Climate Change and Geoengineering

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Abstract

By the end of this century, the climate is likely to warm by 2 ºC since pre-industrial times; model forecasts supported by observational and physical evidence of global warming suggest so (Stocker et al., 2013). On a regional scale, climate change is more evident in lower latitudes than in middle latitudes; warm dry regions are becoming warmer and dryer, and wet regions are becoming wetter. Ice sheets and glaciers are melting, causing together with the thermal expansion of water a notable rise in sea level. In desert regions such as the Middle East, livelihoods are affected, as seasonal mean temperatures are already near the tolerance level for humans and other species. As a result, productivity is decreasing and the pressure for migration is increasing (Hansen & Sato, 2016). The principle cause for climate change is the increase in greenhouse gas concentrations, fundamentally CO_2, in the atmosphere. Reduction of CO_2 emissions is proven to be a difficult and slow process.

There are current negotiations around developing and deploying technologies that aim to decrease global temperatures, and thus diminish the impact of climate change; these technologies include Carbon Dioxide Removal (CDR), and Solar Radiation Management (SRM). The former directly captures CO_2 from the atmosphere, while the latter allows the Earth to absorb less solar radiation. This paper recites facts about each strategy's mode of function, timescale over which it is effective, and the associated risks and uncertainties. Policymakers should invest in research and development for these technologies as soon as possible. SRM seems to be a less costly and fast-acting solution to counter the effects of climate change in the short-term and, if implemented, would buy time for more fundamental adjustments. On the other hand, CDR technologies are likely more effective to diminish future changes in the climate in the long term, with less environmental risks.

Introduction

The purpose of this literature review paper is to present a comprehensive overview of the geoengineering approaches that aim to counteract climate change globally and regionally. This purpose is served by reviewing and synthesizing scholarly texts, which introduce two possible geo-engineering methods: Carbon Dioxide Removal, and Solar Radiation Management. Although these two methods function differently, they are both designed to limit the growing impact of climate change on human life by attempting to decrease global temperatures. Such technologies are not yet fully developed and ready to be implemented at large scales, and so this literature review aims to gather all available information and encourage further studies and development so as to act as quickly as possible on such a time-sensitive matter.

In order to give a broad picture on the problem of climate change, before introducing and evaluating the possible solutions, this paper describes the physical aspects of climate change and discusses future projections as predicted by the best climate models. The data collected is from different authors, experts and technical reports. Firstly, we review the IPCC AR5 technical report on climate change on a global scale; it provides information on natural and anthropogenic drivers of climate change, assesses observational evidence in the past and the present, and uses both qualitative and quantitative data to model future projections of climate change (Stocker et al., 2013).

The second literature uses bell curve mean temperature anomalies to demonstrate the changes in regional climates, highlights the most contributing nations to climate change versus the most affected regions, and discusses the impact on livelihoods (Hansen & Sato, 2016).

As for literature on geo-engineering, several papers will be referenced. They introduce the idea of geoengineering, describe geoengineering methods, discuss their purposes, functionality, lifetime, and costs, as well as their associated uncertainties and risks, with key recommendations on developing and implementing these technologies (Shepherd, 2009; Lomax et al., 2015; Caldeira et al., 2013).

Review of Literature

Global Climate Change

Coordinating lead authors Thomas F. Stocker and others have contributed to writing the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). The AR5 builds on the Nobel Prize winning IPCC Fourth Assessment Report (AR4) (Solomon et al., 2007), as well as the Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) (Field et al., 2012). This highly condensed technical summary provides qualitative and quantitative assessments of the physical principles of climate change (Stocker et al., 2013).

The degree of uncertainty is expressed both qualitatively and quantitatively in this report. Qualitative uncertainty in key findings is expressed by levels of confidence based on the type, quality, amount, and consistency of evidence in the studies, in addition to the level of agreement between the experts' judgements. Quantified measures of uncertainty are based on statistical analyses of model results and observations (Stocker et al., 2013). Key findings in the AR5 provide an assessment of observational evidence for climate change using a variety of acquired data sets; as well as a quantification of the global trend in changes of physical elements of the Earth's lands, oceans, atmosphere and cryosphere (Stocker et al., 2013).

It is virtually certain that the troposphere has warmed and the stratosphere has cooled since the mid-20th century on a global scale. And that the upper ocean has warmed since the 1870s. In the ocean, saline surface water in evaporation-dominant latitudes has become more saline, and fresh surface water in rainfall-dominant latitudes has become fresher. Glaciers and ice sheets are shrinking at a rate higher than that reported in AR4. Ocean thermal expansion and glacier mass loss are the dominant contributors to global mean sea level (GMSL) rise during the 20th century.

The authors clarify the areas of uncertainty after describing observational evidence for each element in the climate system. Mostly, data sets collected prior to the 1970s are sparse and therefore don’t give as reliable trends as more recent data do (Stocker et al., 2013).

Natural and anthropogenic drivers of climate change are summarized and expressed in terms of radiative forcing (RF), which is a measure of net change in the Earth’s systems’ energy balance in response to externally imposed change. RF is expressed in units of watts per square meter. Positive RF leads to warming and negative RF leads to cooling of the planet (Stocker et al., 2013).

The Earth in radiative equilibrium absorbs about 70% of incoming solar radiation and reflects only 30% back into space. This solar heating increases the temperature of the planet until the temperature is high enough, so that the thermal (or longwave) irradiation of the planet compensates for the absorbed solar (or shortwave) radiation. Both absorption of solar radiation and amount of outgoing longwave radiation (OLR) depend on atmospheric composition.

Human (anthropogenic) activity has impacted the chemical composition of the Earth’s atmosphere, either directly by emissions of gases or indirectly via atmospheric chemistry, since the beginning of the Industrial Era (since 1750). The Earth’s surface properties and surface albedo have also changed due to agricultural activity, deforestation and industrial land use. The increase of well-mixed greenhouse gas (WMGHG) concentrations, especially CO_2 resulting from fossil fuel combustion, increase the value of RF (Stocker et al., 2013).

The authors of AR5 state with very high confidence that the RF of all WMGHG in 2011 is 2.83 W m^{-2} (Stocker et al., 2013), which is 0.2 W m^{-2} higher than that measured by the authors of AR4 (Solomon et al., 2007). The uncertainties of RF values are due to uncertainties in the radiative effect of WMGHG, in addition to poorly restraint cloud responses. Carbon dioxide is the biggest contributor out of all WMGHG that cause a positive energy imbalance. As it has been measured, CO_2 increases RF by almost 0.3 W m^{-2} per decade. Other WMGHG including CH_4, N_2O and halocarbons also contributed greatly in increasing RF during the Industrial Era (Stocker et al., 2013).

Another anthropogenic driver for climate change is the radiative effect of anthropogenic aerosols suspended in the atmosphere, which comprise particulate air pollutants like sulfate, black and organic carbon, and organic aerosols. There is high confidence that radiative forcing resulting from anthropogenic aerosols is estimated to be -0.35 W m^{-2}. There is also high confidence that aerosol forcing has offset a great portion of GHG forcing. Stocker et al. (2013) argues that aerosol-cloud interactions have an influence on individual storms, but there is limited evidence to show a systematic effect for aerosols on storms and precipitation intensity in general. There is a wide range of uncertainty when it comes to measuring and modeling aerosols' parameters, and thus there is uncertainty in assessing long-term trends of aerosol forcing (Stocker et al., 2013).

As for natural drivers of global climate change, variation of incoming solar radiation and natural aerosol forcing are the two dominant contributors. Natural aerosols include volcanic aerosols, haze, mist, sea salt, and dust. Solar forcing is associated with periodic changes of the solar constant and is evaluated in terms of total solar irradiance (TSI). The best estimate of solar RF during the Industrial Era is 0.05 W m^{-2}. Solar forcing in the 21st century is very likely much smaller than the forcing due to WMGHG. Possible future changes in solar irradiance will likely influence the rate at which global mean surface temperatures (GMST) increase, but this change will be small compared to the impact of increasing GHG emissions in the atmosphere (Stocker et al., 2013).

CO_2 emissions from volcanic eruptions are at least 100 times smaller than anthropogenic emissions; however, explosive volcanic eruptions eject large amounts of aerosols into the atmosphere, causing Earth to cool. In fact, volcanic eruptions since 1850 have offset 30% of ocean heat uptake (Stenchikov et al., 2009). The largest recent volcanic eruption of Mount Pinatubo in 1991 generated an RF that exceeded -3 W m^{-2} (Stocker et al., 2013).

According to (Stocker et al., 2013), there is high confidence that the frequency of warm days and nights will increase, and the frequency of cold days and nights will decrease in most land regions. The authors state with high confidence that anthropogenic warming will more likely influence tropical and subtropical regions than regions at mid-latitudes, and that surface air temperatures over lands will more likely increase than over oceans by the end of the 21st century (Stocker et al., 2013).

Regional Climate Change

The referenced literature for this section is a scholarly paper written by James Hansen and Makiko Sato on regional climate change and national responsibilities.

According to Hansen & Sato (2016), global warming of barely 1ºC is now at a magnitude large enough so that regional climate change is observable, especially year-round at low latitudes, and in the summer at middle latitudes. Warm conditions that were considered unusual in the past now occur more frequently, and what were considered extreme warming events are more extreme than ever today. However, not all countries around the globe experience the same magnitude of change in the climate. Hansen and Sato (2016) use quantitative evidence to show that countries that are responsible for most of fossil fuel use and CO_2 emissions, the biggest contributors to climate change, may not experience the severe consequences of climate change as much as countries in lower latitudes.

In this literature, significant change is illustrated in a simple and clear way. Changes in the distribution of seasonal mean temperature anomalies for different geographical regions are expressed in units of standard deviation (x-axis), and are seen as "shifts in the bell curve". This method is useful for the characterization of regional climate change, as it measures the change relative to the conditions to which humans and other species are adapted to (Hansen & Sato, 2016).

According to their findings, all regions experience a shift in the bell curve towards warmer temperatures, and an increase in the width and the asymmetry of the bell curve as a result of warming. However, the shifts in the bell curves are larger in the summer than in the winter, and this is mostly true for desert regions. The results of temperature change for different regions in units of standard deviation are analyzed and compared to historical variability. They found that the observed signals exceed natural variability, i.e. they are statistically significant.

The summer bell curves for both the United States and Europe are shifted more than one standard deviation ($+1\sigma$), and the shift in the winter bell curve for both is about half of a standard deviation (0.5σ). The changes in Europe are only slightly larger than the United States. In China and India, regional climate change is larger, as the summer bell curve shift is about 1.5σ, and the winter shift is about 1σ. Arid and semi-arid subtropical regions, such as the Middle East and the Mediterranean, in addition to Sahara and Sahel, experience the most drastic shifts in their climates, far exceeding natural variability, as the shift in the summer bell curve is about 2.4σ.

Moist tropical regions, such as South East Asia and the African Rainforest experience shifts of more than two standard deviations in the summer and the winter ($+2\sigma$). As for areas in the southern hemisphere, which include Australia, South Africa, and South America, the shifts in the summer and winter bell curves are about 1.3σ (Hansen & Sato, 2016).

One of the most notable findings is that the largest warming occurs in the Middle East, the Mediterranean, the Saharan desert, the Gobi desert, and the Southwest of the United States. Warming in such arid climates amplifies heatwaves and drought year by year. Moreover, climatologically wet climates are getting wetter year by year (Hansen & Sato, 2016).

Although the relative warming since pre-industrial times is minor compared to individual weather fluctuations at a regional scale, climate change is already having an impact on human life on social and economic levels. Livelihoods are affected at latitudes where temperature and absolute humidity are already near the tolerance limit for humans who work outdoors, which reduces productivity. Human health is affected by higher temperatures directly during heatwaves, drought, wildfires and floods. Indirect impact on human health includes the changing patterns of vector-borne diseases as they move to higher latitudes towards higher temperatures.

There is great certainty that such significant change in regional climate systems and human lives is associated with increasing atmospheric greenhouse gases (GHGs), especially CO_2 from fossil fuel burning.

According to Hansen & Sato (2016), fossil fuel CO_2 annual emissions in 2014 reached a whopping 9.6 Gt C/yr (gigatons of carbon per year). China was the biggest contributing country for emissions during that year, as it accounted for 25% of emissions. The United States is the second largest contributor, and India is a rapidly growing third. The Middle East, being one of the most affected regions by climate change, contributed to about 6% of emissions in 2014.

Cumulative emissions since the beginning of the Industrial Era up to 2014 reached 396 Gt C. The United States and Europe are the biggest contributors. Each of them accounts for almost 25% of emissions. China caused 10% of cumulative emissions, and the Middle East 3%, in par with India.

As for per capita fossil fuel emissions in 2014, the United States took the lead as it accounted for 4.5 tons Carbon/year/person, far exceeding the global mean of about 1.3 tons Carbon/year/person. China, despite its large contribution for GHG emissions, records lower per capita emissions in comparison to Western countries such as the US, the UK, Canada, and Australia, and also the Middle East. India's per capita emissions are even smaller than China's.

Per capita emissions from the Middle East are among the largest in the world, as GCC countries alone have per capita emissions of 5 to 12 tons of carbon per person per year, much greater than per capita emissions from the US (Hansen & Sato, 2016).

As for cumulative per capita emissions, the US, UK, Canada, as well as Germany, take the lead for that contribution since the beginning of the Industrial Era. Cumulative emissions from the Middle East are not as large as from the countries that have developed earlier, but they are still larger than the global mean per capita cumulative emissions of about 60 tons of carbon per person and continue growing (Hansen & Sato, 2016).

Having said that, the locations of fossil fuel CO_2 emission sources are almost incongruous with the locations of large magnitude climate change, perhaps except for the Middle East. The largest bell curve shift is in tropical rainforests such as Southeast Asia, arid environments such as the Saharan Desert, and semi-arid environments such as the Middle East and Mediterranean. The large shift is associated with lengthened warm seasons, when temperatures are already near the limit of human tolerance (Hansen & Sato, 2016).

Given the approximate linearity between bell curve shifts and mean temperature increase, 2ºC global warming would yield a summer bell curve shift of approximately 6σ in the Middle East, Mediterranean, Sahara, Sahel, as well as African rainforests and Southeast Asia. The impact on livelihoods and economic productivity would become even greater, as it will force migration. Not to mention the threat of global sea level rise as a result of global warming, which in case of the rapid destruction of polar ice sheets, would reach 6-9 meters. This would damage the global coastlines and add another source of migration pressure (Hansen & Sato, 2016).

Hansen and Sato (2016) suggest that the United Nations 1992 Framework Convention on Climate Change's (UNFCCC) objective to stabilize GHG concentrations below 350 ppm is fundamental to avoid irreversible ocean warming and ice sheet disintegration. Restoration of CO_2 below 350 ppm in order to restore the Earth's energy balance would require the immediate reduction of fossil fuel emissions by 5 to 7% per year (Hansen & Sato, 2016). However, even if emissions were reduced, CO_2 concentrations will continue to grow to the point where ocean uptake is higher than current emissions. Therefore, an active carbon dioxide removal approach is still needed alongside significant reduction of annual emissions.

Failure to take such drastic measures will lead to the increase of Earth's energy imbalance, accelerating global mean temperature rise, ice sheet disintegration, and sea level rise. This will increasingly affect livelihoods and economies. In such cases, there will be increasing calls for "geoengineering", which will be explained in the following section. Finally, the authors suggest that it is necessary to include external costs to fossil fuels for climate change and water and air pollution. The carbon fee collected from fossil fuel companies will be used to reduce economic hardships and increase efficiency. This will also make room for carbon-free energies to be used (Hansen & Sato, 2016).

Geoengineering Methods

Two main geoengineering methods will be discussed and compared by referring to a book published by a working group from the Royal Society (Shepherd, 2009), and more recent papers that further evaluate the technicality of these methods (Caldeira et al., 2013) and their political impact (Lomax et al., 2015).

It is likely that global warming will reach and exceed 2 °C by the end of this century, unless GHG emissions are cut by at least 50% by 2050 (Shepherd, 2009). There are many strategies considered to lower the impact of climate change, such as mitigation (reducing/eliminating GHG emissions while producing energy), conservation (reducing demand for goods and services), efficiency (producing goods and services with less energy inputs), and adaptation (increasing resilience to the effects of climate change that are already occurring) (Caldeira et al., 2013).

Although these strategies are fundamental to implement today to limit further global warming, they do not fix climate change impacts of greenhouse gases that have already been emitted into the atmosphere since the beginning of the Industrial Era; this is where geoengineering comes to play. One of these methods of geoengineering is Carbon Dioxide Removal (CDR), which aims to capture and remove CO_2 from the atmosphere. The other method is Solar Radiation Management (SRM), which aims to reflect some of the sun's energy back into space, and thus diminishes the impact of climate change due to high greenhouse gas concentrations (Caldeira et al., 2013).

Both Carbon Dioxide Removal and Solar Radiation Management have the ultimate goal of reducing global temperatures. However, they are very different from each other in terms of modes of action, timescales over which they are effective, and the associated risks (Shepherd, 2009). CDR addresses the root cause of global warming and climate change, as it removes CO_2

from the atmosphere. SRM, however, attempts to reduce the effects of increased GHG concentrations in the atmosphere, for example, by developing an artificial aerosol layer that will effectively cause the Earth to absorb less solar radiation (Shepherd, 2009).

Carbon Dioxide Removal (CDR). According to (Caldeira et al., 2013), anthropogenic CO_2 emissions have reached approximately 10 Pg C/yr (petagrams of carbon per year). Nearly 50% of human-made CO_2 is absorbed by the ocean and biosphere, and the rest is accumulating in the atmosphere. The fraction absorbed by the ocean and biosphere is expected to decrease over time. Significant concentrations of anthropogenic CO_2 in the atmosphere can persist for thousands of years, and the consequences will be surely felt by humans and other species inhibiting the Earth.

The process of climate change can be reversed or slowed down by employing strategies that use natural processes to remove anthropogenic CO_2 from the atmosphere. An example of a CDR strategy such as reforestation has already been negotiated by the UNFCCC. CDR methods essentially tackle the root cause of climate change, which is the excess anthropogenic CO_2 concentration in the atmosphere. CDR aims to remove this human-made CO_2 from the atmosphere and infuse it back into vegetation, soil, oceans, and geological reservoirs (Caldeira et al., 2013).

There are multiple approaches of carbon dioxide removal; they differ in terms of climatological efficiency, the scales at which they are effective, their costs and their risks. Different approaches should be considered for different geographical regions, spatial scales, and timescales, depending on the desired results without causing further environmental damage.

Some CO_2 removal approaches include afforestation/reforestation, which is direct human-induced growth of forests in lands that lack forestation or have been deforested. Studies show that afforestation in tropical regions could increase the cooling effect; whereas in boreal regions, afforestation could result in net warming due to decreased surface albedo despite CO_2 storage (Caldeira et al., 2013).

Another approach is based on using biomass energy for CO_2 capture and storage, which directly removes CO_2 from the atmosphere using power plants fueled with biomass and pumps it into long-term storage sites such as geological reservoirs. This method of capture and storage can result in permanent removal of CO_2 from the atmosphere; and it allows repeated use for the same land, where plants can be farmed and used for biofuels. Economic analysis suggests that this approach's cost competes with more conventional methods that aim to deeply reduce CO_2 emissions (Caldeira et al., 2013).

CO_2 can also be removed by natural chemical weathering reactions, such as the weathering of carbonate minerals or silicate minerals. However, natural chemical weathering reactions take place at a very slow rate, as they consume around 0.1 Pg C/yr of CO_2 from the atmosphere; this is approximately 1% of anthropogenic CO_2 emissions. Accelerated land- or ocean-based weathering could help store CO_2 by dissolving it in ocean water, or by producing solid carbon-bearing minerals. An example of land-based weathering is crushing substantial amounts of silicate minerals and distributing them on agricultural land such that more surface areas for reaction allows a faster rate of weathering; this method would also help counter ocean acidification. An example of ocean-based weathering is promoting the ocean's uptake for CO_2 by adding or dissolving minerals in the ocean to increase alkalinity and/or reduce acidity (Caldeira et al., 2013).

Another approach for CDR is ocean fertilization, where the process of photosynthesis (which involves the uptake of CO_2) is promoted by allowing microscopic photosynthesis organisms to uptake inorganic carbon from the surface. The more near-surface inorganic carbon is consumed, the more CO_2 from the atmosphere will enter the ocean and be stored as organic carbon. Some nutrients such as iron, phosphate and nitrogen are acting as fertilizers accelerating this process. However, this approach could acidify deep oceans by storing more CO_2 and releasing more N_2O (another greenhouse gas) into the atmosphere (Caldeira et al., 2013).

Finally, direct CO_2 capture from ambient air employs chemical processes that separate CO_2 from the atmosphere. The captured CO_2 could be transported into geological reservoirs or used commercially. However, in most circumstances, this method seems to be more costly compared to CO_2 capture from power plants. In fact, almost all CDR approaches are costly if implemented at large scales (Caldeira et al., 2013).

Moreover, CDR technologies may involve many uncertainties, as they are still technically immature (Lomax, 2015). The effects of large-scale deployment for several decades in the future are still ambiguous, and the environmental impacts on the response of the global carbon cycle are unclear. There are also uncertainties concerning the costs and viability of untested technology. Estimates of the costs of direct CO_2 capture range from US$100 to more than US$1,000 per ton.

In addition, CDR approaches would require decades until the desired results on climate change are apparent (Shepherd, 2009). Because of the thermal inertia of the oceans, the decrease in surface temperatures would fall behind the decrease in CO_2 forcing. It is said that if all CO_2 emissions instantaneously cease, climate warming would still persist for decades or even centuries (Caldeira et al., 2013).

And so CDR methods can effectively return the climate system back to its natural state, thus they likely involve fewer risks and uncertainties. Nonetheless, CDR does not provide an immediate solution to reduce global temperatures within a decade, and it has not yet been demonstrated at an effective cost and with acceptable side effects (Shepherd, 2009).

In agreement with (Lomax, 2015), the safest way to determine whether CDR technologies would yield feasible and desirable results for the second half of this century is to initiate a policy framework to invest in research and development.

Solar Radiation Management (SRM). As a result of increased greenhouse gas concentrations in the atmosphere, the Earth is experiencing a radiative imbalance as more solar energy is absorbed than irradiated by Earth back to space. According to (Caldeira et al., 2013), the Earth absorbs around 240 W m^{-2} of solar radiation. In the energy equilibrium regime, the planet returns all absorbed energy back into space by thermal radiation.

Doubling of CO_2 concentrations would decrease the outgoing thermal radiation causing a radiative forcing of around 4 W m^{-2}. To offset this forcing, the Earth would have to reflect 4/240 or 1.7% of incoming sunlight; this can be achieved at large scales using Solar Radiation Management (SRM) technologies (Caldeira et al., 2013). SRM is a geoengineering method which attempts to increase the Earth's reflectivity to force solar energy to deflect back into space, allowing Earth to cool.

There are different SRM approaches, which could cool the climate relatively rapidly in comparison with the CDR approaches. However, SRM approaches do not alter the anthropogenic CO_2 content in the atmosphere, and therefore SRM cannot reduce CO_2-induced ocean acidification or alter the Earth's terrestrial carbon cycle. It does, however, affect the Earth's stratosphere temperature rapidly, which may aggravate the stratospheric chemistry (Caldeira et al., 2013). Thus, SRMs aim to reflect solar radiation away from the Earth; and this reflection could occur either in space, in the stratosphere, in the lower atmosphere, or on the Earth's surface (Caldeira et al., 2013).

There are several space-based SRM approaches that have been proposed to reduce the amount of incoming solar radiation reaching the Earth. Some of these techniques include deploying reflective material (such as glass, mirrors, or lunar material) between the Sun and Earth or orbiting the Earth. However, to offset the annual increase in CO_2 emissions, there would have to be more than 10,000 km^2 of reflection area deployed each year (Caldeira et al., 2013). And thus, large-scale deployment for this approach seems to be a long process and may be unfeasible in the long term.

The most feasible SRM approach is the stratospheric aerosol method, which mimics volcanic eruptions and their associated aerosol injection into the lower stratosphere. Injected aerosols scatter solar radiation back into space and decrease global mean temperatures by several Kelvin in a year or two. This approach was considered after noticing that the eruption of Mount Pinatubo in 1991 caused radiative forcing of $-3.5\ W\ m^{-2}$, cooling the Earth's surface by approximately 0.5 K. If geoengineering SRM were to be deployed at a full-scale and while steadily maintaining aerosol particles in the stratosphere, and the offset of radiative forcing was of the same magnitude as that caused by Mount Pinatubo, the Earth's surface would cool by 3 K (Caldeira et al., 2013).

A range of substances have been considered to potentially scatter solar radiation if placed high in the atmosphere, but the most studied substance to be released for geoengineering is SO_2, which is then oxidized into sulfate aerosols similar to volcanic eruptions.

Several methods for releasing these particles into the lower stratosphere have been proposed, these include high-altitude balloons, artillery guns, high-level aircrafts, and space elevators (Caldeira et al., 2013). This technology requires further investigation as there are many uncertainties and risks which may impact the efficacy of aerosol based SRM. Some climatic side effects are associated with this approach, as it may cause a decrease in precipitation and thus food supply in highly populated monsoon regions such as India. Many parameters like altitudes, locations, and mode of injection need to be carefully considered before deployment so that the stratosphere chemistry, ozone depletion, and regional precipitation and runoff rates are not affected negatively (Caldeira et al., 2013).

Another approach to SRM is enhancing surface albedo, which is the Earth's surface reflectivity. Various methods have been proposed to increase the reflectivities of land and ocean surfaces. However, since land covers less than one-third of the Earth's surface, and almost half of the land is covered by clouds, increasing land surface albedo to alter global mean temperatures could be challenging and not as effective. Nonetheless, numerous simulations have shown that altering surface albedo may yield little yet good-enough results for the short-term, as they could result in decreases in seasonal mean temperatures in higher latitudes (>30º).

For rural areas, a 0.08 increase in crop albedo could induce a radiative forcing of approximately -0.035 W m^{-2}. For urban areas, increasing the worldwide albedo of rooftops would give a radiative forcing of about -0.044 W m^{-2}.

Some studies have suggested that increasing ocean surface albedo is possible by deploying a fleet of ships that eject a large amount of very small bubbles in oceans. An increase of global ocean surface albedo of 0.05 could decrease global mean surface temperatures by the same magnitude of increase caused by a doubling in CO_2 concentrations (Caldeira et al., 2013).

Several model simulations have been done for the aforementioned SRM approaches. The results indicate that using geoengineering methods which reflect solar radiation away from the Earth could potentially cool the Earth's surface rapidly by a few Kelvin within a decade and could prevent undesirable consequences of climate change, such as the collapse of the Greenland ice sheet (Caldeira et al., 2013). Shepherd (2009) states that out of all the approaches, stratospheric aerosols can be much more readily implemented. However, there are still many associated risks and significant uncertainties which require detailed modelling of their impact on all aspects of the climate system. In the meantime, it is concluded that although not as costly as CDR technologies and much faster-acting, deployment of SRM technologies in general at large scales would be risky and unsustainable in the long term (Shepherd, 2009).

Conclusions

Global warming of 2ºC is expected by the year 2100 if greenhouse gas emissions are not reduced by at least 50% (Hansen & Sato, 2016). The impact of climate change is observed in different degrees of severity at different latitudes, where tropical, subtropical, and desert regions are the most severely affected by the increase of anthropogenic CO_2 concentrations in the atmosphere.

If no strong policy framework is implemented, drastic measures may have to be taken this century, and there are significant uncertainties associated with these drastic measures. There is already a call for geoengineering as a way to tackle climate change, but it is important to note it merely offers a new approach to address climate change. However, it is important responsibly research, develop and deploy them while avoiding harming the climate system.

Carbon Dioxide Removal methods that are proven to be safe, effective, affordable and sustainable should be launched along with conventional methods of mitigation. Solar Radiation Management techniques, on the other hand, should not be applied unless there is an urgent need for rapid reductions in global mean surface temperatures; they should be planned for a short period only because there are significant uncertainties and risky side-effects associated with it. CDR is favorable in the long term over SRM, because SRM does not tackle the root cause of climate change, which is the significant concentrations of anthropogenic CO_2 in the atmosphere (Shepherd, 2009).

The success of geoengineering techniques is challenged by political factors much more than technical feasibility. Some methods such as ambient air CO_2 capture already have national mechanisms established, others like ocean fertilizations contradict international legislation. Some methods such as stratospheric aerosols and space mirrors require new international mechanisms for governing such global measures. All CDR and SRM geoengineering techniques must have established regional, national and international mechanisms before they could be applied. Geoengineering should be implemented effectively and responsibly; the enhancement of knowledge and the development of governance mechanisms for this field requires collaborative work between nations, policymakers and scientists.

Collaboration and coordination between international policymakers are especially required for responsible and effective development of geoengineering methods. Governments should initiate a governance framework to responsibly invest in research and development of geoengineering technologies, and make sure they are sustainable, affordable, environment-friendly, and ready to be applied if it becomes necessary (Shepherd, 2009).

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