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Review of geoengineering approaches to mitigating climate change☆

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A B S T R A C T

Geoengineering, which is the intentional large-scale manipulation of the environment, has been suggested as an effective means of mitigating global warming from anthropogenic greenhouse gas emissions. In this paper, we will review and assess technical and theoretical aspects of land-based, atmosphere-based, ocean-based and space-based geoengineering schemes as well as their potential impacts on global climate and ecosystem. Most of the proposed geoengineering schemes carried out on land or in the ocean are to use physical, chemical or biological approaches to remove atmospheric CO_2. These schemes are able to only sequester an amount of atmospheric CO_2 that is small compared with cumulative anthropogenic emissions. Most of geoengineering schemes carried out in the atmosphere or space are based on increasing planetary albedo. These schemes have relatively low costs and short lead times for technical implementation, and can act rapidly to reduce temperature anomalies caused by greenhouse gas emissions. The costs and benefits of geoengineering are likely to vary spatially over the planet with some countries and regions gaining considerably while others may be faced with a worse set of circumstances than would be the case without geoengineering. Since current research on geoengineering is limited and various international treaties may limit some geoengineering experiments in the real world, the Geoengineering Model Intercomparison Project (GeoMIP) provides a framework of coordinated experiments for all earth system modeling groups to test geoengineering schemes. However, these experiments used on a global scale have difficulty with accurate resolution of regional and local impacts, so future research on geoengineering is expect to be done by combining earth system models with regional climate models.

1. Introduction

Due to global warming, the world is facing a series of unprecedented and major global environmental problems (Schaltegger et al., 2011; Princiotta, 2011), e.g. rising sea levels (Moore et al., 2011, 2013); drought (Strauss, F. et al., 2013); increased risk of hurricanes (Grinsted et al., 2013; Mannshardt and Gilleland, 2013); degradation of permafrost (Gao et al., 2013). The 2007 Fourth Assessment Report (AR4) by the Intergovernmental Panel on Climate Change (IPCC) of the United Nations indicated that most of the observed warming over the last 50 years is likely to have been due to the increasing concentrations of greenhouse gases produced by human activities such as deforestation and burning fossil fuel. This conclusion was made even stronger by the Fifth Assessment Report (AR5) released in 2013. The concentration of carbon dioxide (CO_2) in the atmosphere has increased from a pre-industrial value of about 280 ppm–391 ppm in 2011 (IPCC AR5, 2013). Under every future climate scenario except aggressive greenhouse mitigation scenario, global temperature will rise at least 2–3 °C before 2100. Under a "Business as usual" scenario, temperature will rise far higher in some regions and seasons such as the Arctic where virtual

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complete sea ice loss is likely by 2100. Changes of this magnitude will result in what is to all intents a complete different planet than the one we know and have experienced over the last few millennia. Projections of climate at this degree of perturbation from present day present significant challenges to global climate models/earth system models, and so the climate to be expected by the end of the century is, to a large degree, unknowable.

Given the extreme risk to civilization of continuing with essentially unrestrained fossil fuel burning, an important question for all is what are scientifically sound, economically viable, and ethically defendable strategies to mitigate the global warming trend and manage these climate risks? Reducing fossil fuel burning by using energy-saving & emission-reduction technologies in industries & agriculture is clearly the most direct strategy to combat the ongoing change in global climate (e.g. Geng et al., 2014; Upham et al., 2011; Cheah et al., 2013). Negotiations on carbon emissions reduction have largely failed because of lack of international trust and the unwillingness of most governments to pursue anything except blind short-term self-interest. The Kyoto Protocol and subsequent emissions negotiations have been obstructed repeatedly, particularly by representatives of the US government, but also by much of the developed world which has consistently failed to acknowledge their historical contribution to climate damage (Wei et al., 2011), and in some cases continues to deny basic science in the field. In response some scientists have proposed to use geoengineering (or climate engineering) to artificially cool the planet (Royal Society, 2009). Geoengineering is the intentional large-scale manipulation of the environment, particularly manipulation that is intended to reduce undesired anthropogenic climate change (Keith, 2000). Many different types of geoengineering have been proposed (Royal Society, 2009, 2011; Izrael et al., 2009), but while some of them involve slow and virtually risk free lowering of atmospheric CO_2 concentration (e.g. by afforestation), the main attraction of geoengineering lies in schemes that offer low-energy costs and short lead times for technical implementation. These geoengineering schemes would act rapidly to lower temperatures with significant decreases occurring within 1–2 years (Bala, 2009) and may be produce side effects at the same time (Moriarty and Honnery, 2010). Prolonged geoengineering would also curb sea level rise, which is arguably the largest climate risk since 150 million people live within 1 m of high tide globally, and coastal city growth is expected to surpass global average growth in the 21st century. Moderate geoengineering options can constrain sea-level rise to about 50 cm above 2000 levels in the RCP3PD and RCP4.5 future climate scenarios[1], but only aggressive geoengineering can similarly constrain the RCP8.5 future climate scenario (Moore et al., 2010). Importantly once started, geoengineering must be maintained for a very long period. Otherwise, when it is terminated, climate reverts rapidly to maintain a global energy balance. If greenhouse gas concentrations continue to rise, then unprecedented and highly damaging rapid climate change will then occur (the so-called "termination shock", Jones et al., 2013a,b).

Various geoengineering schemes have been suggested. According to the location where geoengineering are carried out, geoengineering can be divided into.

➢ Land-based Geoengineering,
➢ Ocean-based Geoengineering,
➢ Atmosphere-based Geoengineering,
➢ Space-based Geoengineering.

Among all geoengineering schemes, two fundamental difference methodologies are employed: (1) Using physical, chemical or biological approaches to removing atmospheric CO_2 (so-called "Carbon dioxide removal, CDR"). It is clear that CDR methods are least risky method. Main CDR schemes include large-scale afforestation and reforestation, biochar production, chemical weathering, CO_2 capture and storage, ocean fertilization etc. However, CDR schemes are able to only sequester an amount of atmospheric CO_2 that is small compared with cumulative anthropogenic emissions and are thus unable to prevent the mean surface temperature from increasing to well above 2° by the year 2100 (Keller et al., 2014). (2) Increasing planetary albedo (so-called "Solar Radiation Management, SRM"). SRM approach is to adjust the amount of sunlight reaching the Earth in order to balance long wave greenhouse gas forcing. Main SRM schemes include injecting sulfur into the stratosphere to block incoming sunlight, putting sun-shields/dust cloud in space to reflect sunlight, injecting sea salt into the air above the oceans to increase the reflectivity of clouds, etc. All of these schemes have a cooling effect, but the regional climate effects, especially effects on precipitation patterns, differ (Niemeier et al., 2014). Since SRM approach can decrease significantly solar radiation absorbed by the earth, it can rapidly lower global temperatures (Lenton and vaughan, 2009, 2013; Royal Society, 2009). Compared with CDM, SRM has the largest potential for preventing warming. However, SRM also has some large side effects and cannot be discontinued without causing rapid climate change (Keller et al., 2014).

Until now, only some relatively small-scale geoengineering experiments have been attempted, for examples:

➢ In 2010, the UK government approved an experiment to inject reflective particles (actually salt water aerosol at 1 km altitude) into the atmosphere which would help understand one of main geoengineering schemes (stratospheric sulfate aerosol injection). Finally due to public pressure, UK government suspended the experiment.
➢ In July 2012, Russ George and his partners in the Haida Salmon Restoration Corporation spread 100 tonnes of iron sulfate into the Pacific Ocean from a fishing boat 200 nautical miles west of the islands of Haida Gwaii. This kind of geoengineering experiment is an iron fertilization experiment. The aim is to increase the growth of the plankton and so absorb more atmospheric carbon dioxide, part of which will be permanently locked away as ocean sediment as the plankton dies off. Satellite images confirmed that the iron dump by Russ George spawned a plankton bloom as large as 10,000 square kilometers. For geoengineering a complex oceanic system, scientists are debating whether iron fertilization can lock carbon into the deep ocean over the long term, and have raised concerns that may be it harms ocean ecosystems, produces toxic tides and lifeless waters, and worsens ocean acidification. The unlicensed and secret experiment carried out by Russ George was seen by much of the scientific community as both deceitful and irresponsible. Various agencies that had provided support for the other parts of the scientific cruise (such as using monitoring buoys provided by NOAA) distanced themselves from this expedition.
➢ Afforestation and reforestation can offset anthropogenic carbon emissions and are being carried out in Asia, Europe and America,

[1] Representative Concentration Pathways (RCPs) are referred to as pathways of time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. The four RCPs, RCP3PD, RCP4.5, RCP6, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+3, +4.5, +6.0, and +8.5 W/m^2, respectively) due to the increasing concentrations of atmospheric greenhouse gases. "PD" means that radiative forcing peaks at approximately 3 W/m^2 before 2100 and then declines (Moss et al., 2008).

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for example: Three-North Shelterbelt Program (or the Green Great Wall), is the largest afforestation project in China.

Various international treaties may limit some geoengineering experiments in the real world - though it is not at all clear how in practice this would work (Royal Society, 2011; Kintisch, 2007). The technical risks and uncertainties of geoengineering climate are huge. The costs and benefits of geoengineering are likely to vary spatially over the planet with some countries and regions gaining considerably while others may be faced with a worse set of circumstances than would be the case without geoengineering (e.g. Haywood et al., 2013; Xia et al., 2014; Bala and Nag, 2012). Although some features of geoengineering strategies may be testable on small scales or in the laboratory, since we only have one actual Earth, for this moment almost all tests of global geoengineering must be done using Earth System Models (ESM). A suite of standardized geoengineering modeling experiments are being performed by 12 mainstream earth system modeling groups – the Geoengineering Model Intercomparison Project (GeoMIP) (Kravtiz et al., 2011, 2013a,b,c). Based on these experiments, researchers find that although many SRM geoengineering schemes can act rapidly to reduce temperature anomalies caused by greenhouse gas emissions, controlling all climate parameters (e.g. precipitation, climatic extreme events) is not possible.

2. Land-based geoengineering

Many geoengineering projects can be carried out on land. In this section, we will discuss impacts and side effects of these land-based geoengineering projects on global climate and ecosystem.

2.1. Large-scale afforestation and reforestation

Afforestation can increase the plant and soil sink of atmospheric CO_2 through photosynthesis and increase the biomass in both woody plants and soil microbial life. Afforestation and reforestation, such as the Guangxi watershed project in China, and the Haryana cooperative afforestation project in India, are financially supported by UNFCCC Clean Development Mechanism (CDM) which is designed to allow CO_2 emission-capped developed countries to offset part of their carbon emissions by funding carbon removal projects in developing countries. Although the forestry sector accounts for more than 17% of total global carbon emissions (IPCC, 2007), in 2010 afforestation and reforestation projects amounted to just 0.2% of total CDM projects due to financial constraints (international carbon price, transaction costs, additional income from agroforestry products, etc) and deficient technical knowledge in developing countries (Thomas et al., 2010). Globally more than 760 Million Hectare (Mha) of land, which includes 138 Mha for avoided tropical deforestation, 217 Mha for regeneration of tropical forests, and 345 Mha for plantations and agroforestry, is suitable for CDM projects, (Zomer et al., 2008). Hence the development potential for CDM projects on afforestation is huge and should play a larger, increasingly important role in the future. If more CDM projects are proposed and let more smallholder farmers and rural communities participate, it could significantly increase carbon sequestration within rural and agricultural landscapes.

Afforestation and reforestation also affect soil carbon cycling. Amounts of carbon lost or gained by soil are generally small compared with the accumulation of carbon in tree biomass (Paul et al., 2002). Using a Bayesian modeling framework to estimate the mean effects of afforestation on soil carbon sink, Hoogmoed et al. (2012) found that total soil carbon sink does not significantly change when converted from pasture to forest over a 30 year time period, However, in China, afforestation is accumulating soil carbon with rates of 30–74 g/m^2yr in the upper 40 cm of soil, and 10–20 years old plantations have the highest soil carbon accumulation rates (Shi and Cui, 2010). In degraded lands, researches always show that afforestation can add large quantities of carbon to the soil, e.g., in India, a 3–5-year old Jatropha plantation can add around 4000 kg plant biomass, equivalent to 1450 kg C/ha yr, with 800 kg as carbon in leaves, 150 kg of carbon in pruned twigs, and 495 kg carbon as deoiled Jatropha cake (Wani et al., 2012). In addition, since Jatropha grows in degraded, low fertility soils and its seeds yield 28–40% oil which can be used for producing biodiesel, Jatropha is a good biodiesel plant and a good alternative for fossil fuel (Divakara et al., 2010). Recent published literature focuses on the change of soil carbon on topsoil, e.g. Shi et al. (2013) showed that afforested cropland increased carbon storage by 33.3% and 17.5% at soil depths of 40–60 and 60–100 cm, respectively. In order to assess the uncertainty of carbon sequestration in afforestation caused by fire or tree pest hazards, Lewandrowski et al. (2014) set up a nice dynamic nested optimal-control model of carbon sink through afforestation. It will help to avoid over-investment on afforestation.

Large-scale afforestation/reforestation not only affects and alters global and regional carbon cycle, but also affects climate directly. On the global scale, if one converted potentially suitable land to forest, annual evapotranspiration would increase directly. Afforestation will affect runoff more in large river basins than that in small river basins (Iroumé and Palacios, 2013), and runoff in South American will be affected most compared with other regions (Trabucco, 2008). Afforestation of upland catchments with fast growing plantations can have significant impact on in situ water use, with consequent impacts on water availability downstream. In addition, large-scale afforestation/reforestation can decrease the local surface albedo and increases adjacent regional surface air temperatures. Moreover, this kind of albedo change may be results in more warming than that if no geoengineering was implemented (Keller et al., 2014).

2.2. Biochar production

Biochar production can be used to increase the land carbon sink by creating biochar and mixing it with soil. However, this process will involve additional energy cost which will bring additional carbon emissions. Pyrolysis is the most common process to produce biochar. Lehmann et al. (2006) estimated that current global potential production of biochar is about 0.6 gigatons (Gt) per year and by 2100, production of biochar will reach between 5.5 and 9.5 gigatons (Gt) per year.

2.3. Chemical weathering on land

Chemically weathering of silicate rocks, the most common rocks on earth, can reduce atmospheric CO_2 concentration and governs atmospheric/soil CO_2 uptake on very long geological timescales. Many human activities, such as acid rain, can accelerate the weathering process (Pierson-Wickmann et al., 2009; Clow and Mast, 2010). Some geoengineering schemes are just based on artificially increasing weathering processes via carbonic acid reactions (Oelkers et al., 2008; Rau, 2008). The corresponding chemical processes that determine weathering rates are basically simple, but the interactions between the chemical transport pathways, land and biological cover mean that schemes that accelerate atmospheric CO_2 consumption by chemical weathering and then cool climate must be complex. Chemical weathering depends on lithology, runoff or drainage intensity, hydrological flow path and seasonality, temperature, land cover/use, plant composition & ecosystem processes, and so on (Hartmann, 2009; Oelkers

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et al., 2008). The main chemical reactions involved in weathering-based geoengineering approaches are.

$$CaSiO_3 + 2CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2$$

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$$

Groundwater and streams are the major transport vector for products of chemical weathering and will release the dissolved materials into the oceans, so they need to be considered in geochemical weathering budgets (Schopka, 2012). Dissolution of carbonates in the terrestrial system is usually considered to be balanced by carbonate precipitation in the oceans. With the help of a multi-lithological model framework, one can consider to use the following two methods to evaluate the effects of weathering-based geoengineering on the removal of atmospheric CO_2:

➢ A reverse methodology, decomposing river chemistry into rock-weathering products (Gaillardet et al., 1999; Velbel and Price, 2007; Schulte et al., 2011).
➢ A forward-modeling approach based on relations between rock-weathering rates for lithological classes and dominant controls (Amiotte-Suchet et al., 2003)

2.4. Bioenergy with CO_2 storage (BECS)

In order to inhibit the increase of the concentration of atmospheric CO_2 and mitigate global warming, much attention has been paid to the reduction of CO_2 emission through more extensive use of bioenergy as well as the development of corresponding technologies on carbon sequestration. Liquid or solid fuels derived from biomass, such as corn-based ethanol, are a carbon-neutral energy source. Recently, scientists further suggested decreasing the amount of CO_2 emitted from a corn-based ethanol biorefinery through the co-cultivation of microalgae (Rosenberg et al., 2011). Carbon capture and storage (CCS) is an essential component of this type of geoengineering which otherwise would simply serve as less damaging substitute for fossil fuels. Compared with other geoengineering proposals, Bio-Energy with Carbon Storage (BECS) can provides a powerful tool for reducing CO_2 levels that is fast and risk-free. The implementation of a global bio-energy program will provide numerous side-benefits (Read and Lermit, 2005). However, a suitable carbon storage location may be physically far from a bioenergy production region, and this approach may be involves high costs for compression, transportation, and injection of CO_2.

2.5. Glacier-related geoengineering

Across the Arctic and parts of Antarctica, 21st century warming rates are expected to be fastest globally and cause the loss of sea ice and retreat of ice shelves, even the melting of ice sheets, particularly in Greenland. Partial deglaciation of the West Antarctic ice sheet could contribute 4–6 m or more to sea level rise. Sea-level rise damage can be grouped into loss of land, forced migration of people, and increased flood risk. Since 150 million people are living within 1 m of high tide all over the world and a sea level rise of 0.5 m by 2050 is estimated to put at risk about $28 trillion of assets (at today's prices) in major port cities (Lenton et al., 2009), there is an urgent need to design a geoengineering proposal with the aim of preventing the melting of glaciers - and the surrounding permafrost and sea ice cover. With the help of three-dimensional full Stokes ice flow model, Favier et al. (2012) investigated the effect of pinning points (such as high submarine peaks that touch the base of an ice shelf on the grounding line position). The grounding line is a key location where the inland ice begins to float, and conditions at this transition play an important role in the dynamics of the feeder glaciers and ice streams to the ice shelf. They showed that the grounding line can advance with addition of pinning points as the extra drag slows the ice down and increases the mass balance on the ice shelf. Therefore, one can consider to design a geoengineering scenario in the Greenland fjords, i.e., by building a dam in the fjord which would both block incoming warmer Atlantic waters from melting the ice shelves, and serve as a pinning point for the ice shelf to attach to as it advances. The generally cooler local climate induced by reduced melting and a more extensive ice cover compared with open water in the fjords would then serve to act as a larger scale climate feedback as the ice sheet grows and sea level rise is slowed.

2.6. Bio-geoengineering

The bio-geoengineering approach is to engineer climate with the help of the albedo differences between plants (Ridgwell et al., 2009) or land cover type. Recently, the Bristol Bio-geoengineering Initiative (BRISBI) has been created specifically to subject geoengineering schemes to quantitative assessment by using earth system models. In agriculture, crop plants often have a higher albedo than natural vegetation. However, different varieties of the same crop may have different albedo, so to carry out bio-geoengineering may require just a change in the variety of crop grown, which would not necessarily threaten food production. Singarayer et al. (2009) used the Hadley Centre coupled climate model (HadCM3) to assess the impact of crop albedo bio-geoengineering on regional climate and climate variability, finding that the effect of bio-geoengineering is different from region to region, e.g. if one increases crop canopy albedo by 0.04 (which represents a potential 20% increase in canopy albedo), the largest cooling of about 1 °C will occur in the summer of Europe, while the greatest cooling in winter is expected in South East Asia. The relatively low implementation costs of crop albedo bio-geoengineering make it potentially very attractive when compared to other geoengineering proposals (Ridgwell et al., 2009). In addition to crop plantations, the development of the livestock sector also changes land surface albedo, for example: Since the late 1970s, the impact of over-grazing and trampling reindeer has caused the gradual decrease of lichen cover in Fennoscandia and West Siberia, which results in an increase in coniferous forest and a decrease in land surface albedo. So the management of livestock can also be considered as a potential bio-geoengineering.

2.7. White roof method

The white roof method and other brightening of human settlements are also cheap and easy geoengineering schemes. Using light-colored roofing materials or simply painting roofs white can increase urban surface albedo. However, Jacobson and Hoeve (2012) indicated that a worldwide conversion to white roofs, accounting for their albedo effect only, will cool population-weighted temperatures by about 0.02 K but warm the earth overall by about 0.07 K. This is because white roofs will cool urban surfaces, and then prevent moisture from traveling upward to form clouds which will results in more sunlight hitting the Earth's surface. This means that the white roof method probably does not work for mitigating global warming.

2.8. Desert geoengineering

Two main geoengineering schemes are designed to be carried out in desert regions. One is large-scale forest planting in the

Sahara and Australian deserts in order to promote the net land carbon sink and capture atmospheric CO_2 (Ornstein et al., 2009). It is suggested to plant fast growing trees such as eucalyptus since 5 to 8 year-old eucalyptus plantations of about 1000 trees per hectare can sequester about $0.5–1 \times 10^4$ kg carbon per hectare per year. The economic cost for this approach is also reasonable, with only small irrigation costs. One potential side effect of desert afforestation will be the heightened trans-Saharan flux of disease-carrying avian species and so European and sub-Saharan regions may be at a greater risk of avian-borne disease (Manfready, 2011). The other method of desert geoengineering is through use of desert reflectors. Up to 11.6 million km^2 of desert regions might be suitable for albedo modification. Gaskill et al. (2004) suggested covering the deserts by a reflective polyethylene-aluminum surface in order to increase mean albedo from 0.36 to 0.8. One issue however is that the solar reflectors, panels or even reflective sheeting needs to be kept clear of dust for maximum efficiency. Except for covering deserts with reflective material in desert, researchers also consider solar farms as a mitigation method. Solar farms, which are the large-scale application of Solar Photovoltaic (PV) installations used to generate electricity, are quickly emerging as one of the best alternatives to fossil fuels. They do not belong to geoengineering schemes. Solar farms and covering deserts with reflective material could be in conflict—in any given area you can only do one or the other.

2.9. Physical and chemical CO_2 capture and storage

In order to mitigate climate change, a number of technologies aimed at direct carbon removal, such as carbon capture and storage (CCS), have been developed and applied in industries, agriculture and forestry (Chaudhry et al., 2013; Camara et al., 2013). For example, three CO_2 capture technologies for the cement industry are post-combustion absorptive capture, oxy-combustion and calcium looping post-combustion capture (Vatopoulos and Tzimas, 2012). Deep underground disposal is regarded as the most mature storage option, including oil and gas fields, deep rocks containing saline waters and unmineable coal formations, and ocean disposal (Li et al., 2009, 2013a,b). CO_2 geological storage and utilization has shown much potential for carbon mitigation according to the technology roadmap study of carbon capture, utilization, and storage (Li et al., 2013a,b). CO_2 geological storage, when combined with deep saline water recovery, not only achieves the relatively secure storage of CO_2 that is captured from the coal chemical industry, but also enhances saline water for drinking and industrial or agricultural utilization. This storage will undoubtedly become a win–win choice for the enhancement of energy security (Li et al., 2012, 2014a,b). Currently, CCS is advancing towards mature industrialization and commercialization, especially through the commissioning of CCS pilot plants. When one designs a CCS plant for a particular power station, many objectives, such as the capital cost of the new infrastructure, the operating costs, net power generated, the operability of the power station and the environmental impact of the CCS plant, are needed to be considered (Harkin et al., 2012). However, the still-high cost of CCS is one of the major concerns, in particular in developing countries (Li et al., 2011, 2013a,b).

3. Atmosphere-based geoengineering

Due to the burning of fossil fuels and land use change, the concentration of carbon dioxide (CO_2) in the atmosphere has increased from a pre-industrial value of about 280 ppm–391 ppm in 2011 (IPCC AR5, 2013). In order to reduce greenhouse gas effect, many atmosphere-based geoengineering schemes, such as stratospheric aerosols and cloud-albedo enhancement, are proposed.

3.1. Stratospheric aerosols

In June 1991, the second largest volcanic eruption of the twentieth century took place on Mount Pinatubo in the Philippines. In addition to the ash, Mount Pinatubo ejected between 15 and 30 million tons of sulfur dioxide gas which reflected sunlight back into space and so reduced global temperatures. In 1992–1993, the average temperature of the entire planet was cooled 0.4–0.5 °C. Simulating the effect of large volcanic eruptions on global climate is one of the major geoengineering proposals. Artificially increasing sulfate aerosols in the stratosphere will thus definitely mitigate global warming. Annual delivery costs are estimated to be $1–3 billion to deliver 1 megaton(Mt) sulfate aerosols to 20–30 km or $2–8 billion to deliver 5 megaton (Mt) sulfate aerosols (McClellan et al., 2012). The key unknowns are the unwanted impacts on other aspects of the earth system. Robock et al. (2009) pointed out that stratospheric geoengineering with sulfate aerosols have unintended and possibly harmful consequences including potential impacts on the hydrologic cycle and stratospheric ozone depletion. Aerosol geoengineering hinges on counterbalancing the forcing effects of greenhouse gas emissions with the forcing effects of aerosol emissions. If large quantities of SO_2, equivalent to almost a Pinatubo per year, are injected, sea level drops for several decades until the mid 21st century before the increasing greenhouse gas concentrations overcome the aerosol cooling and sea level starts to rise again (Moore et al., 2010). Eliseev et al. (2010) calculated that if the global temperature trend in every decade of this century is not to exceed 0.15 K/decade, geoengineering emissions of 2–7 teragram(Tg) SO_2 per year would be sufficient to mitigate global warming. However the large-scale interactions between continuously injected particles (in contrast with a large sudden volcanic injection) are not well understood. It is likely that aerosols will clump together to less radiatively efficient large particles, which will then fall out of the stratosphere faster than expected. These effects would likely mean that much more aerosol is needed to be injected than these relatively naive estimates suggest.

Kravitz et al. formulated the experiments in the Geoengineering Model Intercomparison Project (GeoMIP) which were designed to evaluate balancing radiative forcing from greenhouse gases with reduced short wave forcing by solar dimming or stratospheric aerosol injection. A suite of standardized climate modeling experiments are being performed by earth system modeling (ESM) groups (Kravitz et al., 2011). The fundamental experiments related to the stratospheric aerosol geoengineering are.

- ➢ (G3) Assume an RCP4.5 scenario. Inject sulfate aerosols beginning in 2020 to balance the anthropogenic forcing and attempt to keep the net forcing constant (at 2020 levels) at the top of the atmosphere.
- ➢ (G4) Assume an RCP4.5 scenario, and starting in 2020 injection of stratospheric aerosols at a rate of 5 teragram (Tg) SO_2 per year (equivalent to a 1991 Pinatubo eruption every four years) to reduce global average temperature to about 1980 values

Five earth system models (BNU-ESM, GISS-E2-R, HadGEM2-ES, MIROC-ESM, MIROC-ESM- CHEM) have been used to run G3 and G4 experiments. Several terabytes of data have been produced by the GeoMIP consortium with output from these modeling experiments. Based on analyzing these ESM outputs, Berdahl et al. (2014) indicated that stratospheric geoengineering is successful at producing some global annual average temperature cooling. During the geoengineering period from 2020 to 2070, the global mean rate of warming in RCP4.5 from 2020 to 2070 is 0.03 K/a (i.e. degrees Kelvin per annum), while it is 0.02 K/a for G4 and 0.01 K/a in G3. In Arctic regions, summer temperatures warming for RCP4.5 is 0.04 K/a, while it is 0.03 K/a and 0.01 K/a for G4 and G3 respectively. But neither G3 nor G4 experiment is capable of retaining 2020 September sea ice extents throughout the entire geoengineering period. After the cessation of sulfate aerosol injection, the climate system rebounds to the warmer RCP4.5 state quickly, and thus, any sea ice or snow retention as a result of geoengineering is lost within a decade (Berdahl et al., 2014).

Economic aspects beyond crude costing for geoengineering schemes have not been very well studied to date. Goes et al. (2011) used global economic model, carbon cycle model and climate model to analyze potential economic global cost-benefit analysis of aerosol geoengineering strategies. They indicated that substituting aerosol geoengineering for CO_2 abatement can fail an economic cost-benefit test, especially as unexpected side effects are inherently hard to properly quantify - this is of course true in both geoengineering and greenhouse gas forced climates (Weitzmann, 2009). Moreover, aerosol geoengineering has the potential to violate the requirements of justice. It is expected to alter regional precipitation patterns and thereby threaten some persons' access to adequate food and drinking water resources. It also poses serious risks to future generations. Some countries and regions gain considerably while others may be faced with a worse set of circumstances than would be the case without geoengineering, e.g. Haywood et al. (2013) discovered that large asymmetric stratospheric aerosol loadings concentrated in the Northern Hemisphere are a harbinger of Sahelian drought whereas those concentrated in the Southern Hemisphere induce a greening of the Sahel. Sudden cessation of aerosol geoengineering will result in rapid and dramatic climate change (termination shock) that leads to severe economic damages for future generations (Svoboda et al., 2011). Research on ethical and scientific analysis of stratospheric geoengineering is just at the beginning, more and more comprehensive researches will be carried out in the very near future (Tuana et al., 2012). In particular, further studies of the detailed regional impacts on the Sahel and other vulnerable areas are required to inform policymakers in developing careful consensual global governance before any aerosol geoengineering scheme is implemented (Haywood et al., 2013).

3.2. Cloud-albedo enhancement

Cloud brightening through seeding of clouds with chemicals or sea water aerosol particles can produce negative forcing sufficient to maintain the Earth's average surface temperature. Latham et al. (1990) proposed that the reflectivity of marine stratocumulus clouds can be increased by spraying submicron drops of sea water into the marine boundary layer. They indicated that with the correct drop size, the amounts of spray needed to give a useful reduction of incoming power are surprisingly small. In order to carry it out, Neukermans et al. (2014) designed a simple apparatus built to heat and spray saltwater through a small orifice. It comprises water reservoirs, a pump, a pressure gage, a serpentine heating tube enclosed in a block heater, and a nozzle enclosed in a separate block heater. Experimental results showed spray seems quite efficient. The costs and benefits of this geoengineering proposal are likely to be widely varying spatially over the planet. Although marine cloud brightening can act rapidly to reduce temperature anomalies caused by greenhouse gas emissions, controlling all climate parameters is also not possible. Alterskjær et al. (2013) indicated that marine cloud brightening can enhance evaporation, cloud formation, and precipitation over low-latitude land regions. Bala et al. (2011) indicated that when cloud droplets are reduced in size over all oceans uniformly to offset the temperature increase from a doubling of atmospheric CO_2, the global-mean precipitation decreases by about 1.3% but runoff over land increases by 7.5% primarily due to increases over tropical land. In comparison, an increase in land albedo leads to precipitation and runoff decreases over land by 13.4% and 22.3%, respectively (Bala et al., 2012). Thus albedo enhancement over oceans produces less impact on the global hydrological cycle than do albedo changes on land (Bala et al., 2012).

Kravitz et al. (2013a,b,c) proposed three new geoengineering modeling experiments to stimulate marine cloud brighten proposal which are added to GeoMIP. The first experiment involves a uniform increase in ocean albedo to offset an instantaneous quadrupling of CO_2 concentrations from preindustrial levels. The second experiment involves increasing cloud droplet number concentration in all low-level marine clouds to offset some of the radiative forcing of an RCP4.5 scenario. The third experiment involves injection of sea spray aerosols into the marine boundary layer between 30°S and 30°N to offset 2 W/m^2 of the effective radiative forcing of an RCP4.5 scenario. Currently, various earth system modeling groups are running these experiments. Based on these model outputs, researchers will further analyze the impact of marine cloud brighten scheme on land-sea temperature contrast, Arctic warming, and large shifts in annual mean precipitation patterns in difference regions.

4. Ocean-based geoengineering

Covering 70% of the earth's surface, the oceans contain approximately 50 times the carbon present in the atmosphere. The annual carbon flux between the atmosphere and the oceans is approximately 100 petagram (Pg) (Raven and Falkowski, 1999), so ocean-based geoengineering has apparently large potential for development.

4.1. Ocean fertilization

Marine phytoplankton plays a very large role in the global carbon cycle. Photosynthesis by marine phytoplankton not only consumes CO_2 but also nitrogen (N), phosphorus (P), and iron (Fe). Since N and P levels are generally sufficient for marine life compared with the concentration of Fe in ocean, adding iron (Fe) into ocean can stimulate phytoplankton growth and photosynthesis. This can potentially enhance carbon sequestration and hence reduce atmospheric carbon dioxide concentrations (Buesseler et al., 2008; Williamson et al., 2012). However, increased phytoplankton growth by iron fertilization could cause positive effects on overfished fish stocks and negative effects on the development of toxic algal blooms (Bertram et al., 2010). Rickels et al. (2009) showed that if ocean iron fertilization is implemented for 10 years, 0.4–2.2 Gt/a carbon will be stored in the Southern Pacific Ocean. Carbon offsets from iron fertilization projects cannot be traded on regulated carbon markets such as the European Union Emission Trading Scheme (EU ETS) or the Chicago Climate Exchange (CCX) (Bertram, 2010). The risk associated with modifying the oceanic carbon cycle may appear immense. Less is known of the oceans than the far side of the Moon. Initiating a change in the basic lowest level food web member (the plankton) will certainly have impacts throughout the whole ecology of the ocean. The furious reactions to the Russ George experiments were a consequence of both scientific deception and fears of unintended side effects. One imagines that implementing such a geoengineering solution will require considerable progress in ocean modeling and a change of heart of both the scientific and general public before it becomes acceptable.

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4.2. Ocean alkalinity

Oceans are the largest active carbon sink on Earth. Although the percentage of anthropogenic CO_2 uptake by the ocean sink with respect to the total CO_2 emissions has decreased during the last decade (Le Quéré et al., 2009), one third of the total anthropogenic CO_2 emissions inventory is stored in the oceans (Sabine et al., 2004). This will reduce further in the future as a warmer ocean can contain less CO_2, and the acidity of the oceans increases. Scientists have considered putting more lime into ocean in order to increase ocean carbon storage. The basic principle for this geoengineering project is.

$$Ca(OH)_2 + 2CO_2 \rightarrow Ca^{2+} + 2HCO_3^-$$

This represents a cure for both increasing ocean acidity and increased atmospheric concentrations of CO_2. The practical problems are probably mainly associated with mining and dispersal of suitable rock into the ocean. However, as with iron fertilization, there are some ethical and ecological questions that must be addressed concerning the impact of changing ocean chemistry.

4.3. Geoengineering ocean currents

The deep ocean has a significantly higher concentration of total carbon than shallow oceans as these waters are much colder than surface ones. Downwelling ocean currents that carry carbon into the deep ocean plays a role in controlling the level of atmospheric carbon. One geoengineering scheme is to add additional carbon dioxide to downwelling currents since sea water is not CO_2 saturated at the point where it sinks (Badescu and Cathcart, 2011). The other geoengineering scheme is to enhance downwelling currents. This is theoretically feasible since a number of industrial methods, such as forced draft heat exchangers, injection of cold air, and formation of thicker sea ice can be used to transfer heat, with or without the transfer of mass, from fluids to the atmosphere (Zhou and Flynn, 2005; Badescu and Cathcart, 2011). However the corresponding technological requirements, costs and side effects are largely uninvestigated at present.

5. Space-based geoengineering

The most common space-based geoengineering scheme is to position sun-shields in space to reflect the solar radiation. The ideal place for sun-shields is the L1 Lagrangian point (1.5×10^6 km from Earth) where the gravitational fields of the Earth and the Sun are in balance and allow a small mass to remain stationary relative to Earth. A dust ring or dust cloud placed in Earth orbit also belongs to space-based geoengineering schemes (Bewick et al., 2012). Their main advantage lies in that they can act rapidly to mitigate climate change with significant global mean temperature decreases.

Space-based geoengineering schemes do not increase global albedo but they reduce total solar insolation mimicking an increase in global albedo, while many schemes in previous sections only deal with increasing regional albedo. Since two experiments in Geoengineering Model Intercomparison Project (GeoMIP) are related to solar dimming (effectively increasing global albedo), one can use the outputs of GeoMIP to analyze the impact of space-based geoengineering on the global climate system. The detail of these two relevant experiments in GeoMIP is as follows.

- (G1). The experiment is started from the pre-industrial climate control run. An instantaneous quadrupling of CO_2 concentration from pre-industrial levels is balanced by a reduction in the solar constant (is equivalent to increasing of albedo in the real world) and the experiment is run for 50 years to allow many medium term feedbacks to occur.
- (G2). The experiment is started from the pre-industrial climate control run. The positive radiative forcing of an increase in CO_2 concentration of 1% per year is balanced by a decrease in the solar constant until year 50, then the geoengineering is switched off and the experiment run with just the greenhouse gas forcing for a further 20 years.

Until now, 12 earth system modeling groups, such as CESM, HadCM3, CanESM2, CSIRO Mk3L, GISS-E2-R, NorESM1-M, BNU-ESM and MIROC-ESM, have participated in GeoMIP and have submitted the corresponding experiment results on G1/G2.

G1 is a completely artificial experiment and cannot be interpreted as a realistic geoengineering scheme, so the results from G1 are designed to discover the main impacts of balancing long wave greenhouse radiative forcing with short wave reductions and may help to interpret the results of more "realistic" geoengineering experiments. Under the G1 scenario, Kravitz et al. (2013a,b,c) showed that the global temperatures are well constrained to pre-industrial levels, though the polar regions are relatively warmer by approximately 0.8 °C, while the tropics are relatively cooler by approximately 0.3 °C. Furthermore land regions warm and oceans cool. Tilmes et al. (2013) showed that a global decrease in precipitation of 0.12 mm/day (4.9%) over land and 0.14 mm/day (4.5%) over the ocean can be expected. For the Arctic region, Moore et al. (2014) showed that G1 returns Arctic sea ice concentrations and extent to preindustrial conditions with intermodel spread of seasonal ice extent being much greater than the difference in ensemble means of preindustrial and G1. Regional differences in concentration across the Arctic amount to 20% and the overall ice thickness and mass flux are greatly reduced (Moore et al., 2014). However, compared with climate under the quadrupled CO_2 forcing which leads to virtual loss of sea ice summer, the G1 scenario is much closer to the conditions experienced in recent decades and centuries. Curry et al. (2014) examined further climatic extreme events under geoengineering scenario. Compared to the preindustrial climate, changes in climate extremes under G1 are generally much smaller than under quadrupld CO_2 alone. However, it is also the case that extremes of temperature and precipitation in G1 differ significantly from those under preindustrial conditions. Globally, G1 is more effective in reducing changes in temperature extremes compared to precipitation extremes.

Compared with G1, G2 is a relatively realistic geoengineering experiment. Jones et al. (2013a,b) focused on the impact of the sudden termination of geoengineering after 50 years of offsetting a 1% per annum increase in CO_2 and found that significant climate change would rapidly ensue upon the termination of geoengineering, with temperature, precipitation, and sea-ice cover very likely changing considerably faster than would be experienced under the influence of rising greenhouse gas concentrations in the absence of geoengineering. Xia et al. (2014) researched the combined effect of simulated climate changes due to geoengineering and CO_2 fertilization. Under G2 scenario, it can change rice production in China by -3.0 ± 4.0 megaton (Mt) ($2.4 \pm 4.0\%$) and increase Chinese maize production by 18.1 ± 6.0 megaton (Mt) ($13.9 \pm 5.9\%$). The termination of geoengineering shows negligible impacts on rice production but a 19.6 megaton (Mt) (11.9%) reduction of maize production.

6. Discussions and conclusions

Scientific discussion and research on geoengineering is today far more acceptable than that in just a few years ago. IPCC AR4(2007) does not consider geoengineering worth more than a passing

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mention while IPCC AR5(2013) has several sections on geoengineering (Section 6.5 for CDR, and Section 7.7 for SRM). Most of the proposed CDR geoengineering schemes are to be carried out on land or in the ocean, while most of the SRM geoengineering schemes are to be carried out in the atmosphere or space. CDR schemes are able to only sequester an amount of atmospheric CO_2 that is small compared with cumulative anthropogenic emissions. At the same time, the general public seems to be anti-SRM-geoengineering at present, which may be related to a trend towards climate change denial amongst parts of the developed world - especially in the US. Few of the population wants to believe a future where the alternatives are between catastrophic climate change and the myriad risks associated with global SRM geoengineering, even fewer want to acknowledge that their lifestyle will lead them to this choice. But given the lack of political will to do serious mitigation, it appears increasingly likely that actually those are the only choices available. Among all SRM geoengineering schemes, injecting sulfur into the stratosphere to block incoming sunlight, putting sun-shields/dust cloud in space to reflect sunlight, and injecting sea salt into the air above the oceans to increase the reflectivity of clouds have relatively low costs, short lead times for technical implementation and can rapidly mitigate climate change with significant global mean temperature decreases, so these three SRM geoengineering schemes have advantages over other schemes and have the largest potential to be used for preventing warming. Current geoengineering research has mostly focused on physical science aspects while research on law, governance, economics, ethics, and social policy of geoengineering is very limited, so geoengineering idea is still far from deployment-ready. The drawbacks of SRM geoengineering schemes remain large, and not easily overcome. Although SRM geoengineering schemes can act rapidly to mitigate climate change with significant global mean temperature decreases, unwanted side-effects, such as diminished rainfall in some regions, would certainly also occur alongside the intended effect. The costs and benefits of geoengineering schemes are likely to be widely varying spatially over the planet with some countries and regions gaining considerably while others may be faced with a worse set of circumstances than would be the case without geoengineering. Importantly once started, SRM geoengineering must be maintained for a very long period. Otherwise, when it is terminated, climate reverts rapidly to maintain a global energy balance. Therefore, with the help of earth system models, evaluating the potential effectiveness, risks and climate feedbacks of different geoengineering schemes is important for governing large-scale field experiments of geoengineering in ways that effectively manage their climatic and societal impacts in the future. The Geoengineering Model Intercomparison Project (GeoMIP) provides a framework of coordinated experiments for all earth system modeling groups, eventually allowing for robustness of results to be achieved. In the current stage of GeoMIP, the four proposed experiments (G1-G4) are underway and three new experiments are suggested to add. However these experiments used on a global scale have difficulty with accurate resolution of regional and local impacts, so future research on geoengineering is expect to be done by combining earth system models with regional climate models.

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