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Review

Geoengineering: Basic science and ongoing research efforts in China

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Abstract

Geoengineering (also called climate engineering), which refers to large-scale intervention in the Earth's climate system to counteract greenhouse gas-induced warming, has been one of the most rapidly growing areas of climate research as a potential option for tackling global warming. Here, we provide an overview of the scientific background and research progress of proposed geoengineering schemes. Geoengineering can be broadly divided into two categories: solar geoengineering (also called solar radiation management, or SRM), which aims to reflect more sunlight to space, and carbon dioxide removal (CDR), which aims to reduce the CO_2 content in the atmosphere. First, we review different proposed geoengineering methods involved in the solar radiation management and carbon dioxide removal schemes. Then, we discuss the fundamental science underlying the climate response to the carbon dioxide removal and solar radiation management schemes. We focus on two basic issues: 1) climate response to the reduction in solar irradiance and 2) climate response to the reduction in atmospheric CO_2. Next, we introduce an ongoing geoengineering research project in China that is supported by National Key Basic Research Program. This research project, being the first coordinated geoengineering research program in China, will systematically investigate the physical mechanisms, climate impacts, and risk and governance of a few targeted geoengineering schemes. It is expected that this research program will help us gain a deep understanding of the physical science underlying geoengineering schemes and the impacts of geoengineering on global climate, in particular, on the Asia monsoon region.

Keywords: Geoengineering; Climate change mitigation; Carbon dioxide removal; Solar geoengineering

1. Introduction

Since the beginning of the industrial revolution, human activities have led to large amounts of CO_2 emissions into the atmosphere. It is estimated that between 1750 and 2011, 555 ± 85 PgC (1 PgC $= 10^{15}$ gC) of CO_2 has released by human activities, including fossil fuel and cement emissions and land use changes (Ciais et al., 2013). The emissions of anthropogenic carbon have caused an increase in atmospheric CO_2 of approximately 40% since pre-industrial times (Ciais et al., 2013). Increasing concentrations of atmospheric CO_2 and other greenhouse gases (e.g. CH_4, N_2O) by trapping more heat in the atmosphere has profound impacts on the Earth's climate system. Observations show that since pre-industrial times, global mean surface temperature has increased by ~0.8 °C and global mean sea level has risen by ~0.2 m (IPCC, 2013). Increase in the ocean heat content, decline in glaciers and snow cover, and shrinkage in Arctic sea ice area are all evidence of a changing global climate (IPCC, 2013). Through the changes in the background climate, global warming also

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influences the frequency and intensity of extreme climate events, which usually have a greater effect on our society than the mean climate state (IPCC, 2013).

If the current trend of anthropogenic CO_2 continues, by the end of this century, the Earth's surface is likely to experience an additional warming of 3–5 °C and the global sea level is likely to rise by an additional 0.5–1 m (IPCC, 2013). Moreover, the possibility for some elements of the Earth's climate system to cross their tipping points would increase (Lenton et al., 2008). Projections have shown the potential possibility for the dieback of the Amazon rainforest, melting of Antarctic ice sheets, disruption of Indian summer monsoon, and release of CH_4 and CO_2 from permafrost (Lenton et al., 2008), which would have far-reaching effects on the ecosystem and our society.

To prevent further warming, the safest way is to reduce anthropogenic CO_2 emissions. However, there is a substantial lag of temperature response to the reduction in CO_2 emissions because of the inertia of the climate system (which mainly stems from the ocean) and the inertia of the carbon cycle. Modeling studies have shown that even if a complete cessation of anthropogenic CO_2 emissions could be achieved, warming caused by previously emitted CO_2 would remain for several centuries (Matthews and Caldeira, 2008; Cao and Caldeira, 2010a). In case of climate emergency, there is a potential need to rapidly cool the Earth. The new concept of geoengineering, also called climate engineering, has been proposed as a potential means to respond to the risks of climate change.

Geoengineering, which is defined as "a broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate impacts of climate change" (IPCC, 2013) involves two broad classes of methods (Caldeira et al., 2013). The carbon dioxide removal (CDR) approach aims to deal with the root problem of global warming by removing excess CO_2 from the atmosphere and sequestering the carbon in the ocean, terrestrial biosphere, or geological reservoirs. The solar geoengineering approach seeks to offset the warming effect from enhanced greenhouse gas levels by increasing the amount of sunlight reflected back to space. In Section 2, we provide an overview of these two categories of geoengineering approaches with the focus on the underlying physics acting on the climate system. In Section 3 we discuss the ongoing geoengineering research program in China. Discussion and conclusions are given in Section 4.

2. Physics of geoengineering

2.1. Solar geoengineering

2.1.1. Overview of proposed approaches

Solar geoengineering, also called solar radiation management, aims to counteract global warming by reflecting solar radiation to space. In principle, to offset the greenhouse gas-induced warming only requires the reduction of a small fraction of incoming sunlight to the Earth. For example, a doubling of atmospheric CO_2 would cause a net radiative forcing at the top-of-the-atmosphere (TOA) of approximately 4 W m^{-2}. On an average, the Earth absorbs approximately 240 W m^{-2} of solar radiation at the top-of-the-atmosphere. Therefore, offsetting the radiative forcing due to a doubling of atmospheric CO_2 only requires a 1.7% reduction (4 W m^{-2}/240 W m^{-2}) of incoming solar radiation. In principle, a reduction of incoming sunlight can be achieved by the following means. In the following, we briefly discuss solar geoengineering approaches with a schematic illustration shown in Fig. 1.

(1) Space-based method.

A few approaches have been proposed to reflect more sunlight back to space via placing certain types of reflectors (a large mirror, trillions of small spacecraft, and a large ring of space dust) in space (Early, 1989; Angel, 2006; Pearson et al., 2006). The reflectors can be placed near the first Lagrange point (L1) of the Earth–Sun system (L1 is a neutrally stable point on the axis between Earth and the Sun where the forces pulling an object toward the Sun are exactly balanced by the forces pulling an object toward the Earth).

(2) Stratosphere aerosol injection.

A widely proposed solar geoengineering method is the injection of scattering aerosols into the stratosphere with the basic idea of using these aerosols to scatter solar radiation back to space (Teller et al., 1997; Crutzen, 2006; Robock et al., 2009). A direct but imperfect natural analog of the stratosphere-aerosol-injection-based method is the eruption of Mount Pinatubo in 1991, which was followed by a peak global cooling of approximately 0.5 °C in the following year (Robock and Mao, 1995; Robock et al., 2013). Most stratospheric

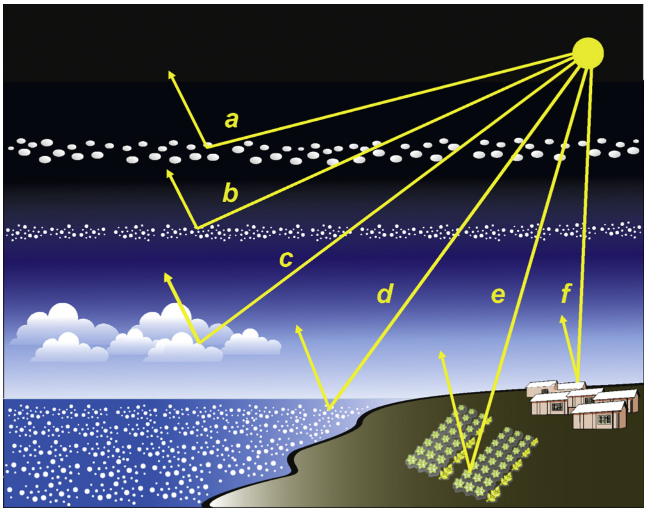

Fig. 1. Schematic diagram illustrating solar geoengineering approaches, *a*—using space mirrors, *b*—injecting aerosols into the stratosphere, *c*—brightening marine clouds, *d*—making the ocean surface more reflective, *e*—growing more reflective plants, and *f*—whitening roofs and other built structures (Caldeira et al., 2013).

aerosol methods have been focused on sulfate aerosols, though other types of stratospheric aerosol particles have been suggested (Teller et al., 1997). A number of factors such as the aerosol particle size and life cycle, spatial and temporal injection strategies, and the chemical interactions with ozone need to be considered for the stratospheric aerosol methods (Robock et al., 2009; Niemeier et al., 2011; Peter and Groß, 2012; Timmreck, 2012).

(3) Marine cloud brightening.

The idea of marine cloud whitening is to deliberately introduce fine particles near the base of low clouds, thereby increasing the cloud droplet number and making the cloud reflect more sunlight (Twomey, 1977). In practice, to increase the number of cloud condensation nuclei (CCN), a fine seawater mist can be sprayed into the remote marine atmospheric boundary layer by conventional ocean-going vessels, aircraft, or specially designed unmanned remotely controlled sea craft (Salter et al., 2008). It was estimated that the net radiative forcing from a doubling of the natural cloud droplet concentrations in regions of low-level maritime clouds could roughly offset the radiative effect from a doubling of atmospheric CO_2 (Latham et al., 2008). However, the processes that control cloud droplet formation and the coupling between salt droplets and clouds remain poorly understood. Interactions between cloud microphysics and indirect effects of aerosols on clouds also complicate the effect of cloud seeding (Chen et al., 2012; Rosenfeld et al., 2013).

(4) Surface albedo-based method.

The Earth can be intentionally cooled by increasing the surface albedo to reflect more sunlight back to space. Various methods have been proposed to increase the albedo of the Earth's surface (Gaskill, 2004; Akbari et al., 2009; Ridgwell et al., 2009). Roof tops and road surfaces in urban areas can be painted white to increase their reflectivity. Specific choices of crop varieties can be used to increase surface albedo. Desert areas can be covered by reflective materials to increase their albedo. Microbubbles can be created under the surface of the ocean to increase the ocean's reflectivity. The cooling effects of these proposed schemes appear to be local in scale; however, there are many unanswered technical and environmental questions associated with these schemes.

2.1.2. Underlying physics of solar geoengineering

Of all the solar geoengineering methods discussed above, the underlying idea is to reduce the amount of solar radiation reaching the atmosphere and/or surface. What is the difference between the climate response to CO_2 forcing and solar forcing? What is the response of the climate system in a world with a high CO_2 concentration and reduced solar irradiance, and what is the fundamental physics underlying the response? These questions are important for a deep understanding of the potential climate consequences in response to solar geoengineering.

A number of idealized climate model simulations of solar geoengineering have been performed wherein the incoming solar radiation is uniformly reduced by a certain amount to offset the warming caused by increased atmospheric CO_2 (Govindasamy and Caldeira, 2000; Govindasamy et al., 2003; Bala et al., 2008; Caldeira and Wood, 2008; Irvine et al., 2009). As discussed above, as a rough approximation, in these model simulations an approximately 2% reduction in solar constant is able to offset the radiative forcing caused by a doubling of atmospheric CO_2. It was found that a uniform reduction in solar irradiance could offset mean global warming caused by increased atmospheric CO_2; however, the cooling effect is not uniformly distributed. In general, a uniform reduction in solar irradiance would cause an overcooling in the tropics and a residual warming at high latitudes. This is because solar insolation has a latitudinally and seasonally dependent pattern, and thus, a uniform fractional reduction in insolation will reduce the downward shortwave radiation more at the tropics than at the high latitudes. In contrast, CO_2 is a well-mixed gas and has a more uniformly distributed radiative forcing with latitude.

Furthermore, if solar geoengineering is used to offset mean global warming, there would be a decrease in the global hydrological cycle. Modeling studies have found that in a geoengineered world when mean global warming is near zero, there is a substantial reduction in the amount of precipitation, particularly in the tropical regions (Fig. 2) (Govindasamy et al., 2003; Bala et al., 2008; Caldeira and Wood, 2008; Ferraro et al., 2014; Kalidindi et al., 2014). This reduction in precipitation is a result of the fundamental difference between the effects of CO_2 forcing and those of solar forcing on the thermal structure of the atmosphere. In the absence of surface temperature changes, absorption of longwave radiation by increased atmospheric CO_2 increases the vertical stability of the atmosphere, suppressing convective activities and precipitation (Cao et al., 2012). Compared with CO_2 forcing, the atmosphere is much more transparent to solar radiation. Therefore, in the absence of surface temperature changes, the change in solar irradiance has a much smaller effect on the vertical stability of the atmosphere and thus little influence on precipitation (Andrews et al., 2009; Cao et al., 2012). Given these facts, in a geoengineered world with near-zero surface temperature changes, there would be a reduction in global precipitation due to CO_2-induced stability changes in the atmosphere.

In addition to causing global warming through the well-known greenhouse effect, increases in atmospheric CO_2 also affect the climate system through their impact on plant physiology (Sellers et al., 1996). Experimental studies have shown that increasing atmospheric CO_2 concentrations tend to reduce the opening of plant stomata, decreasing transpiration to the atmosphere (Field et al., 1995). This effect, called CO_2-physiological forcing, has important implications for the climate system (Boucher et al., 2009; Cao et al., 2010). Solar geoengineering, while aiming to offset the greenhouse effect of increased atmospheric CO_2, is not able to offset the CO_2-physiological forcing. In a geoengineered world, the residual

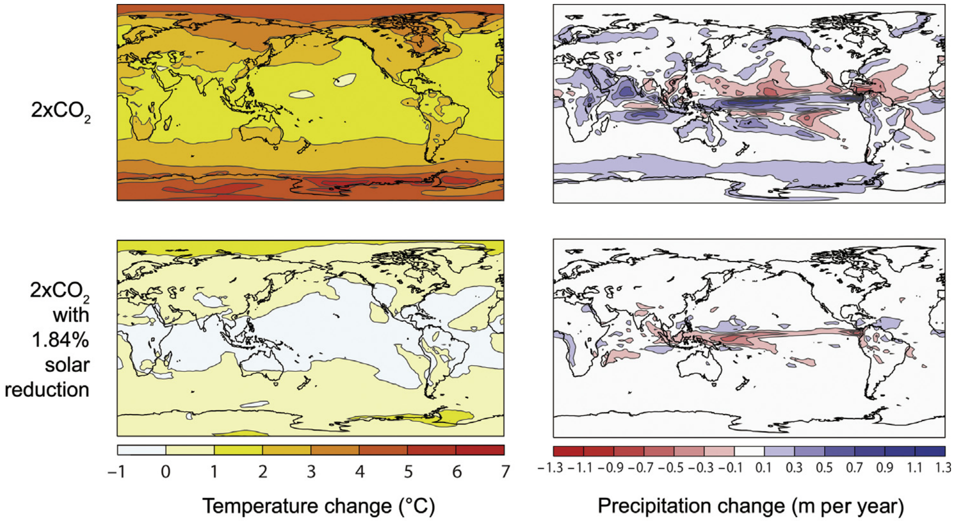

Fig. 2. Model-simulated (Caldeira and Wood, 2008) annual mean changes in temperature (left panels) and precipitation (right panels) for the case of 2 × CO_2 (top panels) and that of 2 × CO_2 with a reduction in global mean solar insolation of 1.84% (bottom panels). The changes are calculated as the departure from the simulation with 1 × CO_2. The idealized solar geoengineering scheme largely offsets most of the CO_2-induced temperature and precipitation changes but leaves some residual warming at the poles and leads to an overall decrease in precipitation.

effect of CO_2-physiological forcing has important implications for the response of the hydrological cycle including precipitation, runoff, and soil moisture (Fyfe et al., 2013).

The above discussions emphasize a few important issues about solar geoengineering. First, in a geoengineered world, restoring a certain climate variable (e.g. temperature, precipitation) to its pre-industrial state (or any unperturbed climate state) at all locations around the globe is not possible. Second, restoring different climate variables (e.g. temperature, precipitation) to their unperturbed values simultaneously is not possible. For example, restoring global temperatures to pre-industrial values would result in a decrease in global precipitation; if the goal is to use solar geoengineering to restore global precipitation, there would be residual warming. Furthermore, solar geoengineering is only capable of offsetting the radiative effects of atmospheric CO_2. The effect of increasing CO_2 on the terrestrial biosphere and its potential feedback on the climate system cannot be counteracted by reduced solar irradiance.

To better understand the physical response of the climate system to solar geoengineering, the Geoengineering Model Intercomparison Project (GeoMIP) was proposed wherein different model groups perform a set of solar geoengineering experiments under the same simulation protocols (Kravitz et al., 2011). Earlier GeoMIP experiments are designed to simulate the climate effects of reduced incoming solar radiation and stratospheric aerosol injections (Kravitz et al., 2011). Newly designed GeoMIP experiments include solar geoengineering schemes of marine cloud whitening (Kravitz et al., 2013a), land and ocean albedo enhancement (Kravitz et al., 2015), and cirrus cloud thinning (Kravitz et al., 2015). A growing body of studies based on GeoMIP simulations has emerged recently, such as climate response to reduced incoming solar radiation (Kravitz et al., 2013b), forcing and feedbacks in response to solar geoengineering (Huneeus et al., 2014), stratospheric ozone response to sulfate geoengineering (Pitari et al., 2014), and Arctic cryosphere response to sulfate geoengineering (Berdahl et al., 2014). Irvine et al. (2014) examined key uncertainties for space-based solar geoengineering by comparing the GeoMIP ensemble simulations and a perturbed parameter ensemble. A more complete list of GeoMIP studies can be found at the GeoMIP website (http://climate.envsci.rutgers.edu/GeoMIP/publications.html).

2.2. Carbon dioxide removal

2.2.1. Overview of proposed approaches

The geoengineering approach of carbon dioxide removal aims to counteract global warming by reducing the CO_2 concentration in the atmosphere. In the following, we briefly discuss carbon dioxide removal approaches with a schematic illustration shown in Fig. 3.

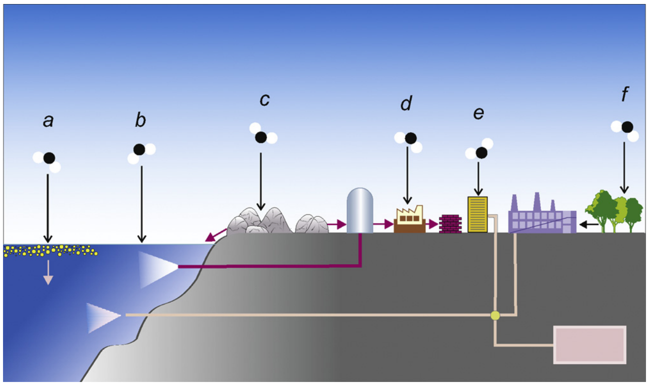

Fig. 3. Schematic diagram illustrating carbon dioxide removal approaches: *a*—ocean fertilization, *b*—ocean alkalinity addition, *c*—accelerated chemical weathering of rocks, *d*—manufacture of products using silicate rocks and carbon from the air, *e*—direct capture of CO_2 from the air, and *f*—afforestation or reforestation (Caldeira et al., 2013).

(1) Afforestation/reforestation.

Afforestation refers to human-induced growth of forest on land that has not historically been forested, and reforestation refers to restoration on recently deforested land (Caldeira et al., 2013). Both afforestation and reforestation act to absorb atmospheric CO_2 through the conversion of terrestrial ecosystems. The rate at which atmospheric CO_2 can be removed from the atmosphere through afforestation and reforestation is determined by many factors, such as forest type and structure, age of trees, and climate condition (Bonan, 2008). In addition to helping absorb atmospheric CO_2, afforestation and reforestation also alter the properties of the underlying ground, including surface albedo, rate of evapotranspiration, and surface roughness (Bonan, 2008), which in turn affect global climate. Therefore, the climate consequences of afforestation and reforestation are determined by the net effect of changes in atmospheric CO_2 and changes in land surface properties (Bala et al., 2007; Pongratz et al., 2011; Keller, 2014).

(2) Enhanced weathering.

Carbonate and/or silicate weathering are important processes for removing CO_2 from the atmosphere. However, it usually takes hundreds to thousands of years for the weathering processes to have a substantial influence on atmospheric CO_2. The idea of enhanced weathering is to accelerate the natural slow weathering processes by intentional efforts. Various enhanced weathering methods have been proposed. Carbonate rock could be processed, ground, and reacted with CO_2 in chemical engineering plants (Rau, 2008; Rau et al., 2013). Alternatively, carbonate minerals could be released to the ocean directly (Harvey, 2008). Moreover, large amounts of silicate minerals could be crushed, mined, transported, and added to soil to absorb atmospheric CO_2 (Schuiling and Krijgsman, 2006; Köhler et al., 2010). The scale, efficiency, and environmental cost of each scheme needs further research.

(3) Ocean fertilization.

The basic concept of ocean fertilization is to add additional nutrients to the ocean to boost its biological production, with the intent being to sequester additional CO_2 from the atmosphere. Of the ocean fertilization approaches, the most extensively discussed method is adding iron in the ocean areas where there is a high abundance of micronutrients including phosphate and nitrogen but with relatively low concentrations of chlorophyll (Martin, 1990; Joos et al., 1991; Watson et al., 2008). The effectiveness of ocean iron fertilization depends on not only the amount of carbon fixed by phytoplankton at the ocean surface but also the fate of fixed carbon in the interior ocean (Gnanadesikan and Marinov, 2008). Modeling studies have shown that, even if ocean iron fertilization can be implemented persistently and over the global ocean, its effect on removing CO_2 from the atmosphere is limited (Cao and Caldeira, 2010b). Fertilization of the ocean with the addition of macronutrients such as nitrogen and phosphate (Lampitt et al., 2008) entails a much larger mass requirement than that of iron fertilization, and therefore macro-nutrient fertilization does not appear to be a practical CDR approach (RS (Royal Society), 2009).

(4) Direct air capture.

Direct air capture refers to the industrial processes that separate and capture CO_2 from the ambient air (Keith et al., 2006; Holmes and Keith, 2012; Lackner et al., 2012; Mazzotti et al., 2013). A few methods have been proposed to capture CO_2 from the atmosphere, including absorption on solids (Gray et al., 2008), absorption into highly alkaline solutions (Mahmoudkhani and Keith, 2009), and absorption into moderately alkaline solutions with a catalyst (Bao and Trachtenberg, 2006). The technical feasibility has been demonstrated at the laboratory scale, but no large-scale prototypes have been tested. More research is needed on the technical feasibility and cost of direct air capture schemes.

2.2.2. Underlying physics of carbon dioxide removal

The basic idea underlying all carbon dioxide removal schemes is to reduce CO_2 content in the atmosphere, either by enhancing the carbon sinks of the ocean and/or terrestrial biosphere or by directly capturing CO_2 from the atmosphere. Carbon dioxide removal approaches can be considered as negative CO_2 emissions. It is important to note that there is a substantial time lag of global temperature response to the reduction in atmospheric CO_2 concentration as a result of the thermal inertial of the ocean (Fig. 4). Moreover, studies have found that if atmospheric CO_2 could be lowered in the future, there would be a short-term intensification of the global hydrological cycle (Wu et al., 2010; Cao et al., 2011). Therefore, even if atmospheric CO_2 could be returned to a safe level, the global climate would be quite different from that when atmospheric CO_2 initially reached that level.

A reduction in the atmospheric CO_2 burden would reduce the gradient of CO_2 between the atmosphere and the land/ocean, which tends to induce an efflux of carbon that was previously stored in the land and/or ocean (Cao and Caldeira, 2010a). Therefore, to maintain atmospheric CO_2 at low levels, not only excess CO_2 in the atmosphere needs to be removed, but excess CO_2 stored in the land and ocean, which could be released into the atmosphere, needs to removed as well (Cao and Caldeira, 2010a). This emphasizes the scale and long-term persistence required for the carbon dioxide revomal schemes to be effective in mitigating climate change.

3. Geoengineering research in China

3.1. Highlights of research on the physical mechanisms of geoengineering

In recent years, scientists from China have been active in the research of physical mechanisms of geoengineering. For

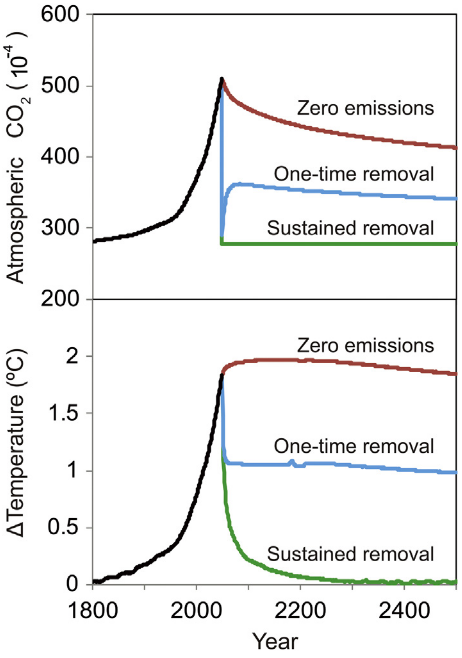

Fig. 4. Model-simulated temporal evolution of atmospheric CO_2 and change in surface air temperature (relative to pre-industrial) from 1800 to 2500. Between 1800 and 2008 the model is forced with observed atmospheric CO_2 concentrations, and between 2009 and 2049 the model is forced with prescribed CO_2 emissions following the SRES A2 scenario. Starting from year 2050 three simulations are performed: 1) zero CO_2 emissions without CO_2 removal from the atmosphere; 2) zero CO_2 emissions with one-time removal of all anthropogenic CO_2 from the atmosphere; 3) zero CO_2 emissions with the maintenance of atmospheric CO_2 at a pre-industrial level (Cao and Caldeira, 2010a).

example, Moore et al. (2010) examined the efficacy of different geoengineering schemes, including aerosol injection into the stratosphere, mirrors in space, afforestation, biochar, and bioenergy with carbon sequestration in limiting sea level rise during the 21st century. Cao et al. (2012) investigated rapid climate adjustment in response to CO_2/solar forcing and associated physical mechanisms responsible for the different climate effects of these two forcing agents; this study provides important insight into understanding the climate response to solar geoengineering. Cao et al. (2014) examined the response of the ocean carbon cycle and ocean acidification to idealized increasing and decreasing scenarios of CO_2 change in the atmosphere, emphasizing the substantial lags in deep ocean acidification to CO_2 reduction. Zhuo et al. (2014) studied the effects of volcanic eruptions on monsoons in China over the past seven centuries as a natural analog to stratospheric geoengineering, shedding additional light on the possible effects that stratospheric geoengineering may have on China. Zhang et al. (2014) provided a review of the technical and theoretical aspects of different geoengineering schemes as well as their potential impacts on the climate and ecosystems.

The Earth system model developed at Beijing Normal University, BNU-ESM, is in the GeoMIP project, and researchers from China have led some GeoMIP studies. For example, Moore et al. (2014) analyzed Arctic sea ice and atmospheric circulation under the GeoMIP G1 scenario.

3.2. Proposed ongoing research in physical mechanisms of geoengineering

Supported by the National Key Basic Research Program of China, a team of scientists from China, led by Prof. John Moore at Beijing Normal University, was formed to conduct coordinated research on geoengineering. This project, being the first for coordinated geoengineering research in China, has three main themes: 1) understanding physical mechanisms of geoengineering and scheme designs; 2) assessing the climate impact of geoengineering by analyzing existing and ongoing GeoMIP simulation results; and 3) evaluating the impact, risk, and governance of geoengineering. We now discuss the first theme in detail.

The first task of the ongoing geoengineering research is to continue research on the physical mechanisms of geoengineering with the aim of designing optimal geoengineering schemes that are targeted to specific regions, in particular, China and the Arctic. This aim will be achieved on the basis of investigation into a few key geoengineering schemes. In particular, the following key research topics will be addressed.

(1) Land-based geoengineering schemes.

The research on land-based geoengineering schemes will focus on a few issues: 1) investigating the physical mechanisms through which surface albedo changes affect the local and global energy and water cycles; 2) examining the effects of irrigation and afforestation/reforestation on the energy, water, and carbon cycles at the local and global scales; 3) investigating the physical and biogeochemical mechanisms through which irrigation and afforestation/reforestation affect global climate; and 4) investigating the mechanisms andmodifying permafrost properties and their effect on the climate and the carbon cycle.

(2) Ocean-based geoengineering schemes.

The research on ocean-based geoengineering will focus on the following issues: 1) estimating the effect of geoengineering on sea level rise using state-of-the-art coupled ice flow and ocean circulation models; 2) examining the effect of ocean albedo modification on air-sea heat exchange and the surface mass balance of ice shelves; and 3) estimating the contribution of small glaciers and ice caps to sea level rise under different geoengineering scenarios.

(3) Atmosphere-based geoengineering schemes.

The research on atmosphere-based geoengineering will focus on aerosol injection into the stratosphere with the following tasks: 1) using historical volcanic eruption and associated radiative forcing changes and the CMIP5/CMIP6 millennium simulation outputs to examine key mechanisms and processes underlying stratosphere-based geoengineering schemes; 2) using proxy records including tree-ring, ice core, stalagmite, and written documents to study the effectiveness of stratosphere-based geoengineering in mitigating global warming and its impacts on storms, sea ice or land-based ice sheet melting, and sea level rise; and 3) combining multi-proxy records with atmospheric general circulation models to investigate the effect of aerosol injection location, injection season, particle size, and injection strategy on the efficacy of stratosphere-based geoengineering.

(4) Optimized geoengineering schemes.

On the basis of the above land/ocean/atmosphere-based geoengineering schemes, the aim here is to design optimized geoengineering scenarios that are suitable for specific climate mitigation targets (e.g. mitigate extreme heat waves, avoid the melting of sea ice and permafrost) and/or specific regions (e.g. China, Arctic). These optimized geoengineering scenarios could be a combination of different geoengineering schemes that use the mediums of land, ocean, and/or atmosphere, after considering the benefits and side effects of each individual scheme.

4. Conclusions and discussion

Global climate change is one of the greatest challenges human society is facing. A deep reduction in anthropogenic CO_2 emissions is the safest way to mitigate global warming. Meanwhile, in the case of climate catastrophe, geoengineering (also referred to as climate engineering), that is, deliberate and large-scale intervention in the Earth's climatic system, has been proposed as a possible option to tackle global warming. Before large-scale implementation of any geoengineering schemes, we need to fully explore and evaluate the associated mechanisms, impacts, and risks of climate engineering.

Geoengineering strategies can be divided into two broad categories: carbon dioxide removal and solar geoengineering. The former aims to address global warming by reducing the content of CO_2 in the atmosphere, and the latter aims to mitigate global warming by deflecting more sunlight back to space. Carbon dioxide removal schemes can be implemented by methods such as afforestation/reforestation, ocean fertilization, accelerated chemical weathering of rocks, and direct capture of CO_2 from the atmosphere. Solar geoengineering schemes can be implemented by methods such as installing giant mirrors in space, injecting scattering aerosols into the stratosphere, seeding marine stratocumulus clouds with cloud particles, and enhancing surface albedo. Each method of geoengineering, by perturbing the physical, chemical, and biological aspects of the Earth's climate system, interferes with the global climate in different ways. Modeling studies are major tools to help understand the underlying mechanisms of each geoengineering method and the possible climatic and environmental impacts and risks.

As the world's largest developing country and the largest emitter of CO_2, China's participation in geoengineering research will be a key element in the implementation and coordination of a geoengineering program if that should become necessary. Located in the East Asian monsoon region, China's regional climate could be strongly affected by the potential implementation of geoengineering. In 2015, the first coordinated geoengineering research project supported by the National Key Basic Research Program of China was initiated. Scholars from different universities and institutes within China will conduct coordinated geoengineering research with three main research themes: basic mechanisms of geoengineering, climate consequences of geoengineering, and risks and governance of geoengineering. It is expected that, as a result of this coordinated geoengineering research project, China will play a key role in the international geoengineering research community by providing scientific advice for climate negotiation, planning, and coping strategies.

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References

Akbari, H., Menon, S., Rosenfeld, A., 2009. Global cooling: increasing world-wide urban albedos to offset CO_2. Clim. Change 94, 275–286.

Andrews, T., Forster, P.M., Gregory, J.M., 2009. A surface energy perspective on climate change. J. Clim. 22, 2557–2570.

Angel, R., 2006. Feasibility of cooling the EARTH with a cloud of small spacecraft near the inner Lagrange point (L1). Proc. Natl. Acad. Sci. U. S. A. 103, 17184–17189.

Bala, G., Duffy, P.B., Taylor, K.E., 2008. Impact of geoengineering schemes on the global hydrological cycle. Proc. Natl. Acad. Sci. U. S. A. 105, 7664–7669. http://dx.doi.org/10.1073/pnas.0711648105.

Bala, G., Caldeira, K., Wickett, M., et al., 2007. Combined climate and carbon-cycleeffects of large-scale deforestation. Proc. Natl. Acad. Sci. U. S. A. 104, 6550–6555.

Bao, L.H., Trachtenberg, M.C., 2006. Facilitated transport of CO_2 across a liquid membrane: comparing enzyme, amine, and alkaline. J. Membr. Sci. 280, 330–334.

Berdahl, M., Robock, A., Ji, D., et al., 2014. Arctic cryosphere response in the Geoengineering Model Intercomparison Project (GeoMIP) G3 and G4 scenarios. J. Geophys. Res. 119, 1308–1321. http://dx.doi.org/10.1002/2013JD020627.

Bonan, G.B., 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320, 1444–1449.

Boucher, O., Jones, A., Betts, R.A., 2009. Climate response to the physiological impact of carbon dioxide on plantsin the met office unified model HadCM3. Clim. Dyn. 32, 237–249.

Caldeira, K., Wood, L., 2008. Global and arctic climate engineering: numerical model studies. Philos. Trans. R. Soc. A 366, 4039–4056. http://dx.doi.org/10.1098/rsta.2008.0132.

Caldeira, K., Bala, G., Cao, L., 2013. The science of geoengineering. Annu. Rev. Earth Planet. Sci. 41, 231–256. http://dx.doi.org/10.1146/annurev-earth-042711-105548.

Cao, L., Caldeira, K., 2010a. Atmospheric carbon dioxide removal: long-term consequences and commitment. Environ. Res. Lett. 5, 024011.

Cao, L., Caldeira, K., 2010b. Can ocean iron fertilization mitigate ocean acidification? Clim. Change 99, 303–311.

Cao, L., Bala, G., Caldeira, K., 2011. Why is there a short-term increase in global precipitation in response to diminished CO_2 forcing? Geophys. Res. Lett. 38 (6), 122–133. http://dx.doi.org/10.1029/2011GL046713.

Cao, L., Bala, G., Caldeira, K., 2012. Climate response to changes in atmospheric carbon dioxide and solar irradiance on the time scale of days to weeks. Environ. Res. Lett. 7, 034015. http://dx.doi.org/10.1088/1748-9326/7/3/034015.

Cao, L., Bala, G., Caldeira, K., et al., 2010. Importance of carbon dioxide physiological forcingto future climate change. Proc. Natl. Acad. Sci. U. S. A. 107, 9513−9518.

Cao, L., Han, Z., Meidi, Z., et al., 2014. Response of ocean acidification to a gradual increase and decrease of atmospheric CO_2. Environ. Res. Lett. 9, 024012. http://dx.doi.org/10.1088/1748-9326/9/2/024012.

Chen, Y.C., Christensen, M.W., Xue, L., et al., 2012. Occurrence of lower cloud albedo in ship tracks. Atmos. Chem. Phys. 12 (17), 8223−8235. http://dx.doi.org/10.5194/acp-12-8223-2012.

Ciais, P., Sabine, C., Bala, G., et al., 2013. Carbon and other biogeochemical cycles. In: Stocker, T.F., Qin, D., Plattner, G.-K., et al. (Eds.), Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York, pp. 465−570.

Crutzen, P.J., 2006. Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? Clim. Change 77, 211−219.

Early, J.T., 1989. Space-based solar shield to offset greenhouse effect. J. Br. Interplanet. Soc. 42, 567−569.

Ferraro, J.A., Eleanor, J.H., Andrew, J.C., 2014. Weakened tropical circulation and reduced precipitation in response to geoengineering. Environ. Res. Lett. 9, 014001. http://dx.doi.org/10.1088/17489326/9/1/014001.

Field, C., Jackson, R., Mooney, H., 1995. Stomatal responses to increased CO_2: implications from the plant to the global scale. Plant Cell Environ. 18, 1214−1255. http://dx.doi.org/10.1111/j.1365-3040.1995.tb00630.x.

Fyfe, J.C., Cole, J.N.S., Arora, V.K., et al., 2013. Biogeochemical carbon coupling influences global precipitation in geoengineering experiments. Geophys. Res. Lett. 40 http://dx.doi.org/10.1002/grl.50166.

Gaskill, A., 2004. Desert Area Coverage, Global Albedo Enhancement Project. http://www.global-warming-geo-engineering.org/Albedo-Enhancement/Surface-Albedo-Enhancement/Calculationof-Coverage-Areas-to-Achieve-Desired-Level-of-ForcingOffsets/Desert-Area-Coverage/ag28.htm.

Gnanadesikan, A., Marinov, I., 2008. Export is not enough: nutrient cycling and carbon sequestration. Mar. Ecol. Prog. Ser. 364, 289−294.

Govindasamy, B., Caldeira, K., 2000. Geoengineering earth's radiation balance to mitigate CO_2-induced climate change. Geophys. Res. Lett. 27, 2141−2144. http://dx.doi.org/10.1029/1999GL006086.

Govindasamy, B., Caldeira, K., Duffy, P.B., 2003. Geoengineering earth'sradiation balance to mitigate climate change from a quadrupling of CO_2. Glob. Planet Change 37 (1−2), 157−168.

Gray, M.L., Champagne, K.J., Fauth, D., et al., 2008. Performance of immobilized tertiary aminesolid sorbents for the capture of carbon dioxide. Int. J. Greenh. Gas Control 2, 3−8.

Harvey, L.D.D., 2008. Mitigating the atmospheric CO_2 increase and ocean acidification by adding limestonepowder to upwelling regions. J. Geophys. Res. Oceans 113, C04028. http://dx.doi.org/10.1029/2007/JC004383.

Holmes, G., Keith, D.W., 2012. An air-liquid contactor for large-scale capture of CO_2 from air. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 370 (1974), 4380−4403. http://dx.doi.org/10.1098/rsta.2012.0137.

Huneeus, N., Boucher, O., Alterskjær, K., et al., 2014. Forcings and feedbacks in the GeoMIP ensemble for a reduction in solar irradiance and increase in CO_2. J. Geophys. Res. 119, 5226−5239. http://dx.doi.org/10.1002/2013JD021110.

IPCC, 2013. Summary for policymakers. In: Stocker, T.F., Qin, D., Plattner, G.-K., et al. (Eds.), Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York.

Irvine, P.J., Lunt, D.J., Stone, E.J., et al., 2009. The fate of the Greenland ice sheet in a geoengineered, high CO_2 world. Environ. Res. Lett. 4, 045109.

Irvine, P.J., Ridgwell, A.J., Lunt, D.J., et al., 2014. Identifying key uncertainties for sunshade geoengineering by comparing the Geo MIP ensemble and aperturbed parameter ensemble. J. Geophys. Res. http://dx.doi.org/10.1002/2013JD020716.

Joos, F., Sarmiento, J.L., Siegenthaler, U., 1991. Estimates of the effect of southern ocean iron fertilization on atmospheric CO_2 concentrations. Nature 349, 772−775.

Kalidindi, S., Bala, G., Modak, A., et al., 2014. Modeling of solar radiation management: a comparison of simulations using reduced solar constant and stratospheric sulphate aerosols. Clim. Dyn. 1−17. http://dx.doi.org/10.1007/s00382-014-2240-3.

Keith, D.W., Ha-Duong, M., Stolaroff, J.K., 2006. Climate strategy with CO_2 capture from the air. Clim. Change 74, 17−45.

Keller, P., 2014. Potential climate engineering effectiveness and side effects during a high CO_2-emission scenario. Nat. Commun. 5, 3304. http://dx.doi.org/10.1038/ncomms4304.

Köhler, P., Hartmann, J., Wolf-Gladrow, D.A., 2010. Geoengineering potential of artificially enhanced silicate weathering of olivine. Proc. Natl. Acad. Sci. U. S. A. 107, 20228−20233.

Kravitz, B., Robock, A., Boucher, O., et al., 2011. The geoengineering model intercomparison project (GeoMIP). Atmos. Sci. Lett. 12 (2), 162−167.

Kravitz, B., Forster, P.M., Jones, A., et al., 2013a. Sea spray geoengineering experiments in the Geoengineering Model 20 Intercomparison Project (GeoMIP): experimental design and preliminary results. J. Geophys. Res. 118, 11175−11186. http://dx.doi.org/10.1002/jgrd.50856.

Kravitz, B., Caldeira, K., Boucher, O., et al., 2013b. Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP). J. Geophys. Res. 118 (15), 8320−8332. http://dx.doi.org/10.1002/jgrd.50646.

Kravitz, B., Robock, A., Tilmes, S., et al., 2015. The Geoengineering Model Intercomparison Project Phase 6 (GeoMIP6): simulation design and preliminary results. Geosci. Model Dev. Disc. 8, 4697−4736. http://dx.doi.org/10.5194/gmdd-8-4697-2015.

Lackner, K.S., Brennan, S., Matter, J.M., et al., 2012. The urgency of the development of CO_2 capture from ambient air. Proc. Natl. Acad. Sci. U. S. A. 109 (33), 13156−13162.

Lampitt, R.S., Achterberg, E.P., Anderson, T.R., et al., 2008. Ocean fertilization: a potential means of geoengineering? Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 366 (1882), 3919−3945. http://dx.doi.org/10.1098/rsta.2008.0139.

Latham, J., Rasch, P., Chen, C.-C., et al., 2008. Global temperature stabilization via controlledalbedo enhancement of low-level maritime clouds. Philos. Trans. R. Soc. Lond. A 366, 3969−3987.

Lenton, T.M., Held, H., Kriegler, E., et al., 2008. Tipping elements in the Earth's climate system. Proc. Natl. Acad. Sci. U. S. A. 105 (6), 1786.

Mahmoudkhani, M., Keith, D.W., 2009. Low-energy sodium hydroxide recovery for CO_2 capture from atmospheric air—thermodynamic analysis. Int. J. Greenh. Gas Control 3, 376−384.

Martin, J.H., 1990. Glacial-interglacial CO_2 change: the iron hypothesis. Paleoceanography 5 (1), 1−13. http://dx.doi.org/10.1029/Pa005i001p00001.

Matthews, H.D., Caldeira, K., 2008. Stabilizing climate requiresnear-zero emissions. Geophys. Res. Lett. 35, L04705.

Mazzotti, M., Baciocchi, R., Desmond, M.J., et al., 2013. Direct air capture of CO_2 with chemicals: optimization of a two-loop hydroxide carbonate system using a countercurrent air-liquid contactor. Clim. Change 118 (1), 119−135. http://dx.doi.org/10.1007/s10584-012-0679-y.

Moore, J., Jevrejeva, S., Grinsted, A., 2010. Efficacy of geoengineering to limit 21st century sea-level rise. Proc. Natl. Acad. Sci. U. S. A. 107 (36), 15699−15703.

Moore, J.C., Rinke, A., Yu, X., et al., 2014. Arctic sea ice and atmospheric circulation under the GeoMIP G1 scenario. J. Geophys. Res. 119, 567−583. http://dx.doi.org/10.1002/2013JD021060.

Niemeier, U., Schmidt, H., Timmreck, C., 2011. The dependency of geoengineered sulfateaerosol on the emission strategy. Atmos. Sci. Lett. 12 (2), 189−194. http://dx.doi.org/10.1002/asl.304.

Pearson, J., Oldson, J., Levin, E., 2006. Earth rings for planetary environment control. Acta Astron. 58, 44−57.

Peter, T., Grooß, J.U., 2012. Polar stratospheric clouds and sulfate aerosol particles: microphysics, denitrification and heterogeneous chemistry. In:

Muller, R. (Ed.), Stratospheric Ozone Depletion and Climate Change. Royal Society of Chemistry, London and Washington.

Pitari, G., Aquila, V., Kravitz, B., et al., 2014. Stratospheric ozone response to sulfate geoengineering: results from the Geoengineering Model Intercomparison Project (GeoMIP). J. Geophys. Res. 119, 2629−2653. http://dx.doi.org/10.1002/2013JD020566.

Pongratz, J., Reick, C.H., Raddatz, T., et al., 2011. Past land use decisions have increased mitigation potential of reforestation. Geophys. Res. Lett. 38, L15701.

Rau, G.H., 2008. Electrochemical splitting of calciumcarbonate to increase solution alkalinity: implications formitigation of carbon dioxide and ocean acidity. Environ. Sci. Technol. 42 (23), 8935−8940. http://dx.doi.org/10.1021/es800366q.

Rau, G.H., Carroll, S.A., Bourcier, W.L., et al., 2013. Direct electrolytic dissolution of silicate minerals for air CO_2 mitigation and carbon negative H_2 production. Proc. Natl. Acad. Sci. U. S. A. 110 (25), 10095−10100. http://dx.doi.org/10.1073/pnas.1222358110.

Ridgwell, A., Singarayer, J.S., Hetherington, A.M., et al., 2009. Tackling regional climate change by leaf albedo biogeoengineering. Curr. Biol. 19, 146−150.

Robock, A., Mao, J., 1995. The volcanic signal insurface temperature observations. J. Clim. 8, 1086−1103.

Robock, A., Marquardt, A., Kravitz, B., et al., 2009. Benefits, risks, and costs of stratospheric geoengineering. Geophys. Res. Lett. 36 (19), L19703.

Robock, A., Macmartin, D.G., Duren, R., et al., 2013. Studying geoengineering with natural and anthropogenic analogs. Clim. Change 121 (3), 445−458.

Rosenfeld, D., Wood, R., Donner, L.J., et al., 2013. Aerosol cloud-mediated radiative forcing: highly uncertain and opposite effects from shallow and deep clouds. In: Asrar, G.R., Hurrel, J.W. (Eds.), Climate Science for Serving Society. Springer, Dordrech.

RS (Royal Society), 2009. Geoengineering the Climate: Science, Governance and Uncertainty.

Salter, S., Sortino, G., Latham, J., 2008. Sea-going hardware for the cloud albedo method of reversing global warming. Philos. Trans. R. Soc. Lond. A 366, 3989−4006.

Schuiling, R.D., Krijgsman, P., 2006. Enhanced weathering: an effective and cheap tool to sequester CO_2. Clim. Change 74, 349−354.

Sellers, P.J., Bounoua, L., Collatz, G.J., et al., 1996. Comparison of radiative and physiological effects of doubled atmospheric CO_2 on climate. Science 271, 1402−1406.

Teller, E., Wood, L., Hyde, R., 1997. Global Warming and Ice Ages: I. Prospects for Physics-based Modulation of Global Change. Lawrence Livermore National Laboratory. UCRL-JC-128715, 20.

Timmreck, C., 2012. Modeling the climatic effects of large explosive volcanic eruptions. Wiley Interdiscip. Rev. Clim. Change 3 (6), 545−564. http://dx.doi.org/10.1002/wcc.192.

Twomey, S., 1977. Influence of pollution on shortwave albedo of clouds. J. Atmos. Sci. 34, 1149−1152.

Watson, A.J., Boyd, P.W., Turner, S.M., et al., 2008. Designing the next generation of ocean ironfertilization experiments. Mar. Ecol. Prog. Ser. 364, 303−309.

Wu, P., Wood, R., Ridley, J., et al., 2010. Temporary acceleration of the hydrological cycle in response to a CO_2 rampdown. Geophys. Res. Lett. 37, L12705. http://dx.doi.org/10.1029/2010GL043730.

Zhang, Z., Moore, J.C., Husingh, D., et al., 2014. Review of geoengineering approaches to mitigating climate change. J. Clean. Prod. 54 (3), 212−231.

Zhuo, Z., Gao, C., Pan, Y., 2014. Proxy evidence for China's monsoon precipitation response to volcanic aerosols over the past seven centuries. J. Geophys. Res. Atmos. 2014 (119), 6638−6652. http://dx.doi.org/10.1002/2013JD021061.