team, R.K. and Reisinger, A. (eds.) (Ed.), *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 104pp). Geneva, Switzerland: IPCC.

Karl, D. M., & Letelier, R. M. (2008). Nitrogen fixation-enhanced carbon sequestration in low nitrate, low chlorophyll seascapes. *Marine Ecology Progress Series, 364*(257-268).

Keith, D., Ha-Duong, M., & Stolaroff, J. (2006). Climate Strategy with CO2 Capture from the Air. *Climatic Change, 74*(1), 17-45.

Keith, D. W., Parson, E., & Morgan, M. G. (2010). Research on global sun block needed now. *Nature, 463*(7280), 426-427.

Kleypas, J. A., Buddemeier, R. W., Archer, D., Gattuso, J.-P., Langdon, C., & Opdyke, B. N. (1999). Geochemical Consequences of Increased Atmospheric Carbon Dioxide on Coral Reefs. *Science, 284*(5411), 118-120.

Knutti, R., & Hegerl, G. C. (2008). The equilibrium sensitivity of the Earth's temperature to radiation changes. *Nature Geoscience, 1*(11), 735-743.

Lampitt, R. S., Achterberg, E. P., Anderson, T. R., Hughes, J. A., Iglesias-Rodriguez, M. D., Kelly-Gerreyn, B. A., . . . Yool, A. (2008). Ocean fertilization: a potential means of geoengineering? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 366*(1882), 3919-3945.

Latham, J. (1990). Control of global warming? *Nature, 347*(6291), 339-240.

Latham, J., Rasch, P., Chen, C.-C., Kettles, L., Gadian, A., Gettelman, A., . . . Choularton, T. (2008). Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 366*(1882), 3969-3987.

Law, C. S. (2008). Predicting and monitoring the effects of large-scale ocean iron fertilization on marine trace gas emissions. *Marine Ecology Progress Series, 364*, 283-288.

Lenton, T. M. (2010). The potential for land-based biological CO2 removal to lower future atmospheric CO2 concentration. *Carbon Management, 1*(1), 145-160.

Lenton, T. M. (2011). Beyond 2°C: redefining dangerous climate change for physical systems. *Wiley Interdisciplinary Reviews: Climate Change, 2*(3), 451-461.

Lenton, T. M., & Schellnhuber, H. J. (2007). Tipping the scales. *Nature Publishing Group*(0712), 97-98.

Lenton, T. M., & Vaughan, N. E. (2009). The radiative forcing potential of different climate geoengineering options. *Atmos. Chem. Phys. Discuss., 9*(1), 2559-2608.

Long, S. P. (1991). Modification of the response of photosynthetic productivity to rising temperature by atmospheric CO2 concentrations: Has its importance been underestimated? *Plant, Cell & Environment, 14*(8), 729-739.

Lovelock, J. E., & Rapley, C. G. (2007). Ocean pipes could help the Earth to cure itself. *Nature, 449*(403), 403.

Lunt, D. J., Ridgwell, A., Valdes, P. J., & Seale, A. (2008). ''Sunshade World'': A fully coupled GCM evaluation of the climatic impacts of geoengineering. *Geophys. Res. Lett., 35*(12), L12710.

Macintosh, A. (2010). Keeping warming within the 2ºC limit after Copenhagen. *Energy Policy, 38*(6), 2964-2975.

MAGICC/SCENGEN 5.3: user manual (Version 2). Retrieved February 11, 2011, from http://www.cgd.ucar.edu/cas/wigley/magicc/UserMan5.3.v2.pdf

Matthews, H. D., & Caldeira, K. (2007). Transient climate-carbon simulations of planetary geoengineering. *Proceedings of the National Academy of Sciences, 104*(24), 9949-9954.

Meehl, G. A., Stocker, T. F., Collins, W., Friedlingstein, P., Gaye, A., Gregory, J., . . . Co-authors. (2007). Global climate projections. In D. Q. S. Solomon, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds. (Ed.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 747-846). Cambridge.

Meinshausen, M., Hare, B., Wigley, T., Van Vuuren, D., Den Elzen, M., & Swart, R. (2006). Multi-gas Emissions Pathways to Meet Climate Targets. *Climatic Change, 75*(1), 151-194.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., . . . Allen, M. R. (2009). Greenhouse-gas emission targets for limiting global warming to 2ºC. *Nature, 458*(7242), 1158-1162.

Meinshausen, M., Raper, S. C. B., & Wigley, T. M. L. (2011). Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmos. Chem. Phys., 11*(4), 1417-1456.

Meinshausen, M., Smith, S., & et al. (in prep.). The RCP greenhouse gas concentrations and their extension from 1765 to 2500. *Climate Change*(Special RCP Issue).

Meinshausen, M., Wigley, T. M. L., & Raper, S. C. B. (2011). Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 2: Applications. *Atmos. Chem. Phys., 11*(4), 1457-1471.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., . . . Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment. *Nature, 463*(7282), 747-756.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., . . . Dadi, Z. (2000). Special Report on Emissions Scenarios. In N. Nakicenovic & R. Swart (Eds.), *Cambridge Univ. Press*. Cambridge.

NAS. (1992). *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*. Washington, D.C: National Academy Press.

Orr, J. C., Fabry, V. J., Aumont, O., Bopp, L., Doney, S. C., Feely, R. A., . . . Yool, A. (2005). Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature, 437*(7059), 681-686.

Osborn, T., Raper, S., & Briffa, K. (2006). Simulated climate change during the last 1,000 years: comparing the ECHO-G general circulation model with the MAGICC simple climate model. *Climate Dynamics, 27*(2), 185-197.

Pearson, J., Oldson, J., & Levin, E. (2006). Earth rings for planetary environment control. *Acta Astronautica, 58*(1), 44-57.

Rajagopal, D., Sexton, S. E., Roland-Holst, D., & Zilberman, D. (2007). Challenge of biofuel: filling the tank without emptying the stomach? *Environmental Research Letters, 2*(4), 044004.

Raper, S. C. B., Wigley, T. M. L., & Warrick, R. A. (1996). Global Sea- level Rise: Past and Future. In J. Milliman & B. Haq (Eds.), *Sea-level rise and coastal subsidence: causes, consequences, and strategies* (pp. 11-45). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Riahi, K., Grubler, A., & Nakicenovic, N. (2007). Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technological Forecasting and Social Change, 74*(7), 887-935.

Ridgwell, A., Singarayer, J. S., Hetherington, A. M., & Valdes, P. J. (2009). Tackling Regional Climate Change By Leaf Albedo Bio-geoengineering. *Current Biology, 19*(2), 146-150.

Robock, A. (2008). 20 reasons why geoengineering may be a bad idea. *Bulletin of the Atomic Scientists, 64*(2), 14-59.

Rogelj, J., Nabel, J., Chen, C., Hare, W., Markmann, K., Meinshausen, M., . . . Hohne, N. (2010). Copenhagen Accord pledges are paltry. *Nature, 464*(7292), 1126-1128.

Ross, A., & Matthews, H. D. (2009). Climate engineering and the risk of rapid climate change. *Environ. Res. Lett., 4*(4), 045103.

Salter, S., Sortino, G., & Latham, J. (2008). Sea-going hardware for the cloud albedo method of reversing global warming. *Phil Trans R Soc A, 366*(1882), 3989-4006.

Scott, C., Vaughan, N., & Forster, P. (2011). *Potential temperature induced carbon-cycle feedbacks from solar radiation management geoengineering*. Paper presented at the EGU General Assembly 2011. http://meetingorganizer.copernicus.org/EGU2011/EGU2011-718.pdf

Shepherd, J., Cox, P., Haigh, J., Keith, D., Launder, B., Mace, G., . . . Watson, A. (2009). Geoengineering the Climate: Science, Governance and Uncertainty. In The Royal Society (Ed.). London.

Stenchikov, G., Hamilton, K., Stouffer, R. J., Robock, A., Ramaswamy, V., Santer, B., & Graf, H.-F. (2006). Arctic Oscillation response to volcanic eruptions in the IPCC AR4 climate models. *J. Geophys. Res., 111*(D7), D07107.

Stenchikov, G., Robock, A., Ramaswamy, V., Schwarzkopf, M. D., Hamilton, K., & Ramachandran, S. (2002). Arctic Oscillation response to the 1991 Mount Pinatubo eruption: Effects of volcanic aerosols and ozone depletion. *J. Geophys. Res., 107*(D24), 4803.

Tilmes, S., Müller, R., & Salawitch, R. (2008). The Sensitivity of Polar Ozone Depletion to Proposed Geoengineering Schemes. *Science, 320*(5880), 1201-1204. doi: 10.1126/science.1153966

Trenberth, K. E., & Dai, A. (2007). Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering. *Geophys. Res. Lett., 34*(15), L15702. doi: 10.1029/2007gl030524

United Nations Framework Convention on Climate Change. Retrieved August 11, 2011 from http://unfccc.int/essential_background/convention/background/items/2853.php

van Vuuren, D., den Elzen, M., Lucas, P., Eickhout, B., Strengers, B., van Ruijven, B., . . . van Houdt, R. (2007). Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic Change, 81*(2), 119-159.

van Vuuren, D. P., Meinshausen, M., Plattner, G.-K., Joos, F., Strassmann, K. M., Smith, S. J., . . . Reilly, J. M. (2008). Temperature increase of 21st century mitigation scenarios. *Proceedings of the National Academy of Sciences, 105*(40), 15258-15262.

Vaughan, N., & Lenton, T. (2011). A review of climate geoengineering proposals. *Climatic Change*, 1-46.

Wigley, T., Clarke, L., Edmonds, J., Jacoby, H., Paltsev, S., Pitcher, H., . . . Smith, S. (2009). Uncertainties in climate stabilization. *Climatic Change, 97*(1), 85-121.

Wigley, T. M. L. (2006). A Combined Mitigation/Geoengineering Approach to Climate Stabilization. *Science, 314*(5798), 452-454.

Wigley, T. M. L., & Raper, S. C. B. (1992). Implications for climate and sea level of revised IPCC emissions scenarios. *Nature, 357*(6376), 293-300.

Wigley, T. M. L., & Raper, S. C. B. (2001). Interpretation of High Projections for Global-Mean Warming. *Science, 293*(5529), 451-454.

Wingenter, O. W., Elliot, S. M., & Blake, D. R. (2007). New Directions: Enhancing the natural sulfur cycle to slow global warming. *Atmospheric Environment, 41*(34), 7373-7375.

Zeman, F. (2007). Energy and Material Balance of CO2 Capture from Ambient Air. *Environmental Science & Technology, 41*(21), 7558-7563.

Zhou, S., & Flynn, P. (2005). Geoengineering Downwelling Ocean Currents: A Cost Assessment. *Climatic Change, 71*(1), 203-220.