CLIMATE ENGINEERING: WHICH ROLE FOR SPACE?

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Abstract

Global efforts made by the international community to reduce anthropogenic greenhouse gas emissions have not been successful yet to adequately address the challenge posed by climate change. On the contrary, global carbon emissions are still rising, raising the need to consider alternative back-up options to mitigate global warming. Such solutions are known as climate engineering or geoengineering and involve a deliberate large-scale intervention in the Earth's climate system as defined by the Royal Society in its geoengineering report in 2009. To ensure an adequate evaluation of climate engineering concepts the Royal Society recommended international collaborative research into the benefits, environmental impacts, feasibility, risks and opportunities presented by geoengineering and to develop international regulatory frameworks to guide both short-term and long-term research and deployment.

This paper identifies and evaluates possible contributions from space to different potential climate engineering concepts currently considered for mitigating the impact of climate change. These include technical aspects as well as contributions to organisational and regulatory aspects of such concepts. In particular, Earth remote-sensing instruments such as imaging spectrometers and Lidar systems could be employed to detect signs of illicit geoengineering activities or to collect data from small-scale legitimate field tests. The space sector could also play a more active role by deploying large solar shields in space to reduce the amount of solar energy reaching the Earth. The present assessment of potential space contributions to climate engineering is therefore intended to cover the entire range of such contributions, from the use of existing sensors up to more advanced visionary concepts such as the deployment of structures in space to reduce the total radiation level from the sun.

Keywords: Climate Engineering, Space Systems, Geoengineering, Climate Change

1. Introduction

Driven by the continuously rising level of anthropogenic greenhouse gasses in the atmosphere, the Earth's climate is changing. Climate models show that the consequences could be severe if no immediate actions were to be taken to stop global warming [1, 2]. According to the fourth and most recent assessment report of the Intergovernmental Panel on Climate Change (IPCC), the global atmospheric temperature rise corresponding to several future trajectories of greenhouse gas emissions lies within a range of 1.1-6.4 degrees Celsius in the 2090's. Furthermore, changes in the climate are expected to occur abruptly and unpredictably [3]. Reducing global greenhouse gas emissions is seen as the most direct way to prevent potentially dangerous levels of climate change. However, despite the effort of many countries, emissions are still rising [4].

If reductions of greenhouse gasses are not achieved in time and severe climate change becomes apparent, other methods to cool the Earth, including geoengineering, might be required. Climate models show that the climate could be brought closer to the pre-industrial climate by applying geoengineering methods to decrease global temperatures [5–11].

Although the deliberate and global manipulation of Earth's climate has long been ignored as a serious option to counteract global warming, recent advances in atmospheric and climate system science combined with a larger geoengineering community have increased the quality and quantity of research studies on active climate change options. Figure 1 demonstrates the increasing importance of geoengineering in public searches on the intranet following the publication of the report on the topic by the UK Royal Society [12]. Moreover many new studies, reports and overview papers on geoengineering have been published over the past years [13, 14].The increasing interest in non-technical and non-scientific aspects of geoengineering might furthermore be seen as an important sign of the increasing relevance of this option, including questions related to the ethics, governance, politics and economics of climate change [9, 15–21].

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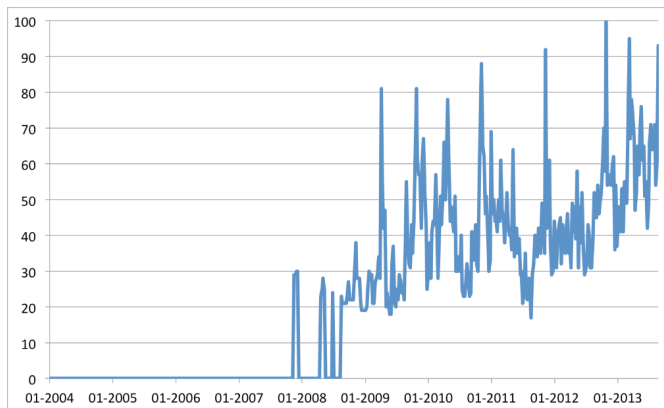*Email addresses:* `Isabelle.Dicaire@esa.int` (I. Dicaire), `Leopold.Summerer@esa.int` (L. Summerer)

Figure 1: Relative frequency of the search term "geoengineering" in Google science searches normalized to maximum value=100.

However, despite the evident advantage of such an approach, geoengineering research is still in the germinal stage, with various potential methods being proposed and investigated, and that this process has not yet advanced to the phase that would allow the screening of industrial methods or even representative field experiments.

Climate change is a global phenomenon with global as well as regional and local effects. Space activities by their very physical nature are global activities. Traditionally, data collected from space has been fundamental in measuring climate change effects in the first place, and in understanding its parameters and interactions. Some climate engineering concepts are entirely space based, taking advantage of the unique properties of space [8, 22, 23]. The space community has however not yet embraced the potential needs to be addressed via space activities for different climate engineering concepts.

This paper is intended to complement the scholarly literature and enlarge this discussion by providing an assessment of recent findings on geoengineering from the perspective of potential contributions from space, aiming at the same time to generate more interest on the topic from within the space research community. Chapter 2 of this paper provides a summary overview of the different basic physical mechanisms proposed for influencing the Earth's climate. Chapter 3 contains a list of current geoengineering proposals and assesses for each of these potential contributions from space.

2. Basic Physics of Climate Engineering

Climate engineering concepts can be divided into two broad categories:

- Carbon dioxide removal (CDR) techniques, by trying to reduce the CO_2 content of the atmosphere by actively removing it, and thus increasing the level of outgoing, long-wave radiation leading to overall cooling;

- Solar radiation management (SRM) techniques, by attempting to directly influence the solar radiation balance of the Earth system. This second approach includes compensating the reduced outgoing, long-wave radiation due to higher levels of greenhouse gases by either increasing the amount of generally short-wave radiation that is reflected back into space or by directly reducing the total amount of sunlight reaching the Earth's atmosphere.

The first category is generally viewed as preferable since it attempts to restore pre-industrial atmospheric conditions by addressing the root cause i.e. the high concentrations of greenhouse gases in the atmosphere. This method therefore seems more natural, but reducing greenhouse gas levels is of course subject to the same time scales as increasing them, thus the effects will have delays of decades typically. When considering time scales, efforts and resource levels as parameters, the second approach, influencing directly the solar radiation balance of the Earth to accommodate and compensate for higher concentrations of greenhouse gases, might appear more favourable. The moral dilemma of climate change and sharing the burden of climate change efforts could thus be complemented by the moral dilemma of choosing between a morally superior but more difficult and long-term approach in the form of active greenhouse gas extractions, and the more hazardous but potentially faster and cheaper approaches of actively influencing the radiation balance.
The following sections will briefly describe these two approaches, which will then lead to the engineering proposals listed in Chapter 3.

2.1. Carbon Dioxide Removal Techniques

Earth's surface emits about 390 W/m2 in the form of thermal radiation, of which only a small portion (40 W/m2) is emitted directly into space. The remaining energy is absorbed by clouds and greenhouse gases in the atmosphere, of which 195 W/m2 are then further emitted from the atmosphere into space. Changes in the levels of greenhouse gases in the atmosphere directly influence the percentage of energy transmitted via thermal radiation through the atmosphere into space. Some of the geoengineering approaches aim at increasing the level of outgoing, long-wave radiation re-emitted into space by reducing the level of greenhouse gases in the atmosphere. These include all types of methods to either reduce the source or increase the sinks of greenhouse gases, primarily CO_2.

The following list of methods for carbon dioxide removal can be considered:

- Land use management to protect or enhance land carbon sinks (the use of biomass for carbon sequestration);

- Enhancement of natural weathering processes to remove CO_2 from the atmosphere;

- Direct engineered capture of CO_2 from ambient air;

- The enhancement of oceanic uptake of CO_2, e.g. by fertilization of the oceans with naturally scarce nutrients or by increasing upwelling processes.

2.2. Solar Radiation Management Techniques

On average, incoming solar radiation is 342 W/m2, of which 77 W/m2 are directly reflected by clouds and an additional 30 W/m2 are reflected back by the Earth's surface (essentially snow and ice). The remaining 235 W/m2 are either absorbed by the Earth's surface or by its atmosphere.

Reducing the average incoming solar radiation would therefore have an immediate effect on the total amount of energy absorbed by the Earth's surface and atmosphere, representing ~70 % of the incoming energy. Thus assuming there are no changes in the spectral distribution of the incoming radiation, every incoming Watt reduced would directly and almost immediately reduce the energy absorbed by 0.7 Watt. This is the basis of concepts e.g. placing large sunshade structures in space between the Earth and the Sun.

Changing the 30:70 ratio of reflected to absorbed energy has a similar immediate strong effect. This is the basis of concepts aiming at increasing the Earth albedo by injecting reflecting aerosols in the upper atmosphere or increasing the surface albedo.

Solar radiation management concepts currently under consideration are the following:

- Increasing the surface reflectivity of the planet, by brightening human structures (e.g. by painting them white), planting of crops with a high reflectivity, or covering deserts with reflective material;

- Increasing the reflectivity of marine clouds, this concept in also known as cloud albedo modification;

- Mimicking the effects of volcanic eruptions by injecting sulphate aerosols into the lower stratosphere;

- Placing shields or deflectors in space to reduce the amount of solar energy reaching the Earth.

2.3. Regional Climate Change

Solar radiation and greenhouse gas forcing operate in different ways. Because of the different nature of the forcing, solar radiation management methods are unlikely to exactly counteract global warming on global to local scales. Studies on the climate impact of solar radiation management techniques suggest that regional climate change (compared with preindustrial climate) remains after applying such methods. However, climate simulations also show that the remaining local climate changes after applying solar radiation management, should be relatively small compared with the cases in which no geoengineering is applied [24]. In their most recent paper Kravitz et al. (2013) simulated the climate response to an abrupt quadrupling of CO_2 concentration from preindustrial levels using 12 different climate models. All models showed that a globally uniform reduction in solar radiation cannot simultaneously return the regional and global temperature and

hydrological cycle intensity to preindustrial levels. Typical temperature and annual precipitation anomalies were (-0.3 K, +0.8 K) and 0.2 mm/day, respectively [25].

2.4. Costs, Effectiveness and Risks

Uncertainties remain in the estimation of the costs of geoengineering. The costs of geoengineering can best be compared with mitigation, i.e. the costs of reducing CO_2 emissions in order to obtain an equivalent cooling effect with eventually the cost of adapting to a changed climate [26].

The total costs of solar radiation management methods include costs for technical development, installation and maintenance. The total costs of cloud seeding and stratospheric aerosol injection are estimated to be small relative to mitigation or other climate control options [26]. Space based sunshades appear as one of the most expensive solar radiation management methods, depending strongly on critical parameters such as the continuation of the decline in the cost of access to space [23]. Estimated costs, effectiveness and risks of different geoengineering methods were summarized and compared in [12, 14]. One of the potential moral dilemmas is that many of them seem substantially cheaper than addressing the root causes of climate change and thus might even be at the reach of individual states and wealthy individuals.

An interesting perspective on estimating geoengineering costs is given by two recent publications related to the economic viability of aerosol-based geoengineering options. By framing the question differently, Goes et al. (2011) and Bickel et al. (2011) come to exactly opposite conclusions using the very same models [9, 27].

2.5. Field Tests

One common technical characteristic of all different geoengineering proposals is the need for small-scale experiments that are ideally reversible, relatively cheap and easy to implement to test the effectiveness of the proposed concept and the validity of the underlying simulation models.

Based on its inherent global reach, space-based verification methods will likely be central to such a process, ideally made fully independent from the space-based data acquisition systems that might be involved in control systems.

3. Different Climate Engineering Proposals and their Respective Contributions from Space

In this Chapter different technical proposals for climate engineering options are reviewed with the focus on potential contributions from space that each of these can offer. For that purpose a short description of the concept is provided, referring to respective publications for more in-depth information.

Table 1: Geoengineering Concepts

	Geoengineering Concept	Space "Affinity"	Space Contributions
CDR[a]	Land use management	low	Biomass level measurements
	Enhanced Weathering	low	limited
	Direct CO_2 capture from ambient air	low	limited
	Enhancement of oceanic CO_2 uptake	medium	indirect measurements
SRM[b]	Enhanced Surface reflectivity	medium	Reflectivity measurements
	Cloud Albedo Modification	medium	Reflectivity measurements
	Stratospheric Aerosols Injection	medium	Aerosol Measurements, Injection by rockets
	Large solar shields or deflectors	high	Entirely spaced-based

[a]Carbon Dioxide Removal
[b]Solar Radiation Management

3.1. Solar Shields

3.1.1. Concept Description

Solar shields belong to the second of the above outlined geo-engineering categories, namely the solar radiation management concepts. The basic principle relies in reducing the total amount of sunlight reaching the Earth's atmosphere and surface. Large-scale structures acting as screens would be placed in space to reflect or deflect solar light at an angle sufficiently large to prevent it from reaching the Earth's atmosphere [23]. One important advantage of this method compared to other geoengineering approaches relies in keeping the composition of the atmosphere and ocean unaltered; only one single parameter, the solar radiation flux would be modified, promising easier modelling and better predictions.

The present status of sunshade research is still in the germinal stage, with various potential methods being proposed and investigated, but has not yet converged towards a practical and most favourable method, nor have there yet been any attempt to demonstrate the method. On the other hand, the principle is fairly simple and scholarly work has not yet identified scientific showstoppers to their implementation.

3.1.2. Main Issues

The two main possibilities for the location of the sunshades are either in orbit around Earth or at the Lagrangian L1 point between the Sun and the Earth. Angel assessed placing the shields in the near Earth-Sun inner Lagrange point (L1) in an orbit with the same 1-year period as the Earth [8]. Such shades in L1 could have relatively long lifetimes and could be controlled to modify the percentage of blocked or reflected sunlight. The stability of the orbit was mentioned as a major technical hurdle. Possible solutions include using a cloud of small spacecrafts holding their orbits by active station-keeping and using solar radiation pressure as a stabilizing force [8]. Baoyin and McInnes demonstrated that constant acceleration from a solar sail could be used to generate artificial libration points in the Earth-Sun three-body problem [28, 29].

For their production on Earth, the overall mass of the designed solar shields should be made as small as possible. The excessive cost of launching the required mass is reported as one of the most important barriers towards implementing space solar shields. The development of novel lightweight materials and investigating optimal shapes and design of the sunshades would be necessary. McInnes concludes that *the shield mass can be minimized if the shield is positioned at an optimum location along the Sun-Earth line, sunward of the classical L1 Lagrange point. The location of the solar shield can be optimized since the solar radiation pressure force exerted on the shield will modify the location of the classical L1 Lagrange point.* [30]. Angel argues that *sunshades could be built with lower mass if its reflectivity is reduced by applying coatings that absorb light energy on the sunward side and reemit it as heat mostly on the earthward side. The corresponding minimum mass at a distance of 2.5 Gm would be 80 million tonnes* [8]. Early proposed using transparent material to deflect sunlight rather than absorbing it [31]. This would minimize the shifting due to radiation pressure. Three advances aimed at practical implementation were proposed by Early:

1. A very thin refractive screen with low reflectivity, leading to a total sunshade mass of 22 Mt.
2. A concept aimed at reducing transportation cost to 50 USD/kg by using electromagnetic acceleration to escape Earths gravity, followed by ion propulsion.
3. Implementating the sunshade as a cloud of several spacecrafts, autonomously stabilized by modulating solar radiation pressure. These meter-sized flyers would be assembled completely before launch, avoiding the need for construction or unfolding in space. They would have a mass of 1g each, be launched in stacks of 800,000, and remain in orbit for a projected lifetime of 50 years within a 100,000 km long cloud. In 1989, Early postulated that given the concept builds on existing technologies, its development and deployment within 25 years would seem feasible at a cost of a few trillion dollars [31]. Although many proposals and theoretical studies by different scientists are pushing the boundaries of what could be possible, the mass and costs involved are still largely considered as major hurdles.

3.1.3. Estimated Costs, Effectiveness and Risks

Kosugi (2010) calculated that the total climate control cost can be reduced by US$240 billion using space-based sunshade

technology [23]. The sunshade mass-effectiveness coefficient required to offset the increase in radiative forcing due to a doubling of the atmospheric CO_2 concentration should not exceed 100 Mt/2xCO_2, assuming a continuous decline of sunshade deployment from 6000 to 1000 US$/kg over half a century [23].

3.2. Aerosols

3.2.1. Concept Description

The use of aerosols belongs to the second geoengineering category outlined in Chapter 2, namely the Solar Radiation Management concepts. The basic principle relies in increasing the total amount of sunlight reflected in the atmosphere by changing its properties slightly and thus reducing the amount of sunlight and energy reaching the Earths surface. Compared with other geoengineering approaches, an advantage of this method is that it does not seem to require substantial technical advances for its feasibility; it relies on a mechanism that is already working in nature (e.g. volcanic eruptions), and that in principle could be finely controlled to adjust its geographic location and local intensity. Such a concept can additionally be tested on a relatively small scale.

Aerosols could be injected into the upper atmosphere so as to scatter more the incident sunlight (naturally on average 77 W/m2 are reflected by clouds and the atmosphere) and thus producing a cooling effect. Initial studies have focused on sulphate aerosols, which have a natural equivalent in the form of volcanic eruptions. Research on geoengineering aerosols is now expanding to nonsulphate particles such as titanium dioxide (TiO_2) which could be more efficient to scatter radiation [32]. Keith (2010) examined the possibility of injecting engineering nanoparticles to take advantage of photophoretic forces [7].

Studies suggest that sulphate aerosols could counteract the globally averaged temperature increase associated with increasing greenhouse gases [24]. The relative maturity of this approach is also demonstrated by the higher interest in understanding its functioning by comparing different models [33]. It is likely that some regional climate change (compared with the preindustrial climate) remains after applying this method, with some regions experiencing significant changes in temperature or precipitation [34]. Sulphur dioxide emissions of 1.5 – 5 Mt S/yr would be needed to offset a doubling of CO_2 concentrations [24, 35, 36]. Individual volcanic eruptions, such as the 1982 eruption of El Chichón, may increase the stratospheric SO_2 mass by over an order of magnitude [37]. An estimated 7 Mt of SO_2 was released during the eruption of El Chichón; in comparison the 1991 eruption of Mount Pinatubo released an estimated 19 ± 4 Mt SO_2 [38].

Pyle et al. have estimated that the SO_2 flux from explosive volcanic eruptions to the stratosphere is 1 Mt/yr. Historic records derived from residual sulphate peaks in the Greenland ice core suggest that the minimum flux of volcanic sulphur to the stratosphere during the Holocene has varied between 0.5 and 1 Mt SO_2 per year. The sulphate concentration of the ice cores furthermore places an upper limit on the sulphur flux into the stratosphere of 1.8 Mt/yr [39].

3.2.2. Main Issues

The comprehensive review of Rasch et al. in 2008 concludes that based on best evidence, regional climate changes will likely remain after sulphur-based geoengineering. Potentially significant side-effects include changes in the natural sulphur cycle in the atmosphere, changes in ozone levels, with a likely depletion of these due to chemical reactions of sulphur in the atmosphere, and implications related to changes in frequencies reaching Earth since sulphur would alter its natural frequency spectrum [24, 40].

Furthermore, there are still a number of open technical questions related to the delivery of sulphur species to the stratosphere in a way that will produce particles of the right size. One important consequence of continuously injecting sulphate aerosol particles is that the particles are expected to grow to larger sizes than observed during volcanic eruptions due to coagulation and condensation [40]. Due to their large size, these particles result in a reduced albedo and therefore a lower cooling efficiency. Other delivery mechanisms such as the emission of condensible vapour from aircraft are considered to reduce some of the adverse effects of sulphate aerosol geoengineering [41].

3.2.3. Potential Contributions from Space

This approach relies on a suitable method to continuously inject SO_2 into the lower stratosphere. Furthermore, it will likely require some control on the injection rate as well as on the geographical location and altitude of injection. Different technical solutions are in principle available, including rockets for injection into higher atmospheric layers.

Space-based instruments including lidars and spectrometers could be used to measure the distribution of injected aerosols, their diffusion rate and patterns as well as their decay. SO_2 measurements have been successfully performed from space since the early 1980s, when the 1982 eruption of El Chichón inspired a new technique for monitoring volcanic clouds using data from the Total Ozone Mapping Spectrometer (TOMS) instrument [42] on-board of the US Nimbus-7 satellite [43]. It enabled measurement of the sulphur dioxide mass in eruption plumes as they were carried by winds, thus enabling the distinguishing of magmatic eruptions from phreatic ones [44, 45].

In 1998 Eisinger and Burrows demonstrated the use of the GOME instrument on-board of ESAs ERS-2 spacecraft, operational from 1995 to 2011, to measure total atmospheric SO_2 columns after volcanic eruptions [46]. The GOME spectrometer, a nadir-looking across-track scanning instrument, has been able to measure the concentration of a number of minor atmospheric trace constituents including sulphur dioxide with a typical footprint size of ∼ 320 x 40 km2. It measured the backscattered radiation from the Earth-atmosphere system between 240 nm and 790 nm with a moderately high spectral resolution of ∼ 0.2 nm to 0.4 nm [47].

Recently it has been shown that satellite measurements of volcanic SO_2 emissions can also be used to provide information for aviation hazard mitigation purposes. These uses are potentially interesting for geoengineering purposes since they tend to require fast revisiting times, regional precision and global

range. Simon et al. have surveyed such instruments, including the Ozone Monitoring Instrument (OMI) on NASAs Aura satellite. Its high sensitivity to SO_2 permits long-range tracking of volcanic clouds in the upper troposphere and lower stratosphere and accurate mapping of their perimeters [48]. Aerosols and clouds are closely linked since e.g. aerosols affect cloud properties and some of the measurement techniques for aerosols and clouds use the same sensors and spacecrafts [1].

3.3. Cloud albedo Modification

3.3.1. Concept Description

The approach of modifying the albedo of clouds to influence the energy balance of Earth also belongs to the second of the geoengineering categories outlined in Chapter 2, namely the solar radiation management concepts. Similar to using stratospheric aerosols, the basic principle is to increase the total amount of sunlight reflected before reaching the Earth's surface [6]. Clouds are already responsible for reflecting part of the sunlight back to space. Low-level marine clouds contribute strongly to this overall cooling, whereas higher, colder clouds have a warming effect as they reflect long wave heat radiation back to Earth. Increasing the cloud cover or cloud reflectivity of low-level marine clouds would reduce the amount of sunlight and energy reaching Earths surface. Compared to other geoengineering approaches, it takes advantage of a natural phenomenon [49]. In principle only wind and seawater are needed, and the cooling effect could be targeted at specific locations and during specific periods of time (relying on the relatively small scale of low-level clouds and the short lifetime of cloud particles). It also offers potential for small-scale field tests.

The concept has been proposed in the form of whitening clouds over parts of the ocean [6, 50–52]. This could be achieved by seeding low-level maritime clouds with seawater particles, which would increase the cloud condensation nuclei concentration. Then a larger concentration of condensation nuclei would lead to a smaller average droplet size. In a larger reflective surface area, a larger quantity of micro-droplets can reflect more light than a smaller quantity of larger droplets of the same total mass. As such this principle can be used to decrease the incoming solar radiation [12, 53]. Rasch et al. (2009) calculated that their proposed seeding strategy, consisting of automated sea-going vessels spraying sea salt particles, could not simultaneously restore global averages of temperature, precipitation and sea ice extent to present day values, but could counteract global warming [51]. In particular it could produce a short-wave negative forcing of up to about -4 W m-2, which would be sufficient to balance the positive forcing associated with a doubling of the atmospheric CO_2 concentration from present day values [51, 54]. Recently, Partanen et al. (2012) presented so far the most detailed model of the efficacy of sea spray geoengineering, including an explicit online calculation of cloud droplet activation, aerosol-cloud interactions and radiation to estimate the relative importance of direct and indirect aerosol effects of

this geoengineering scheme. Their simulations seem to indicate that reducing the size of injected particles from 250 nm to 100 nm can be an efficient way to raise the efficacy of sea spray geoengineering. When all oceanic areas were geoengineered, the global mean direct forcing was –1.5 W/m2 compared to the indirect effect of –3.6 W/m2 [55].

3.3.2. Main Issues

There are a number of technological and scientific questions that have to be resolved before it is clear whether significant negative forcing is achievable. The main issues for the successful implementation of this strategy are the creation of a supply of particles and the distribution of these particles. The particles need to be of the right diameter and quantity. Most studies on this technique consider the generation of fine particles of sea-salt derived from ocean water, delivered by either ocean-going vessels or aircrafts [50, 53, 54]. Such a spraying system would need to operate continuously at sea in a reliable manner in various atmospheric conditions and for long periods of time (at least several months).

In particular the wind speed dependence of the spray emissions, the atmospheric transport and the particle loss via deposition and precipitation scavenging may affect the geographical distribution of the cloud droplets [56].

This geoengineering approach may also cause non-negligible cooling also in the case the injected sea spray is transported to clear-sky regions [55].

3.3.3. Potential Contributions from Space

Passive imaging radiometers of multiple types have provided observations of global cloud cover and aerosol layer distributions since the first Earth remote sensing instruments were launched into orbit. Such passive instruments however lack accuracy in height distribution and coverage. Active laser remote sensing of the atmosphere has the major advantage of a direct and unambiguous detection and height measurement of all scattering layers [57]. In 2003, NASA launched the Geoscience Laser Altimeter System (GLAS), the first polar-orbiting satellite lidar instrument launched on board the Ice, Cloud and land Elevation Satellite in January 2003 [58, 59].

In June 2006, NASA launched CALIPSO, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations with the satellite-borne lidar CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) experiment [60]. An interesting capability comparison between active sensor cloud profiles provided by the CALIOP experiment on board the CALIPSO spacecraft with the passive sensor cloud products from MODIS on the Aqua platform can be found in [61]. CALIOP is able to provide global, 4-dimensional aerosol and cloud data.

The ESA ADM-Aeolus mission (Atmospheric Dynamics Mission) is planned for launch in the coming years with its Aeolus payload, including Aladin, the Atmospheric Laser Doppler-Lidar Instrument, a direct detection Lidar incorporating a fringe-imaging receiver (analysing aerosol and cloud backscatter) and a double-edge receiver (analysing molecular backscatter) [62].

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[1] For a summary discussion of these sensors readers are referred to the discussion on cloud measurements

Also in the coming years, the 6th of ESA's Earth Explorer missions, called EarthCARE (Earth Clouds, Aerosols, and Radiation Explorer) conducted together with the Japan Aerospace Exploration Agency JAXA will be launched. EarthCARE will address the need for a better understanding of the interactions between cloud, radiative and aerosol processes by acquiring vertical profiles of clouds and aerosols, as well as radiances at the top of the atmosphere. EarthCARE will have the ATLID atmospheric lidar on board, further improving the aerosol and cloud data set and in the meantime our understanding of their influence and role in Earths climate system [63].

While CALIOP is a two-wavelength backscatter lidar, which provides aerosol and cloud optical properties at 532 and 1064 nm, these next-generation space-borne lidar missions will operate high-spectral-resolution lidars at 355 nm. In order to relate the measurements at these different wavelengths, extensive calibration campaigns with ground-based multi-wavelength lidars are ongoing (e.g. EARLINET, European Aerosol Research Lidar Network) [64]. Even though the details would need to be looked at with greater care, this data and the combined observation capabilities of these and future space-born sensors, especially active lidar sensors, seem to provide a solid basis for inclusion into a monitoring system for cloud geoengineering validation experiments.

Space-based sensors would be well positioned to measure the immediate effect of these clouds on local atmospheric temperatures at the cloud formation locations. Furthermore, such low-level maritime clouds would likely have effects on the local wind patterns, thus having consequences on the height of waves and eventually on ocean currents and local ocean salinity and water oxygen levels, all of which might be measured from space, via e.g. multi-spectral and infrared sensors for radar distance measurements.

3.4. Reflective Mirrors

3.4.1. Concept Description

The reflectivity of the Earths surface could be altered by albedo modification of desert grassland, croplands, human settlements and urban areas [65–67].

3.4.2. Main Issues

Surface albedo modification that covers small fractions of the Earths surface, such as white roof methods in urban areas, needs to produce large local albedo changes to significantly cool the local climate. Summerer and Maan (2012) showed that increasing the desert reflectivity by applying locally large negative radiative forcing induced relatively large changes in temperature and precipitation [68]. Their model also predicted a substantial effect on the amount of precipitation in the rain forests.

Other issues include potential conflicts with other human land-use such as agriculture and forestry [12]. Especially for large scale and very regional forcing methods, such as increasing the reflectivity of desert, there is a risk of changing the atmospheric circulation and other side effects, such as counterproductive reduction in cloud cover and rainfall, could be possible [69].

3.4.3. Potential Contributions from Space

Earth observation satellites already measure the reflectivity of Earth surface regions [70, 71]. As shown in the previous section, one of the potential impacts of large-scale land cover reflectivity changes might be changes in world-wide precipitation levels. Space instruments are already providing the main data for understanding and measuring precipitation. Given the large variations, such data needs to be collected at local scales over a global domain. Such a comprehensive description of the space and time variability of global precipitation can only be achieved from the vantage point of space [72]. Different observation techniques are currently employed to derive precipitation data, including observation of cloud tops with visible and infrared sensors from geostationary orbits. In particular the Geostationary Operational Environmental Satellites (GOES) spacecraft can be used to deduce precipitation data, though these are not given on the vertical structure and microphysics of clouds. To obtain such information active radars at Ku, Ka and W band (14, 35 and 95 GHz, respectively) can measure vertical profiles of precipitating hydrometeor characteristics within clouds. Passive precipitation radiometers (10–89 GHz) measure the integrated cloud water and ice paths and can estimate precipitation rates.

In 1997 NASA and JAXA launched a combined radar-radiometer system, the Tropical Rainfall Measuring Mission (TRMM), which enables deduction of the rainfall rates especially over the tropics [73]. In 2014, the next dedicated spacecraft, the Global Precipitation Measurement (GPM) Mission, is planned for launch. It is currently designed to provide integrated and uniformly calibrated precipitation measurements at every location around the globe every 24 h. While changes in the precipitation levels as suggested by the geoenginnering model runs would probably not be taken as risk, spacecraft might be able to provide timely and detailed feedback data on rainfall especially in the tropics.

4. Conclusions

The present paper has provided an overview of different technical geoengineering options from the perspective of possible contributions from space systems. These range from actual space-based geoengineering approaches to space applications providing timely data and being possibly part of the control system during both early test phases as well as deployed systems. Most of the paper naturally relies on interpreting and referring to various publications in the fields of geoengineering and different space applications, though some sections required relying on new simulations. Given the combination of large number of options of using space with the increasing number of climate engineering proposals, the present paper only intends to trigger a wider discussion among the space community on the topic, potentially leading towards a more systematic approach to the uses of space for climate engineering.

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