2

Technologies

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This chapter examines the two main methods of deliberately tinkering with the atmosphere to cool the planet: solar radiation management and carbon dioxide removal.

2.1. SOLAR RADIATION MANAGEMENT

Solar radiation management (SRM), also known as albedo modification, seeks to address the energy imbalance that is at the heart of the global warming challenge (the word albedo comes from *albus*, the Latin for white). Two hundred thirty-five watts of energy from the Sun pour onto every square meter of the planet, getting absorbed by the climate system. Before the buildup of anthropogenic greenhouse gases, a roughly equal flux of energy, in the form of heat, flowed out of the planet. But scientists estimate the Earth system is now absorbing a small amount of that outgoing energy – one study estimated the amount was a little more than half a watt per square meter – because of the buildup of greenhouse gases in the atmosphere[1] (a doubling of the concentration of CO_2 in the atmosphere would cause a total of about 4 watts per square meter of additionally absorbed energy[2]). That small imbalance, over the entire planet's surface, is the fundamental reason that the Earth's temperature has risen by roughly one degree Celsius since preindustrial times.

One of the key findings regarding SRM is that small perturbations in the Earth's atmosphere can have immediate and profound effects on the globe. That gives SRM the potential to be used in a hurry: According to a 2015 report of the National Research Council, SRM technologies are the "only ways that have been suggested by which humans could potentially cool Earth within years after deployment."[3] It also explains why estimates of their costs are surprisingly low given their potential to affect the global climate. "Some SRM approaches are thought to be low in cost, so the scale of SRM deployment will likely depend primarily on considerations of risk."[4]

Albedo modification techniques could theoretically be implemented at several different levels of the atmosphere: in the upper atmosphere (Section 2.1.1), in space (Section 2.1.2), in low-lying clouds at the sea surface (Section 2.1.3), in cirrus clouds at the lower atmosphere (Section 2.1.4), or at the Earth's surface (Section 2.1.5).

2.1.1. *SRM in the Upper Atmosphere: Stratospheric Aerosol Albedo Modification (SAAM)*

The most commonly proposed technique for managing solar radiation is to mimic the natural cooling effect of volcanoes by spreading sulfurous particles in the atmosphere. Russian scientist Mikhail Budyko was the first to propose this technique in 1974, but Nobel laureate Paul Crutzen gave the idea a measure of legitimacy in an editorial essay proposing research into SAAM in 2006.[5]

Harvard physicist David Keith calls injection of aerosols into the stratosphere as a means of geoengineering "fast, cheap, imperfect and uncertain."[6] Natural aerosols, including dust or chemicals emitted by marine or terrestrial plants, not only transport chemicals and microbes around the planet but also affect its climate. The particles emitted by volcanoes are particularly potent, as seen in studies of the 1991 eruption of Mount Pinatubo, which sprayed 14 to 26 megatons of aerosol into the stratosphere as sulfur dioxide.[7] Those particles created a haze in the sky, scattering light away from the Earth and cooling the planet by 0.3°C over three years.[8] Previous volcanoes during the Earth's geologic history have been even more powerful in terms of their cooling effect.

Modeling studies suggest that if a similar quantity of sulfur aerosol were artificially injected into the stratosphere, the cooling would begin within months – which on geologic timescales is essentially instantaneous.[9] To compensate for the warming that a doubling of CO_2 would cause, an albedo modification scheme would have to block between 1.7 percent and 2.5 percent of incoming solar radiation.[10]

In the lower portion of the atmosphere, the troposphere, the weather washes aerosols out of the atmosphere in days. But models show that in the stratosphere, a layer that begins roughly 8 kilometers above the ground and extends to about 50 kilometers, aerosols mix readily, can last for years before removal, and spread about the planet in a matter of weeks. For that reason SAAM involves releasing aerosols into the stratosphere, where they can modify the Earth's albedo. "[I]f one can inject aerosol a bit above the bottom of the stratosphere in the tropics, it would be carried upwards and then towards the poles, resulting in a long lifetime and a relatively even distribution of aerosol throughout the stratosphere," wrote one proponent of the idea, based on modeling.[11]

Modeling has shown some of the opportunities and risks of the global application of the technique. Global mean temperatures may be lowered using albedo modification, but the effect would likely be patchy. In a widely-cited comparison of 12 major climate models from around the world, researchers found that applying SAAM alone to attempt to restore a preindustrial climate would overcool the tropics and insufficiently cool the Arctic.[12] Several modeling studies have suggested that SAAM could be deployed to protect and regrow Arctic ice, including the Greenland ice sheet.[13]

Different studies have made varying conclusions when it comes to the impact of SAAM on precipitation. In a simulation of SAAM sufficiently deployed to counteract a quadrupling of preindustrial atmospheric CO_2, the multimodel study found that precipitation was affected, but not much: Over 92 percent of the globe, the difference in either direction was less than 0.2 mm of rain per day.[14] But in a study in which one model was used to simulate five different albedo modification techniques, "[p]otentially damaging changes in regional precipitation were a feature of all [the methods]." The reason for the difference may be that in the multimodel study the differences between the models can cancel one another as their results are averaged.[15]

2.1.1.1. Techniques for Implementing SAAM

A number of approaches have been proposed for placing aerosol particles into the stratosphere, including utilizing aircraft, artillery, and rockets. The technique proposed for albedo modification that has received the most attention is release of aerosols by planes from within the stratosphere.

Rockets and naval guns have also been proposed as vehicles for the delivery of aerosols to altitude but have received little serious attention. An even simpler approach has also been proposed: using a high-altitude balloon and a tube. Intellectual Ventures, a Seattle-based firm run by US inventor Nathan Myrvold, has promoted the Stratoshield, a scheme for delivering aerosols to high altitude that allows the production of the sulfates to be done on the ground, after which they would be delivered to altitude and released there. As discussed in detail in Chapter 6, in 2010, British academics began an experiment that would use the same basic approach. Funded by the UK government's Engineering and Physical Sciences Research Council, the Stratospheric Particle Injection for Climate Engineering (SPICE) experiment, sought to study how the release of harmless water particles affected the stratosphere. But it was halted before any particles could be released.

Only a handful of close analyses of costs of SAAM have been conducted, but the initial findings are that the cost of deploying various approaches would be on the order of billions of dollars per year. In 2012 Aurora Flight Science Corporation found that the technology to deliver sufficient aerosols to altitude in order to counteract the warming caused by a doubling of preindustrial CO_2 "exists today."[16] The study looked at a number of techniques to deliver aerosols to high altitude. While dirigibles were seen as having potential for geoengineering operations, given their potential to carry large payloads and stay aloft for extended periods, Aurora found that their use at high altitude would be more risky than using airplanes known to be able to operate there. Use of rockets and naval guns had estimated annual costs of $390 billion and $137 billion, respectively – one or two orders of magnitude more expensive than using airplanes.

Aurora Flight Sciences offered this analysis of the blimp-and-tube approach: "Pipes suspended by floating platforms provide low recurring costs to pump a liquid or gas to altitudes as high as 20 km, but the research, development, testing and evaluation costs of these systems are high and carry a large uncertainty; the pipe system's high operating pressures and tensile strength requirements bring the feasibility of this system into question."[17] The analysis concluded that delivery of material required for stratospheric solar radiation management appears to be feasible in terms of engineering considerations.[18]

For airplanes, delivering this quantity – on the order of 1 million to 5 million metric tons of aerosol – would require an initial investment of $1 billion to $11 billion, with yearly operating costs between $0.6 billion and $2.6 billion (the costs on the high end of the estimate are linked to building and operating new aircraft with specialized capabilities for cargo delivery and dispersal in the stratosphere). The size of that operation would be roughly equivalent to flying 25 fully loaded 747 jets each day.[19]

Operating a global SAAM system would presumably require a robust observational system to monitor its operation and impacts. Such a system would likely have costs on the order of those for standard Earth-observing satellites, with a cost to build and operate in the billions of dollars per year.[20]

2.1.1.2. Environmental Impacts of SAAM

2.1.1.2.1. PHOTOSYNTHESIS An important difference between using a sunlight-reflecting approach in space and spraying aerosols in the upper atmosphere is that, by deploying aerosols, a large amount of diffuse solar radiation reaches the ground (that is why some scientists believe the spread of these particles in the upper atmosphere could make the sky look hazy). Several studies have suggested that this increase in diffuse light could potentially increase photosynthesis in plants, since such photons can reach plants in the canopy that cannot receive direct light from the Sun. In a 2009 study, researchers used a global climate model to study the last four decades of the twentieth century, when a "global dimming" was caused by aerosol pollution in the lower atmosphere, including sulfates emitted by power plants. From 1960 to 1980, for example, they found that the increased diffuse light caused plants to take up an additional 4.4 million tons of carbon each year via enhanced photosynthesis.[21] But this effect has not been directly considered in modeling studies of stratospheric aerosol geoengineering.

2.1.1.2.2. STRATOSPHERIC OZONE SAAM can disrupt the chemical cycle that maintains the stratospheric ozone layer, a chemical layer that protects biological life from ultraviolet sunlight. Theoretical and modeling studies suggest that sulfates in the lower portion of the stratosphere can provide surfaces for chlorine to change into forms that deplete ozone. After the 1991 Pinatubo eruption, total ozone measured in tropical and temperate latitudes declined by 4 percent, though scientists say that anthropogenic emissions of chlorine and bromine aerosols may have played a role. The chlorine in the stratosphere comes from long-lived chlorofluorocarbon (CFC) pollutants, whose levels peaked in the 1980s and continue to drop. So the impact of SAAM on the ozone layer in part depends on when it is attempted and the CFC levels in the atmosphere at the time.

Most scientists who have examined the matter believe that there is significant potential for sulfate aerosols to damage the ozone layer, but that is only one aspect of the risk to biological life. Stratospheric aerosols may scatter ultraviolet rays in the upper atmosphere before they can pass to the lower atmosphere. So even if the ozone layer is weakened, the effect on human health and ecosystems may be attenuated if fewer harmful rays pass through the stratosphere to the planet.

2.1.1.2.3. COLOR OF THE SKY In the same way that city residents sometimes experience a brightening of their sky due to pollution, SAAM would tend to whiten the sky. A 2012 study found that blocking just 2 percent of the sun's light would cause the skies to appear three to five times brighter. "Although our study did not address the potential psychological impact of these changes to the sky, they are important to consider," a coauthor of the report said in a press release.[22]

2.1.1.3. Halting Albedo Modification

Once a global albedo modification scheme begins, suddenly halting it could have profound effects. First, such a halt could cause warming to resume at a rate many times faster than the current warming rate. "Whereas the non-geoengineered world warms relatively slowly with relatively slow increases in atmospheric CO_2, in the case of a catastrophic failure of a solar geoengineering system, Earth would experience a large climate forcing at the time of system failure and would warm rapidly for several decades."[23] Second, as shown in a 2007 modeling study,[24] such a sudden warming would trigger the release of stored carbon in the ocean and land, compounding the total amount of greenhouse warming.

2.1.2. *In Space: Solar Sunshades*

A number of proposals to cool the Earth envision deploying solar sunshades, launched into orbit around the Earth or the Sun. Soviet scientists in 1960, for example, proposed creating rings of dust in the upper atmosphere that would reflect additional sunlight onto the planet to warm certain areas, a proposal in line with real attempts to warm Siberia by rerouting Russian rivers.[25] Subsequent published proposals involve orbiting clouds of dust particles placed in an equatorial plane like the rings of Saturn, or random clouds of mirrors flying in low Earth orbit. A key challenge for sunshades launched into Earth orbit, however, is to balance weight and costs. Heavier ones incur greater costs to launch, but lighter ones are vulnerable to being "blown out of orbit by the light pressure force exerted by the sunlight they are designed to scatter."[26]

Such a tradeoff would be less of a problem if a ring of sunshades were launched into orbit near the so-called LaGrange 1 point. There, in a position between Earth and the Sun, the gravitational forces of each body pulling on the ring, along with the force of the Sun's rays pushing on the scattering ring, could counteract one another. In a 2006 paper[27] astronomer Roger Angel elaborated on a previous proposal[28] to install a "space sunshade" at such a position with the aim to reduce the solar energy striking the planet by 1.8 percent to counteract the warming effects of a doubling of CO_2.[29]

Angel's envisioned project would involve a swarm of roughly ten trillion disks, each roughly 0.1 mm thick and about 60 cm in diameter. Angel proposed using magnetic energy to launch a stack of one million such disks from the Earth's surface every second for 30 years.[30] That rate has led some experts to conclude that deploying such a space-based approach would be infeasible for decades.[31] Moreover, if coal plants were used to generate the needed electricity, the sunshade would require 30 kilograms of coal for each kilogram of sunshade launched. But each kilogram of sunshade launched would mitigate the direct warming effect of 1,000 kilograms of coal.

But other problems loom. As with using stratospheric aerosols to cool the planet, reducing solar radiation with solar shields does not precisely counteract the additional warming caused by greenhouse gases. It leads to cooler tropics – since the Sun's heating is more dominant there than greenhouse gas heating – and warmer poles, which are warmed more by the greenhouse effect than by the Sun. Turning down the Sun in this way would reduce the gradient between the tropics and poles, a key driver of air in global circulation patterns. The effects could be profound, including a reduced "amplitude of the seasonal cycle … giving warmer winters and cooler summers." Plus, as with proposals to cool the planet by injecting stratospheric aerosols, modeling studies have shown that by preferentially cooling the tropics, this method could reduce precipitation worldwide, which is driven by sunlight striking the tropics.[32] Among scientists considering various geoengineering proposals, solar sunshades have received far less attention than other methods. But the Royal Society says they should not be discounted out of hand.[33]

If in the future it became probable that some form of geoengineering would be needed for a period approaching a century or longer, on such a timescale (and with the continual advance of technical capabilities) it is quite possible that the best examples of this type may offer a cheaper and less risky approach to SRM than approaches that seek to alter either the higher or lower layers of the atmosphere.[34]

2.1.3. *Lower Atmosphere: Marine Cloud Brightening*

Low-lying, layered clouds, known as stratocumulus clouds, provide a reflective white cover on top of the dark ocean, to an altitude of up to 1,500 meters.[35] Several scientists have proposed increasing the albedo of such clouds, which cover 20 to 40 percent of the world's ocean,[36] to enhance their ability to reflect sunlight. This geoengineering technique is known as marine cloud brightening, or MCB.

The idea is to spray salt particles into these low clouds where they would serve as additional nuclei for cloud droplets.[37] Those particles would attract existing water droplets in the clouds to condense around them, creating clouds with smaller drops but more of them. This rearrangement of water in the cloud would mean fluffier clouds with more surface area. Clouds with more surface area are more reflective.[38]

A real-life example of how this would roughly work comes from ocean-going ships emitting aerosol pollution from their smokestacks. These particles catalyze the formation of white cloudy "shiptracks" in their wake, visible by satellite. The carbon emissions from these ships contribute to greenhouse warming. But during the moments when they happen to be under clouds, under the correct conditions to allow brightening, unwitting geoengineers in cargo ships may cause twice as much cooling as warming over a century timescale, one study estimated.[39]

That study involved running smoke generators on a small vessel operating off the California coast, to measure its ability to whiten clouds. The project found an even better ratio of 50 times more cooling (due to whitening clouds) than warming (due to carbon emissions). The experiment also found, however, that MCB worked only a fraction of the time, even when conducted beneath cloud conditions that were theoretically conducive.[40] One reason may be that as more nuclei particles are added to clouds, the effectiveness of each additional particle at growing the cloud is reduced.[41] A 2013 modeling study found another problem: Once sprayed out, aerosol particles can coagulate, slashing MCB's efficacy in half.[42]

Climate modeling of the technique to understand its potential usefulness and risks presents a big challenge for atmospheric scientists. The problem is that representing the interplay of clouds and aerosols, and their impact on global patterns, is "a huge challenge" for models, in fact "one of the largest sources of uncertainty" in Earth system modeling.[43] The cloud features in the models are crude versions of the real world, and field studies have shown that today's models do a mediocre job at predicting how local perturbations can affect cloud structure.

That said, such model studies have suggested that the technique could be used to mitigate regional warming patterns, which could be useful in the mitigation of specific impacts of climate change. Simulations also suggest that MCB could be effective at restoring the global climate in a world in which emissions of greenhouse gases continue to rise, though as with other varieties of solar geoengineering, the cooling is not uniform and the technique cannot restore both temperature and precipitation to preindustrial conditions.

"Models consistently indicate that MCB can reduce temperatures," wrote the National Research Council in its 2015 geoengineering report. "Model simulations show that MCB targeted at susceptible marine stratocumulus will cool preferentially the eastern North/South Pacific and eastern South Atlantic, and will also cool globally and reduce Arctic warming."[44]

Most model studies show that MCB reduces evaporation and precipitation over tropical oceans. On impacts on precipitation more broadly, models show a variety of results, but that range could be as a result of using different models. A 2013 study used three different state-of-the-art Earth system models to obtain more robust results about the effectiveness of MCB. The team used the same experimental design with each model to see how MCB would perform under a scenario of relatively moderate greenhouse gas emissions in the twenty-first century. The amount of MCB deployed in the experiment was meant to counteract the total greenhouse warming at a constant level beginning in 2020. As with previous modeling studies, the effort showed that MCB can cancel warming for the century. It also found, however, that each of the three models showed that the intervention would make tropical and mid-latitude continents cloudier, wetter, and less prone to drought.[45]

Given that MCB operates over maritime waters, scientists have explored how the technique would affect the oceans in two specific ways that are pertinent to a warming world: the melting of the Arctic and the global loss of reefs. A study published in 2012, using a climate model, suggests that in a future scenario in which CO_2 concentrations have risen to twice the preindustrial levels, MCB could roughly restore global temperatures and ice cover to levels predicted in 2020.[46] MCB may be particularly effective in targeting polar regions because it can reduce a feedback loop in which a warming Arctic leads to more water vapor, a greenhouse gas, and less reflective ice cover, which amplifies the warming still further.[47]

In 2013 a study used a climate model to see how MCB could be used to lower sea surface temperatures in three regions suffering from coral bleaching: the Caribbean, French Polynesia, and the Great Barrier Reef. In the simulation, the scientists more than quintupled the number of cloud droplets in low clouds, from 60 per square centimeter to 375 in the three regions to make them more reflective. In a scenario in which global CO_2 was doubled, the model showed that cloud brightening successfully lowered sea temperatures, almost entirely eliminating coral bleaching events, which generally happen when sea temperatures rise by more than 1 degree Celsius over a period of three months or more.[48]

Side effects of the technique include the fact that blocking sunlight from striking reefs could deprive photosynthetic organisms of the key energy they need; one paper estimated that the technique would reduce the annual mean sunlight striking the ocean beneath brightened clouds by 20 percent, though this effect has not been measured directly.[49]

Additionally, if the technique were to be used as a palliative as global greenhouse gas levels continued to rise, “as with any SRM geoengineering technique, the MCB process would have to be continued indefinitely. Cessation of MCB … could result in very rapid warming, which for coral reefs is the most common condition leading to coral bleaching."[50] (The authors do note that MCB, like all other methods of albedo modification, does nothing to stop ocean acidification, which along with pollution and fishing harms reefs and has many other adverse impacts on the marine environment.)

Using the MCB approach on a global scale would require an armada of boats. To counteract the global warming caused by current anthropogenic carbon emissions, researchers have calculated that 45,000 kilograms of seawater per second would be needed to be lofted into the sky in areas where marine clouds were found. This translates, roughly, into a fleet of 1,500 vehicles, each spraying 10^17 nuclei per second in the form of salt particles.[51]

To actually maintain this level of spraying would require having ships ready to move when nearby clouds are experiencing conditions making them conducive to being brightened. "The largest cooling effects could be achieved by staging several fleets around the world that are available for deployment on a daily basis and that can be scaled back to reduce energy and emission expenditures when suitable track-forming conditions are not available."[52]

In terms of hardware, conducting spraying at sea may be a technical challenge itself, though not impossible to achieve. A 2012 study looked at various spraying techniques and determined that long, thin capillaries made of silicon or short polymer capillaries could both work.[53]

2.1.4. *SRM in the Lower Atmosphere: Cirrus Cloud Seeding*

One proposed technique for solar radiation management that has received relatively little attention is seeding cirrus clouds. The goal is to dissipate these high-altitude clouds, which form in the troposphere above 6,000 meters and contribute to the greenhouse effect by trapping heat reflected up from the ground, warming the atmosphere. Most solar radiation management techniques seek to diminish the amount of the Sun's energy that strikes the Earth. By contrast, the goal of seeding cirrus clouds is to reduce the amount of heat that gets trapped in the atmosphere after infrared radiation is reflected up from the planet's surface.

Scientists have explored cirrus cloud seeding because it lacks some of the flaws that could plague aerosol injections, including damage to stratospheric ozone or alteration of the global hydrological cycle. The approach is based on the widely-used weather modification technique known as cloud seeding: spraying particles into clouds in an attempt to cause rain in one place or deter it in another. Despite little scientific proof that it works, farmers and land managers spend billions on the technique globally, and it is usually deployed to affect low clouds. But as a geoengineering tool this technique would focus on clouds that sit high in the troposphere.

A 2014 modeling study suggested that the technique could cool the planet by 1.4 degrees Celsius.[54] Furthermore, utilizing the technique at high latitudes could be more efficient than at middle latitudes or in the tropics. This is because in addition to trapping reflected heat via the greenhouse effect, cirrus clouds block a portion of the Sun's rays that strike the atmosphere in the first place. The latter effect, however, is more acute at lower latitudes when sunlight strikes the Earth more directly.

For this technique, scientists have proposed using aerosols that would serve as nuclei for ice crystals that would otherwise form normal cirrus clouds. These could include bismuth tri-iodide, a chemical related to the iodide-containing species that has been used for decades for low-altitude cloud seeding. The seeding particles could be released via tanks carried by high-altitude planes, a technique "safer and more viable than adding material to the fuel or exhaust of commercial aircraft, as has previously been suggested," asserted the authors of the 2014 study.[55] "Cirrus seeding appears to represent a powerful [SRM technique] with reduced side effects." Scientists have estimated that 140 tons of bistmuth tri-iodide, for example, could effectively counteract the current level of anthropomorphic greenhouse gas warming, and is easily deliverable by a small fleet of planes.[56]

2.1.5. *Albedo Modification at the Earth's Surface*

2.1.5.1. Crop Albedo Bioengineering

The mixture of plants growing on the Earth's surface can have a profound impact on the regional and global climate both in terms of their effect on the carbon cycle and their reflectivity. A 2007 study, for example, found that the deforestation in agricultural regions of the northern hemisphere have cooled those areas by 2 degrees Celsius since 1750 because of albedo: Croplands were more reflective than the forests they had replaced.[57]

A few studies have subsequently explored how deliberate selection and planting of more reflective plants could increase the planet's albedo and cool the climate. A 2009 study proposed "a 'bio-geoengineering' approach to mitigate surface warming, in which crop varieties having specific leaf glossiness and/or canopy morphological traits are specifically chosen to maximize solar reflectivity."[58] Some plant varieties offer a range of reflectivities, the authors report: Waxy types of barley are 16 percent more reflective than non-waxy varieties, and waxier varieties of sorghum, a tall grain, are 19 percent more reflective than less waxy types. In several cases, the genes that are expressed in relevant cultivars have been identified in previous studies.[59] A subsequent modeling study looked at several factors that crop geneticists successfully select for – leaf area, vertical profile, and reflectivity – and found that the scientists could increase the albedo of the crop by 34 percent without a change in water use.[60]

A computer model used in the 2009 study suggested that raising global crop albedos from .20 to .28 would lower global surface air temperatures by roughly 0.2 degrees C.[61] That is a relatively inefficient cooling scheme compared to other geoengineering techniques, but the experiment suggested strong regional effects: Converting plants to more reflective varieties could cool summer regional surface temperatures in mid-latitude North America and Eurasia by 1 degree Celsius.[62] Cooling also extended into the Barents Sea and North Atlantic, the modeling showed. "An unexpected benefit of cropland albedo change could thus be a small delay in Arctic sea-ice retreat."[63] But a 2015 study that compared the technique to other albedo modification techniques found a minimal global impact. "This scheme could at best be used to reduce warming locally and deliver local scale benefits to soil moisture and primary productivity," the authors wrote.[64]

Compared with other albedo modification schemes, bioengineering plants to make them more reflective could offer certain logistic advantages. While injecting particles into the stratosphere or launching sunshades into orbit would require new infrastructure, "the infrastructure required to create and propagate specific physiological leaf and canopy traits to large-scale cultivation is already in place. In addition, because arable crops are primarily grown for food, the annual replanting of modified varieties that is needed in order to retain continued climatic benefits is automatically achieved."[65]

2.1.5.2. Other Surface Albedo Modification Technologies

According to one overview of geoengineering methods:

> [a]chieving substantial global-mean temperature reductions through altering land-surface albedo represents a daunting challenge … Because land represents somewhat less than one-third of the planetary surface and approximately half of the land surface is cloud covered, ~10 percent of radiation incident on the global land surface would need to be reflected to offset the radiative forcing from a doubling of atmospheric CO_2 content.[66]

A group of Californian academics and private engineers calling themselves ICE911 have proposed adding materials to Arctic ice and snow in order to increase the albedo of those materials.[67] Another proposal is to create artificial whitewater – known as microbubbles – to enhance the albedo of those materials.[68]

In 2015 a study used a climate model to see the regional and global effects of raising surface albedo in the Arctic, concluding that "although ocean albedo alteration could lead to some sea ice recovery, it does not appear to be an effective way of offsetting the overall effects of CO_2 induced global warming."[69]

2.1.6. *Comparative Efficacy and Costs of Various Albedo Modification Technologies*

Another study used a single model to analyze the effect of various albedo modification schemes on temperature, precipitation, and other factors. It found that stratospheric SO_2 injection, marine cloud brightening, seeding cirrus clouds, and brightening the ocean surface all are "potentially able to return surface air temperature to 1986–2005 climatology under future greenhouse gas warming," though cirrus cloud thinning may not be able to cool the planet more than 1 degree Celsius.[70]

The study found each method has drastic impacts on the hydrological cycle. "Widespread regional scale changes in precipitation over land are significantly different from the 1986–2005 climatology and would likely necessitate significant adaptation despite geoengineering." The study's findings on land albedo modification suggested that the technique would cause "severe shifts in tropical precipitation." Other than the cirrus approach, it said, among the other schemes, "none has significantly less severe precipitation side effects than other schemes."[71]

In its review of albedo modification technologies, the National Research Council focused on SAAM and marine cloud brightening, the two most studied approaches. In summarizing its findings, the authors stressed the importance of further scientific and technical research on both methods. It may be possible to change the Earth's energy balance significantly:

> via either of these technologies without the need for major technological innovations. However, albedo modification strategies may introduce major and rapid perturbations to the planet with secondary and tertiary effects on environmental, social, political, and economic systems that are very difficult to predict currently and with effects that could be severely negative. Without further information on these risks, the low initiation costs of albedo modification cannot be balanced against other potential costs and risks of not deploying albedo modification methods.[72]

2.2. CARBON DIOXIDE REMOVAL (CDR)

Annual emissions of CO_2 globally are about 30 billion metric tons, and some 600 billion tons of anthropogenic CO_2 have accumulated in the atmosphere since the preindustrial era.[73] As discussed in Chapter 1, it will be essential to remove a great deal of CO_2 from the atmosphere, even if global emissions peak and begin to decline, in order to meet the temperature goals of the Paris Agreement.

In contrast to albedo modification strategies, which involve myriad moral, geopolitical, and economic challenges, CDR methods are mostly uncontroversial. According to the National Research Council, CDR strategies:

> are generally of lower risk and of almost certain benefit given what is currently known of likely global emissions trajectories and the climate change future. Currently, cost and lack of technical maturity are factors limiting the deployment of carbon dioxide removal strategies for helping to reduce atmospheric CO_2 levels. In the future, such strategies could, however, contribute as part of a portfolio of responses for mitigating climate warming and ocean acidification.[74]

This technique may require long timescales to be useful. A 2013 study estimated that "large scale application of [CDR] approaches could remove up to ~150ppm of CO_2 from the atmosphere," but that the methods "have only marginal potential to affect atmospheric CO_2 this century."[75] A 2015 modeling study found that to maintain global warming below 2 degrees Celsius above preindustrial values, negative emissions between 0.5 gigatons of CO_2 per year and 11 gigatons per year would be needed between now and 2100, depending on how optimistic one is about future energy and emissions trends.[76] The authors concluded that because technologies that could produce such negative emissions "have not been shown to be feasible … development of negative emission technologies should be accelerated, but also that conventional mitigation must remain a substantial part of any climate policy aiming at the 2 degree C target."[77]

Scientists routinely emphasize that such approaches should not be viewed as an alternative to cutting carbon pollution. "There is no substitute for dramatic reductions in the emissions of CO_2 and other greenhouse gases to mitigate the negative consequences of climate change, and concurrently to reduce ocean acidification," the National Research Council (NRC) wrote in its assessment of CDR technologies.[78]

CDR has come into focus in recent years as countries have concentrated on limiting global warming to 2 degrees Celsius or less by 2100, roughly equivalent to CO_2 concentration in the atmosphere of 450ppm. To accomplish that goal, models evaluated by the Intergovernmental Panel on Climate Change in 2014 show that negative emissions would play a central role to reach major goals of limiting emissions and climate change. The panel said in its summary for policymakers that most scenarios that achieve the 2-degree Celsius target "rely on the availability and wide-spread deployment of" carbon-negative technologies in the second half of the century.[79] The two technologies that the panel highlighted in this regard were bioenergy with carbon capture and storage and afforestation.

2.2.1. *Direct Air Capture and Storage*

Relying heavily on CDR as part of a climate response strategy to remove CO_2 emissions from the sky could mean creating a massive industry – perhaps the biggest engineering project in human history – to steadily remove this mass of gas from the atmosphere one molecule at a time.

Direct air capture is the technique of scrubbing CO_2 directly from the sky through large facilities. The technique can be used to obtain carbon for making a byproduct or fuel. Direct air capture and storage (DACS) means storing that CO_2 in a long-term reservoir. Multiple studies have concluded that this approach "could theoretically remove total annual global anthropogenic CO_2 emissions."[80]

The technology to remove CO_2 from the atmosphere economically is in its early stages of development. "Direct air capture of CO_2 is probably decades away from commercialization, even though its fundamental chemistry and processes are well understood."[81] A study by the American Physical Society (APS) in 2011 concluded that collecting CO_2 directly from the atmosphere "is not currently" economically viable despite "optimistic" technical assumptions.[82] It estimated that the basic cost of a system that could be built today would be about $600/ton, an order of magnitude more than the estimate for low carbon energy sources, though, as set forth below, experts in the field have challenged that number.

The two main approaches involve either (1) liquids or surfaces that chemically interact with CO_2, or (2) membranes that physically trap the CO_2 gas on solid surfaces. A handful of startup companies are trying to commercialize DACS. They are performing carbon capture from air in an open cycle in which CO_2 collected from the sky is used to make products. Some of these products will eventually release their carbon back into the atmosphere, like fuels.

The largest commercial demand in the US for CO_2 is for enhanced oil recovery, which uses the gas to push oil or gas from partly depleted reservoirs.

There is an ongoing debate whether this really advances the cause of addressing the climate problem. Some argue that it merely releases more fossil fuels, whose use negates the benefit of capturing CO_2; others argue that fossil fuels will be extracted somewhere in order to satisfy the demand for them, and therefore enhanced oil recovery just moves the location of the extraction while storing CO_2.[83]

As is apparent from the sales materials of companies that produce and sell gases to industry,[84] there are several current uses of CO_2, including beverage carbonation; flour and dough cooling; freezing and chilling; greenhouse growing; meat mixing; respiratory therapy; controlling pH in water and wastewater treatment plants; welding and metal fabrication; and various uses in the pulp and paper industry. However, the current demand for CO_2 is not nearly enough to utilize the quantity that would be captured if CO_2 removal were conducted on a massive scale. Several efforts are underway to develop new uses for CO_2 to help make chemicals, construction materials, plastics, and other products. This would be done through a variety of electrochemical, petrochemical, biochemical, and thermochemical processes. Almost all of these require the use of large quantities of energy; the plummeting cost of renewable energy (especially solar power) means that it may be possible to conduct these processes without creating large new CO_2 emission sources. One nonprofit organization has formed with the objective of finding ways to capture 10 per cent of annual global CO_2 emissions and transform them into valuable products.[85] If these efforts are successful, they could create carbon-negative processes that would result in a reduction of CO_2 in the atmosphere.

2.2.1.1. Methods of DACS

The basic technologies required to do DACS with chemicals build off commercial absorption techniques that work in submarines and space shuttles to clean air of CO_2 gas. In its 2009 report on geoengineering, the UK Royal Society said that, given the commercial operation of these techniques, there is no "obvious limit" to the amount of CO_2 that could be collected from the atmosphere using chemical means.[86]

The first commercial-scale direct air carbon capture plant, by Swiss firm Climeworks, near Zurich, began operations in May 2017. It uses excess heat from a solid waste incineration plant to produce a concentrated stream of CO_2 for greenhouses nearby that are growing food. The company is also partnering with Danish Union Engineering to produce carbonated beverages, but the eventual goal includes producing fuel with carbon taken from the air, and eventually creating carbon-negative technologies. Advocates of carbon-negative approaches say this is important news. "The fact they're getting to commercial-scale prototypes is incredibly encouraging," Noah Deich, executive director of the Center for Carbon Removal in Berkeley, California told *Nature* magazine.[87]

In late 2015 Climate Engineering in Squamish, British Columbia partially opened a pilot demonstration plant that captures one metric ton of CO_2 per day. Right now it is releasing that gas into the atmosphere, but there are plans to install a small fuel synthesis plant to combine that CO_2 with hydrogen to make synthetic gasoline; the facility has plans to provide fuel for buses. The plant works by reacting air with a strongly basic solution, creating a chemical called potassium carbonate. Through a regeneration step that occurs at 900 degrees Celsius, the chemical is stripped of its carbon to create pure CO_2, and the basic solution is regenerated. Natural gas is burned to produce the heat for the reaction, but the CO_2 produced from that combustion is collected and processed, so the process produces no new carbon emissions.

Global Thermostat is a company that is using plastic surfaces coated with chemicals called amines to bond with CO_2 from the air. The firm has won investment from major energy firms, including energy giant NRG for its CO_2-scrubbing process, which occurs at under 100 degrees Celsius. Its 40-foot-high test facility is in Menlo Park, California.[88]

While carbon-scrubbing technologies are finding initial promise in niche markets, the cost of scaling up such technologies to affect the global concentration of CO_2 in the sky will be high. The precise amount of that cost is a matter of much contention among experts. The APS's $600/ton estimate is roughly six times the estimate of the cost to capture and store a ton of CO_2 from a power plant, which itself is much higher than the price of CO_2 in any of the world's carbon markets. The figure was based on an optimized case study in which the cost of capturing the CO_2 with a reagent and regenerating that reagent were both considered. A well-regarded critique of that report in 2012 estimated the cost of just the capture phase at $60/ton.[89] The two estimates used different assumptions about a number of factors, making it "difficult to directly compare these estimates."[90]

A number of approaches to DACS using membranes have been proposed, including materials called zeolites which have micropores that have been used to trap gases in industrial applications. The technology remains promising but has yet to exit the laboratory stage.

Driving the early development of direct air capture is demand for CO_2 for enhanced oil recovery and carbon-based fuels, sometimes aided by government policies promoting fuels with a low carbon footprint. In order to significantly reduce the amount of CO_2 that has built up in the atmosphere would require that air capture be scaled up into a massive global project. To reduce the atmospheric concentration of CO_2 by 50ppm, for example, requires sequestering 400 billion tons of CO_2,[91] presumably underground in saline aquifers and other formations. The authors of a recent study on carbon capture and storage concluded that an "effective" global geological storage capacity exists for 13,500 billion tons of CO_2, and a "practical" capacity of 3,900 billion tons of CO_2.[92]

2.2.2. *Bioenergy with carbon capture and storage*

Policymakers have focused on bioenergy with carbon capture and storage (BECCS) as one of the most important potential technologies for creating negative emissions. As biomass in plants grows, it removes carbon from the atmosphere via photosynthesis; BECCS works by burning or processing that carbonaceous material to create energy or chemicals, including fuels, and then storing the CO_2 that is formed in that process in a long-term storage facility such as an underground reservoir. The storage step is similar to the approach in a carbon capture and storage facility connected to a fossil fuel plant.

According to the IPCC in its 2014 assessment, "[t]here is uncertainty about the potential for large-scale deployment of BECCS."[93] Other scientists wrote "credibility as a climate change mitigation option is unproven and its widespread deployment in climate stabilization scenarios might become a dangerous distraction."[94]

First, there are questions about obtaining sufficient biomass. A major review of the potential of the technology for CDR found that the technique could likely be scaled to produce 100 exojoules of energy a year,[95] about half the current energy produced by the fossil fuel industry.[96] In its 2015 report, the NRC estimates that up to 500 million hectares of dedicated cropland would be needed for that scale – a whopping 10 percent of existing crop and grazing land worldwide. One study estimated that sequestering 1 gigaton of CO_2 from the atmosphere with this technique would require more than 52 million hectares of land for feedstock plants.[97] Probably the only way to free up sufficient land for BECCS to have a global impact would be to shift human diets away from meat, since direct food crops require less land per calorie provided. Otherwise, using massive new tracts of land to produce biomass for energy could create new competition with farms that produce feed for animals.

The 2015 NRC report argues that there is no reason to deploy carbon capture and storage with bioenergy until fossil fuel use has been reduced significantly. "Prior to that point, there is no difference in net carbon emissions to the atmosphere whether the CCS is tied to bioenergy or fossil fuel use."[98]

Converting forests to cropland to make BECCS fuel stocks creates a short-term spike in greenhouse emissions, as a result of the trees removed; to recover that lost carbon and get into "the red" may require "decades or more."[99] Depending on the current use of land that is converted to biomass production, biomass production at massive scale would likely also divert water supplies, increase use of fertilizer, alter wild ecosystems, and affect global food markets.

BECCS capture technology builds on existing technologies currently deployed at a few coal and gas facilities nationwide to capture carbon emissions. A handful of industrial plants planning to demonstrate the technique at full scale have yet to come online, including facilities in Decatur, Illinois and North Yorkshire, England.

Burning biofuels, like burning coal, creates a concentrated stream of CO_2, making its cost to capture and store the gas lower than that of DACS, which uses a diffuse stream. Available technologies include using biomass for combined heat and power. This process involves gasifying biomass fuel stocks to produce power and fuel simultaneously. Estimates range from $60 to $250 per ton of CO_2 sequestered, along the lines of carbon capture and storage from fossil fuel plants.[100]

2.2.3. *Storage or Utilization of CO_2*

As with carbon capture and storage from power plants, DACS and BECCS both rely on large-scale storage facilities or utilization to provide a final destination for the carbon they seek to sequester. Among technologies related to CDR, geologic storage has been a major focus of the scientific community. The US National Energy Technology Laboratory believes "the capacity for sequestering CO_2 in deep underground saline formations is vast enough to store essentially all CO_2 emissions from coal-fired power plants within the United States."[101] Formations of similar size exist on other continents, and scientists have proposed storing CO_2 in other environments, including in the deep ocean.[102] For decades the oil industry has stored CO_2 underground as part of efforts to obtain oil from old fields, so the technology for injection is mature. An unknown issue is the readiness of the technology to scale this storage up to a far larger size.

A study published in 2016 reported a successful effort in Iceland to inject CO_2 into a basalt formation, where it quickly mineralized into a harmless solid.[103] Basalt is the most common igneous rock in the world. If this technique is replicated in other types of locations, including possibly under the ocean, and if it could be employed economically, it could provide a satisfactory way to store massive quantities of CO_2.

Injection of gas into underground formations raises public concerns. Fracking to obtain natural gas has been shown capable of causing small- to medium-sized earthquakes and has led to allegations of water contamination, fueling public opposition to the practice and intense study of the phenomenon.[104] Large-scale storage of CO_2 underground could face similar political hurdles (there is a complex nexus between fracking and CO_2 storage; one factor is that shale sites viable for CO_2 storage could also be targeted for fracking projects, which would involve fracturing the caprock needed to secure the CO_2 long term). As discussed above, utilizing the CO_2 would be better than storing it, if it becomes embedded in products that have a long life.

2.2.4. *Ocean Fertilization*

Ocean fertilization seeks to take advantage of the ocean's natural carbon pump, which uses CO_2 at the sea surface and incorporates the carbon, via photosynthesis, into biological tissues which can fall or be transported to the deep ocean. Over long time scales, models show, the process described below can change atmospheric levels of CO_2 by more than 100ppm.[105]

Certain areas of the ocean, including the Southern Ocean, have plentiful nutrients but lack iron, a key trace micronutrient that sea plants known as phytoplankton need to grow. So fertilization with iron has been proposed as a means of accelerating the carbon pump and increasing the size of the ocean carbon sink. (Other fertilization techniques that have received less attention involve the addition of nutrients like nitrogen, in the form of urea, or phosphate.)

Small-scale experiments designed to study how phytoplankton blooms grow and die have been executed by marine biologists since 1993. As part of the 2004 European Iron Fertilization Experiment, German oceanographers and colleagues released some 13 metric tons of iron sulfate fertilizer into a rotating eddy in the Southern Ocean, catalyzing the creation of an algae bloom. In 2012 they reported in *Nature* that at least half the biomass of the bloom sank "below a depth of 1,000 metres and that a substantial portion is likely to have reached the sea floor. Thus, they argued, iron-fertilized diatom blooms may sequester carbon for timescales of centuries in ocean bottom water and for longer in the sediments."[106] Some colleagues agreed that the experiment had successfully sequestered carbon. Writing in an accompanying piece in *Nature*, geochemist Ken Buesseler said that the experiment shows "how the addition of iron to the ocean not only enhances ocean productivity, but also sequesters carbon" and that its success means that "larger and longer [ocean iron fertilization] experiments should be performed to help us to decide which, if any, of the many geoengineering options at hand should be deployed."[107]

Others have questioned Smetacek's conclusions regarding the fate of the bloom. In 2014 a study conducted a simulation of geoengineered carbon particles at depth. It found that two-thirds of the carbon sunk during the fertilization exercise was re-exposed to the atmosphere, taking an average of 38 years in their simulation.[108]

Commercial interests have looked into the approach as a means of CDR. In the summer of 2012 the Haida Salmon Restoration Corporation conducted privately funded commercial iron fertilization with the goal of increasing salmon returns.[109] The project, which involved the addition of more than 100 tons of iron into the Gulf of Alaska, drew criticisms from scientists and policymakers because it appeared to contravene an international treaty on dumping and another on biodiversity, as described in Chapter 6. Due to the bloom's small size and duration, the amount of annual carbon drawdown by the operation was roughly one-tenth the size of natural carbon fertilization events, including one catalyzed by iron-laden dust spewed by a volcano in the same area of the North Pacific in 2008.[110]

One technique of enhancing ocean uptake of atmospheric carbon is to use pipes that stimulate upwelling via the motion of waves. Theoretically, the tubes could pull nutrient-rich waters from the deep to the surface, where they could feed algae blooms, enhancing carbon uptake. But several studies have raised concerns that the technique would create waters with enhanced CO_2 levels in them "that would effectively cancel most, if not all, of the benefit of biological carbon drawdown."[111]

Ocean fertilization has also been informally proposed by commercial firms as a means of mitigating acidification.[112] But a climate modeling exercise in 2010 showed this approach is probably counterproductive in this regard. It explored a scenario in which greenhouse gas emissions continue to grow and the average global surface pH level had dropped by .44 units relative to preindustrial levels by 2100. An aggressive iron fertilization effort could only reduce total ocean pH change by .06 units, and this marginal improvement comes at the cost of acidifying the deep ocean, where organisms are highly sensitive to small changes in pH.[113]

2.2.5. *Biochar*

Biochar is a material created when organic material like agricultural waste is burned in the absence of oxygen. That process, called pyrolysis, creates a carbon-rich product that is stable or "biologically recalcitrant." Some call biochar "green charcoal" because it is produced in the same way as the popular fuel, and contains essentially the same ingredients. But biochar is used not for combustion, but as a soil additive. Its role as a means of CDR is that, by transforming biomass into charcoal, the carbon in the plant material is locked up instead of being released into the atmosphere when the biomass is burned or biodegraded in soil (biochar has also been used on a small scale for wastewater remediation).

If biochar production and use were to be scaled globally, some scientists believe the technique has a large potential to mitigate global greenhouse gas emissions. By allowing farmers to use less fertilizer, the technique reduces emissions from the production of those chemicals. Biochar also alters the way microorganisms process nitrogen, possibly reducing emissions of N_2O from the soil. Writing in *Nature Communications* in 2010, researchers estimated that this technique could draw down atmospheric greenhouse gases while reducing emissions of CO_2, methane, and nitrous oxide – greenhouse gases produced by agriculture – with a net reduction of 1.8 gigatons of CO_2-equivalent per year.[114]

But that depends on how the biochar was obtained; researchers warn that obtaining biochar at mass scale from forested land cleared to produce feedstock would be "disastrous" for global carbon emissions, for example. Harvesting lands improperly would also cause soil erosion and biodiversity loss, while also reducing the total carbon sequestered in the technique.[115]

A 2015 meta-analysis looked at 24 studies that estimated CO_2 emissions from biochar in soil. The scientists found that "biochar can persist in soils on a centennial scale," during which time 97 percent of its carbon is sequestered; during that time, additionally, the substance stimulates microbial activity, a boon to agriculture in poor soils.[116] Other studies have pointed to other advantages for agriculture, including slowing carbon return to the atmosphere during photosynthesis, improving soil productivity in degraded soils, the retention of nutrients, water and agricultural chemicals by runoff, and the use of biomass waste as a feedstock.[117] The authors of the 2010 *Nature Communications* paper wrote that, in terms of its side benefits, compared to "the possible strategies to remove CO_2 from the atmosphere, biochar is notable, if not unique, in this regard."[118]

But the technology is in its early stages of development. Globally, the biochar market is focused on niche applications for farmers, and was valued at $4.27 million in 2015, a minuscule size relative to global agriculture and carbon emissions.[119] As such, in a 2011 technology assessment of the method as a tool for global CDR, the US Government Accountability Office rated the maturity of biochar, on a scale of 1 to 9, at 2, citing "uncertainties in experimental data demonstrating the efficacy of biochar as a carbon sink."[120]

2.2.6. *Enhanced Weathering*

CO_2 emitted into the atmosphere reacts with water to form first carbonic acid, in the sky, and then, via a process of reaction with rocks, known as weathering, bicarbonate ions. (This generally occurs because the carbonic acid is weakly acidic, while the rocks are weakly basic.) Over a long time scale, via flow to the ocean and other chemical reactions, these ions form carbonate sediments on the floor of the ocean. One carbon dioxide removal technique is to accelerate this process to store massive quantities of carbon as either dissolved bicarbonate at sea or carbonate compounds on land, enhancing a natural carbon sink. "Enhanced weathering employs naturally occurring minerals and reactions, and therefore falls in the category of 'soft geoengineering' along with reforestation and agricultural techniques increasing soil carbon storage."[121]

Some proposed strategies would operate on land, others in the ocean. On land, engineers could distribute ground-up silicate rocks across terrestrial landscapes, where it would react with rainwater via the weathering process to lock up CO_2. A modeling of this method in 2015 found that an application of 1 kilogram of the pulverized rock on every square meter in an area comprising roughly one-third of the Earth's tropics could lower atmospheric CO_2 by 30ppm by 2100. Adding 5 kilograms of silicates on every square meter of the same area, paired with aggressive mitigation of carbon emissions by the end of the century, would cut atmospheric CO_2 by 300ppm and reverse ocean acidification.[122] (This is a separate technique from the idea of adding alkaline powder, like olivine minerals, to seawater to directly buffer the acidifying ocean, though the concept is similar.) Potential impacts include disruption of land from where the rocks would be taken and alteration of soil, stream, river, and ocean chemistry, with subsequent effects on plants and aquatic and marine ecosystems.

Ocean-based methods involve deriving alkaline materials from silicate rocks and dissolving them in the ocean, which would cause the sea to take in more CO_2. One source of that alkalinity could be lime, produced by the heating of limestone. Another is to grind up carbonate rocks and react them with CO_2 produced in a concentrated stream from a power plant.[123] Side effects could include alterations of ocean chemistry and a reduction of ocean acidification.

The cost of either category of weathering geoengineering is considerable because of the scale and complexity of the operation, which would require mining the minerals, processing them, grinding them up, and then transporting them to sites for distribution. In an analysis of several studies, the National Research Council concluded that weathering approaches could remove 1 gigaton of CO_2 per year between now and 2100, at a cost of between $50

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and \$100 per ton of CO_2. The Council suggested that the approach deserves further study, including kinetic studies to see how to more efficiently dissolve carbonates and silicates, and research into mineral extraction and seawater pumping. Thus far, only laboratory-scale experiments focused on the ocean-based approach have been done.[124]

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