Chapter 8: Geoengineering

1. Counteracting Climate Change

Geoengineering, or climate intervention, is a large-scale technological effort to change the Earth's climate. It differs fundamentally from **climate change mitigation**, because instead of aiming to slow warming by decreasing carbon emissions, it involves either removing carbon dioxide from the atmosphere or decreasing heat received from the sun. Such methods could be used to supplement climate change mitigation, or used even while carbon emission rates continue increasing. Many scientists and policymakers are wary of geoengineering for this reason, because they are concerned that climate intervention will be seen as a magic bullet or easy solution that allows us to go on with business as usual, releasing more and more carbon. Geoengineering would be anything but easy, however, and could have tremendous financial and environmental cost. Intervening with Earth's climate systems also has great uncertainty at our current level of understanding, and could have harmful unintended consequences. In a report on geoengineering from The Royal Society in the U.K., the world's oldest scientific association, the authors discuss the nature of this uncertainty:

See Chapter 7: Climate Change Mitigation for more information about efforts to reduce carbon emissions.

geoengineering • *a large-scale technological effort to change the Earth's climate, typically either by removing carbon dioxide from the atmosphere or by blocking incoming solar radiation.*

climate change mitigation • *actions taken to limit or eliminate emissions of greenhouse gases in order to reduce future climate warming.*

> When analysing potential problems associated with geoengineering in relation to long-term climate change, the language of 'risk' is often used, implying some knowledge about both potential outcomes of geoengineering technologies and their probabilities. But so embryonic are geoengineering technologies that there is commonly little knowledge yet about the nature of (potentially unwanted) outcomes and still less knowledge of probabilities. This is a situation of 'indeterminacy' (or 'ignorance') rather than risk.[1]

Given the concerns about geoengineering, why consider it at all? Some scientists view climate intervention as an undesirable but important method of last resort that deserves study. Others think that geoengineering methods that remove carbon dioxide (CO_2) from the atmosphere could contribute to emissions reduction efforts, and some methods may even cost less than certain types of mitigation. Other interventions which effectively block sunlight from reaching the Earth could theoretically begin to cool the climate within a few years of deployment, so they could be emergency options. If the climate

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[1] The Royal Society's report, Geoengineering the climate: science, governance and uncertainty. London, UK (2009), is an extensive review of geoengineering methods.

[2] These studies include the Royal Society report mentioned in (1) and two reports from the US National Research Council: Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration (2015), and Climate Intervention: Reflecting Sunlight to Cool Earth (2015), The National Acadamies Press, Washington, D.C.

greenhouse gas • *a gas that absorbs and re-radiates energy in the form of heat; carbon dioxide, water vapor, and methane are examples.*

ocean acidification • *the increasing acidity, or lowered pH, of ocean waters, caused by absorption of atmospheric carbon dioxide.*

approached a tipping point—a threshold beyond which the Earth would enter a vastly different climate state—then emergency measures would likely garner more serious attention. Major studies of geoengineering[2] conclude that while research into climate intervention is prudent in order to be prepared for the worst, it is most important that we focus on reducing carbon emissions quickly.

1.1 Types of Climate Intervention

Geoengineering methods fall under two classes: 1) Carbon dioxide removal (CDR), which removes CO_2 from the atmosphere, and 2) solar radiation management (SRM), which reflects sunlight back into space. The advantage of carbon dioxide removal is that, together with conventional emissions reduction, it could potentially reduce atmospheric CO_2 down to lower, even pre-industrial, levels. Carbon removal may be necessary even if we stopped emitting all **greenhouse gases** today, because of the cumulative effects of the greenhouse gases we've already emitted. CDR also addresses the critical problem of **ocean acidification**, which results from atmospheric CO_2 dissolving in sea water and which could have catastrophic effects on ocean ecosystems. Disadvantages of CDR are that to be effective it may need to take place on vast spatial scales, and it would take decades after implementation to see the effects.

An advantage of the second class of methods, solar radiation management, is that it could work relatively quickly after deployment—within a few years. Disadvantages of SRM are that it does nothing to address the underlying problem of increasing CO_2 in the atmosphere, so ocean acidification would only get worse without serious mitigation efforts. It would also require maintaining a tricky balance between incoming sunlight and atmospheric CO_2, and if systems failed or were turned off the climate could quickly revert to a much warmer state because of all the remaining CO_2 in the atmosphere.

Both CDR and SRM would be expensive to different degrees, could require large amounts of energy to run and maintain, and would likely harm the environment in various ways. Both would require international cooperation and run the risk of unknown consequences if a single country or even a wealthy individual or business decided to act on their own. The following sections are not a comprehensive overview of all types of geoengineering proposals, but they discuss examples of several geoengineering methods most commonly promoted and concerns about their implementation.

2. Examples of Carbon Dioxide Removal (CDR) techniques

2.1 Enhanced Chemical Weathering

Nature already has several ways of removing carbon from the atmosphere, including chemical weathering of rocks (*Figure 8.1*). For example, a chemical reaction describing weathering of albite (a variety of the most common kind of silicate mineral in the crust, plagioclase feldspar) is as follows:

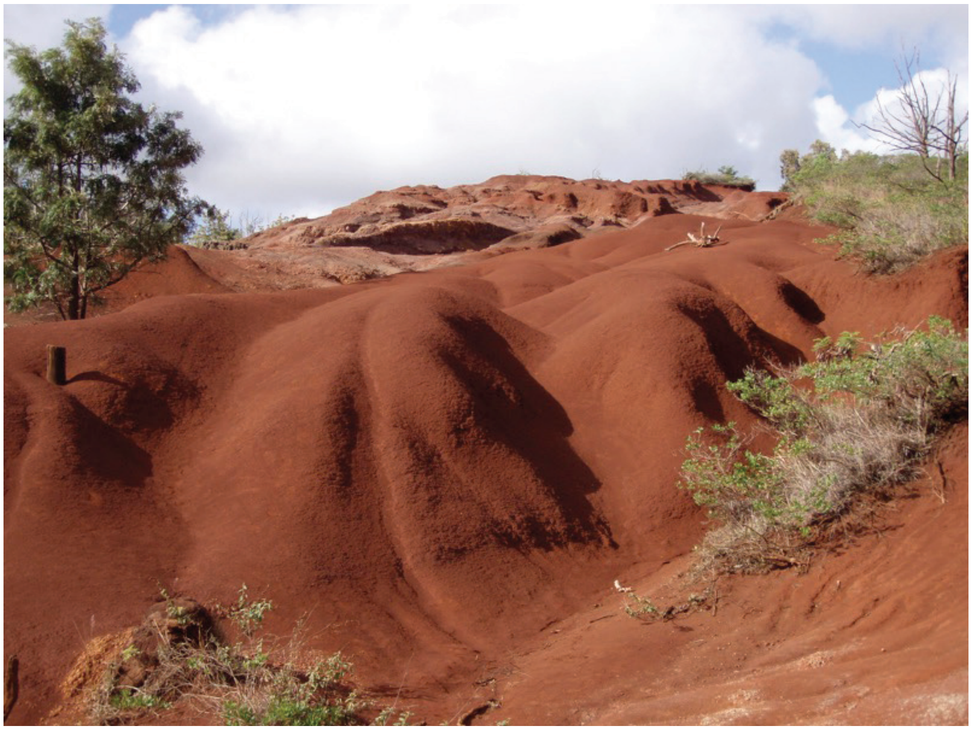

Figure 8.1: Hawaii's famous red dirt: chemically weathered rock (basalt) on the island of Kauai, HI.

$$2NaAlSi_3O_8 + 2CO_2 + 11H_20 \text{ -> } Al_2Si_2O_5(OH)_4 + 2Na^+ + 2HCO_3^- + 4SiO_2 + H_20$$
silicate minerals + carbon dioxide + water → clay minerals + cations + bicarbonate + silica + water

In this example, the weathering of plagioclase feldspar results in sodium, bicarbonate ions, and silica ions in solution, and the clay known as kaolinite. These products are eventually washed to the ocean or become part of the soil. For each molecule of albite, a CO_2 molecule is used up from the atmosphere. Natural weathering processes such as these take a long time to remove carbon from the atmosphere, on the order of tens to hundreds of thousands of years. This is much slower than the rate at which **fossil fuel** burning is adding carbon dioxide to the atmosphere.

fossil fuel *• a non-renewable, carbon-based fuel source like OIL, NATURAL GAS, or COAL, developed from the preserved organic remains of fossil organisms.*

Geoengineering techniques aim to enhance or accelerate the rate of natural chemical weathering by exposing more rock to weathering. One way to do this is to mix a silicate mineral such as olivine into soil, exposing it to weathering. While the approach seems simple, it could be expensive and energy-intensive, and it would need to operate on a scale similar to the energy systems which are currently responsible for CO_2 emissions:

> Large quantities of rocks would have to be mined and ground up, transported, and then spread over fields. It is estimated that a volume of about 7 km^3 per year (approximately twice the current rate of coal mining) of such ground silicate minerals, reacting each year with CO_2, would remove as much CO_2 as we are currently emitting.[3]

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[3] The Royal Society, Geoengineering the climate: science, governance and uncertainty. London, UK (2009).

Enhanced chemical weathering could also take place by replicating natural weathering processes in a factory setting, for example, capturing CO$_2$ from a fossil fuel-burning power plant and reacting it with ground up silicate rock. Another approach would be to heat limestone (the carbonate rock made of CaCO$_3$) to the point where the limestone releases CO$_2$, capture this CO$_2$, and react it to form lime (Ca(OH)$_2$). In both approaches, the product of the reaction would be added to the ocean. Adding lime to the ocean would increase its alkalinity, which in turn would promote absorption of CO$_2$ from the atmosphere.[4] A third approach is to grind and deposit powdered calcium carbonate directly into the ocean, reducing the acidity of the ocean and enhancing CO$_2$ absorption from the atmosphere. This would be a very slow process: by adding 4 billion tons of calcium carbonate to the ocean per year it would take 200 years to reach a rate of atmospheric CO$_2$ absorption of about 1 Gt per year.[5] To put this in perspective, our fossil fuel burning worldwide released around 32 Gt of CO$_2$ into the atmosphere in 2014.

What are the environmental costs of enhanced chemical weathering? Land degradation and pollution from large-scale mineral mining and transportation projects are concerns. Enhanced weathering in an industrial setting would require energy, which would lead to further release of CO$_2$ if it came from fossil fuel sources. Finally (and critically), the chemical, biological, and ecological consequences of releasing minerals into the ocean or changing the ocean's alkalinity are not well understood.

Box 8.1: Exercise to examine the mass scales involved in one type of enhanced chemical weathering[6]

Assume that 32 Gt of CO$_2$ are released into the atmosphere in a year from fossil fuel burning. If all of this CO$_2$ is to be reacted to form calcium carbonate (CaCO$_3$) that would be stored in the ocean, how much calcium carbonate would result? The reaction under consideration is:

$$CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2.$$

Using the molar masses of CO$_2$ (44 g/mole) and CaCO$_3$ (100 g/mole), one finds that the ratio of mass of CaCO$_3$ to CO$_2$ is approximately 2.3. Using up 32 Gt of CO$_2$ in one year through storage in CaCO$_3$ would result in 2.3 × 32 Gt = 74 Gt of calcium carbonate. For comparison of mass, this is about ten times the mass of coal mined worldwide in 2014,[7] and would require tremendous resources to process and transport.

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[4] Carbonate chemistry can be counterintuitive: the formation of CaCO$_3$ releases CO$_2$ and its dissolution removes CO$_2$ ($Ca_2^+ + 2HCO_3^- <-> CaCO_3 + CO_2 + H_2O$). Shifts in alkalinity and pH change the relative ratios of the ions that make up the aqueous carbonate system (CO_2^g, H_2CO_3, HCO_3^-, CO_3^{2-}), which changes the partial pressure of CO_2^g in the water, and whether the ocean takes up or releases CO2 into the atmosphere.

[5] More detail on this can be found in: Harvey, L. 2008. Mitigating the atmospheric CO$_2$ increase and ocean acidification by adding limestone powder to upwelling regions. Journal of Geophysical Research Oceans, 113, C04028.

[6] This exercise was derived from a similar calculation in US National Research Council, Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration (2015), The National Acadamies Press, Washington, D.C.

[7] Data on coal mining come from a webpage of the World Coal Association: https://www.worldcoal.org/coal/coal-mining, retrieved 3/17/2016.

2.2 Ocean Fertilization

Another of Nature's ways of removing CO_2 from the atmosphere is through **photosynthesis** by **phytoplankton** at the surface of the ocean (*Figure 8.2*). These organisms eventually die or are eaten by other organisms that die or release fecal material, and these wastes and dead organisms sink to the bottom of the ocean. Bacteria in the deep ocean consume most of this organic matter and re-release CO_2 through respiration. As the ocean circulates this carbon is eventually brought back to the surface and released, but the ocean's waters turn over slowly, on time scales from decades to millenia. A small percentage of the organic matter becomes buried in sediments, potentially storing carbon for up to millions of years. The process from surface photosynthesis to deep ocean respiration, often referred to as a "biological pump," effectively takes carbon from the atmosphere and stores it deep in the ocean.

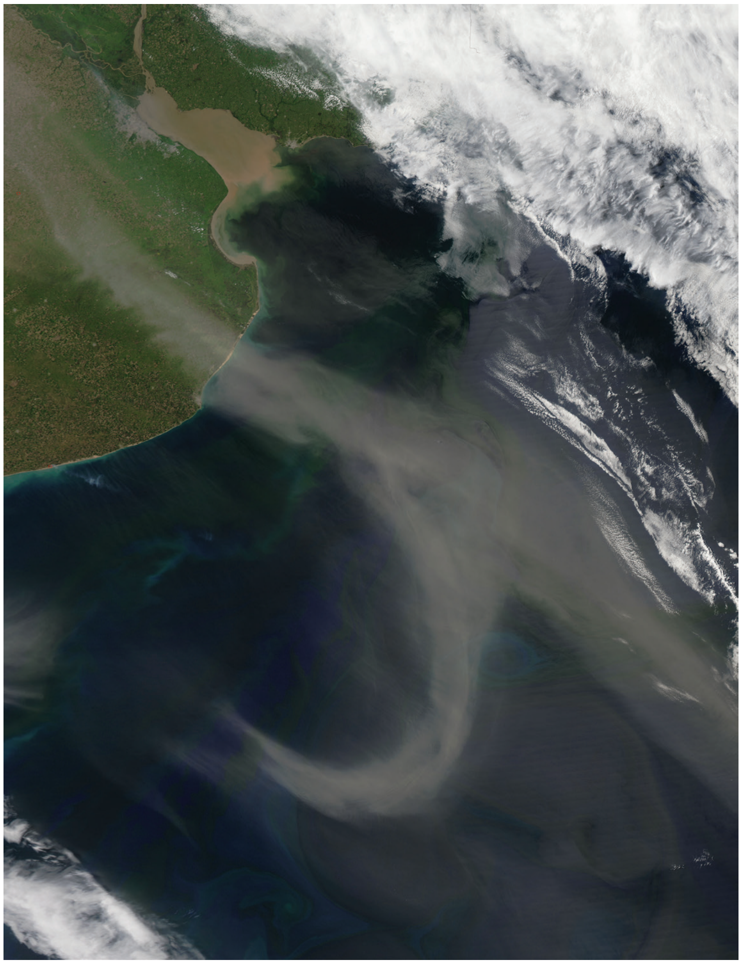

Figure 8.2: A pale brown plume of dust swept out of Argentina's Pampas, a heavily farmed grassland, and split into two plumes over the South Atlantic Ocean. The wide arc and subtle curls within the dust plume complement the patterns visible in the ocean beneath it. Peacock-colored, the South Atlantic Ocean was in full bloom: a display of blue and green streaks and swirls peek from beneath the dust storm. The wind-blown dust also carries iron and other nutrients that fertilize already fertile ocean waters. The surface-dwelling phytoplankton color the ocean, contributing to the brilliant color seen in the image. Sediment from the Rio de la Plata may also be contributing to the ocean color. The southern edge of the brown, sediment-filled estuary is visible along the top of the image. Like dust, sediment from river plumes also adds nutrients to the ocean, further supporting phytoplankton blooms.

photosynthesis • *a chemical process in plants and other organisms which converts light energy and carbon dioxide into chemical energy (sugars that provide fuel) and oxygen.*

phytoplankton • *one-celled photosynthetic algae that float near the surface of bodies of both marine and freshwater.*

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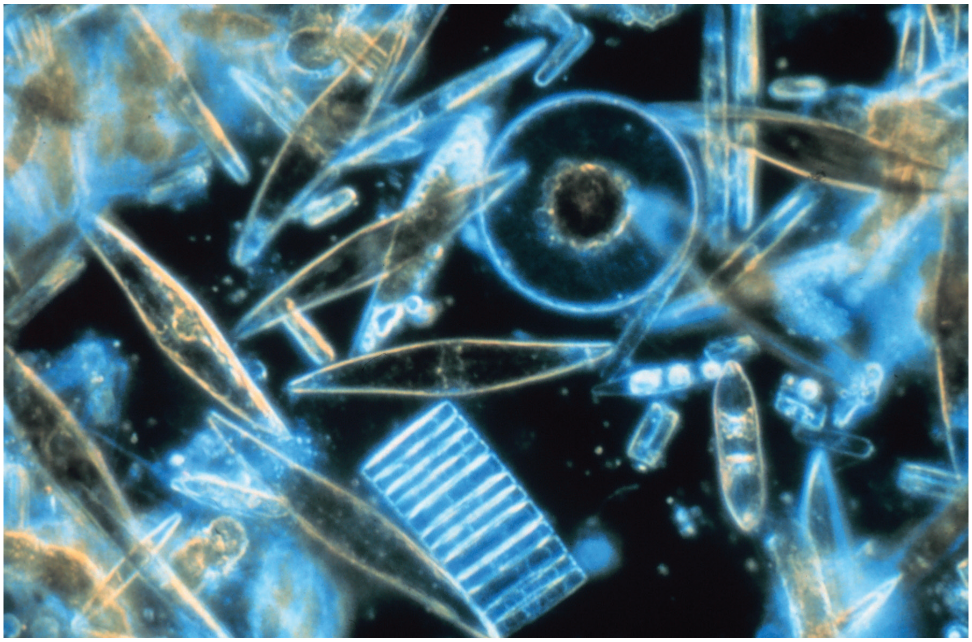

Figure 8.3: Diatoms (a type of phytoplankton) seen through a microscope. These specimens were living between crystals of annual sea ice in McMurdo Sound, Antarctica.

Scientists have proposed enhancing this process by “fertilizing” the ocean: adding nitrogen, phosphate, or iron to seawater to boost phytoplankton growth near the surface. Iron fertilization has been the preferred approach since phytoplankton produce much more carbon per mole of iron than they do per mole of nitrogen or phosphate. Researchers have focused on the Southern Ocean as a candidate location for iron fertilization. Phytoplankton growth there is currently limited by relatively little iron in surface waters, but the water is rich in nitrogen and phosphorus which could feed phytoplankton growth once it is stimulated by adding iron to the water. *Figure 8.3* shows a close-up view of some types of phytoplankton found in the Southern Ocean.

Estimates are that global-scale iron fertilization of the oceans would remove less than 1 Gt of carbon per year from the atmosphere. By comparison, fossil fuel burning worldwide released around 9 Gt of carbon into the atmosphere in 2014. There are concerns and unknowns about it as well. The success of CDR through accelerating the ocean’s biological pump depends partly on ocean circulation taking a long time to bring carbon in the deep ocean back up to the surface. One of the problems with this method is that climate change which has already begun will likely change ocean circulation patterns in ways we don’t fully understand. These changes could reduce the effectiveness of ocean fertilization.

As with any large-scale intervention in Earth’s systems, iron fertilization may harm ecosystems. Increased iron and increased phytoplankton growth could affect fish, birds, and other organisms, and indeed the entire marine food web. Iron fertilization could lead to changes in nutrient supplies and oxygen levels (through increased respiration of more organic material). It could also alter the ocean’s biogeochemistry in other ways, such as producing increased release of the greenhouse gas nitrous oxide (N_2O) from marine microorganisms.

3. Examples of Solar Radiation Management (SRM) Techniques

SRM techniques involve reducing solar heating of the Earth by increasing the Earth's or the atmosphere's reflectivity (albedo), or blocking sunlight before it reaches the Earth. Since these techniques do not remove any greenhouse gases from the atmosphere, they do nothing to address the problem of ocean acidification. These techniques are so controversial, poorly understood, and risky that a recent report published by the US National Academy of Sciences recommends quite definitively that "albedo modification at scales sufficient to alter climate should not be deployed at this time."[8] The report does recommend studying SRM, however, in the event that there is pressure to use it as an emergency option or that it is attempted by an individual nation or organization. Research connected to SRM can also further climate science, especially if it leads to a better understanding of the role of clouds, **albedo**, and **aerosols** in Earth's climate system.

albedo • *the fraction of solar energy that a surface reflects back into space.*

aerosol • *the suspension of very fine solid or liquid particles in a gas.*

3.1 Marine Cloud Brightening

The ocean covers most of the Earth, and absorbs more sunlight per unit area than land, **sea ice**, and **ice sheets**. Low clouds, however, cover from 20 to 40 percent of the ocean surface. These clouds reflect sunlight, and several proposals have looked at ways to enhance the brightness of these clouds so that they reflect even more sunlight. This could be done by spraying particles—maybe small grains of salt produced by evaporating sea water—into the clouds from airplanes or ships. The salt particles would serve as **nucleation sites** for water droplets, and these additional water droplets in the clouds could reflect additional sunlight away from the Earth.

sea ice • *frozen seawater at the surface of the ocean.*

ice sheet • *a mass of glacial ice that covers part of a continent and has an area greater than 50,000 square kilometers (19,000 square miles).*

nucleation sites • *suspended particles in the air which can serve as "seeds" for water molecules to attach to, in the first step in the formation of clouds. See also CONDENSATION NUCLEI.*

Advantages of marine cloud brightening using salt spray are that the raw material (sea water) is readily available and the salt particles that would eventually fall as rain would not pollute the ocean. Further, if problems arose the process could be stopped quickly. Disadvantages are the cost (and fossil fuel use) of deploying machinery to spray particles into the atmosphere, the uncertainty of how cloud brightening could affect local and regional weather and ocean currents, and the uncertainty of the basic efficacy of the method. We know from satellite observation that trails of exhaust from ocean-going ships form bright clouds; the particles in the exhaust act as cloud nucleation sites. *Figure 8.4* shows a satellite image of ship tracks in the Pacific Ocean. We don't know whether cloud brightening methods work reliably, and even if they did, whether cloud brightening could be done economically on a large enough scale to produce substantial cooling.

3.2 Stratospheric Aerosol Distribution

People have observed over centuries that volcanic eruptions can have a rapid, dramatic effect on climate. The sulfur dioxide (SO_2) particles released into the

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[8] US National Research Council, Climate Intervention: Reflecting Sunlight to Cool Earth (2015), The National Acadamies Press, Washington, D.C.

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SRM Techniques

stratosphere *• the second layer above the Earth's surface in the ATMOSPHERE. The stratosphere reaches to about 50 kilometers (30 miles) above the Earth's surface.*

infrared *• electromagnetic radiation in the part of the spectrum with wavelengths from 750 nanometers to 1 millimeter. People sense infrared radiation as heat.*

ozone *• a molecule* (O_3) *found in the STRATOSPHERE which absorbs ultraviolet light. When found near the surface of the Earth, ozone is considered a pollutant because it is a component of smog and can cause lung irritation.*

"ozone hole" *• a region of ozone depletion in the STRATOSPHERE above Antarctica, caused by destruction of ozone from ANTHROPOGENIC chemicals released into the ATMOSPHERE.*

volcanic sulfates *• sulfate molecules in the atmosphere formed from chemical reactions with sulfur dioxide released in volcanic eruptions.*

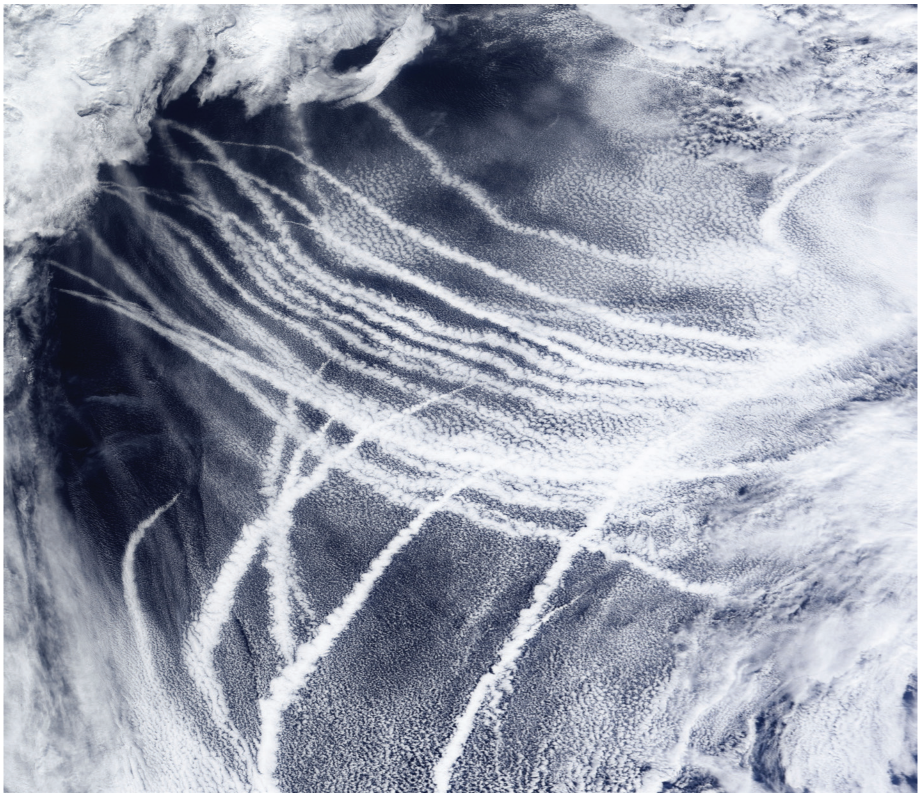

Figure 8.4: Bright linear clouds—ship tracks—formed from the exhaust trails of ships south of Alaska.

stratosphere from large volcanic eruptions reflect away incoming sunlight, cooling the Earth for up to a few years. The most recent example was the 1991 eruption of Mount Pinatubo in the Philippines (*Figure 8.5*), which led to an almost 0.6°C (1°F) decrease in average global temperatures over 15 months.[9] A temporary and substantial decrease in rainfall over land has also been attributed to the eruption of Mount Pinatubo.[10]

A geoengineering proposal that seeks to mimic this cooling effect involves injecting aerosols such as sulfur dioxide into the stratosphere continuously over the course of decades or centuries. If the particles are the right size they will reflect incoming sunlight back to space without scattering outgoing **infrared** radiation (i.e., heat) back towards the Earth. This technique could work very quickly, reducing Earth's temperature within a year of deployment.

Injecting aerosols into the stratosphere has substantial unknowns about how it would affect temperature, precipitation, and weather patterns regionally and globally. In addition, it carries the risk of changing **ozone** concentrations in the stratosphere. Ozone in the atmosphere protects life on Earth from damaging ultraviolet rays, and after an "**ozone hole**" (a region of depleted ozone) was detected over Antarctica there was a major international effort to ban substances that lead to ozone depletion. **Volcanic sulfates** in the atmosphere can undergo chemical reactions that lead to ozone depletion. After the eruption of Mount Pinatubo, ozone concentrations decreased in the Northern Hemisphere and

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[9] A summary of the effects of Mt. Pinatubo's eruption ten years afterward can be found here: http://earthobservatory.nasa.gov/IOTD/view.php?id=1510 .

[10] See Trenberth, K. E., & Dai, A. (2007). Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering. Geophysical Research Letters, 34, L15702.

Figure 8.5: Ash cloud of Mt. Pinatubo during 1991 eruption.

increased in the Southern Hemisphere. These changes have been attributed to changes in the movement of global air masses due to temperature effects from the eruption. Our understanding of the complex interactions that link aerosols, atmospheric chemistry, and global weather patterns is far from complete, and must be improved before we consider injecting aerosols into the atmosphere as a geoengineering technique.

3.3 Surface Albedo Alteration

Another way to reflect more sunlight away from the Earth is to alter the Earth's surface itself. This could include planting crops or grasslands that have a higher albedo than other plants, covering large areas of desert with reflective material, or painting roofs white. Most of the Earth's surface is covered by the ocean, which has a lower albedo than land or ice (see *Figure 8.6*), and some proposals suggest producing bubbles near the ocean's surface to increase its reflectivity. These options have not been studied thoroughly, and preliminary analyses suggest that their costs would far outweigh their effectivity. As with other geoengineering proposals, they raise questions of environmental and societal impact. For example, how would we balance the need to plant crops or grasses that have higher albedo with the need to grow certain plants for food and biofuels? What damage would occur to desert ecosystems if we covered large areas of land with reflective materials? How would surface bubbles in the ocean affect phytoplankton, an important part of the **carbon cycle**?

carbon cycle *• the exchange and recycling of carbon between the geosphere, hydrosphere, atmosphere, and biosphere.*

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Figure 8.6: Map of the albedo of the Earth's land surfaces for the month of March, 2016, measured by Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on NASA's Aqua and Terra satellites. The lighter colors seen in areas covered by ice, snow, and sand indicate high albedo, and the darker colors seen in forest-covered areas indicate low albedo.

Box 8.2: Exercise to estimate the costs of painting roofs white to increase reflectivity[11]

Assume that the cost of painting roofs white is \$0.30 per square meter per year (including materials and labor and factoring in repainting every 10 years). Assume that the paintable roofs covered 1% of the Earth's *land* surface. What would be the total annual cost for this endeavor?

One can look up that the Earth's total surface area is about 197 x 10^6 square miles, and that about 30% of that surface area is land. This means that the Earth's land surface area is approximately:

$$0.30 \times 197 \times 10^6\ \mathrm{mi}^2 = 59 \times 10^6\ \mathrm{mi}^2.$$

Convert this to square meters:

$$\text{Earth's land surface area} = 59 \times 10^6\ \mathrm{mi}^2 \times (1609\ \mathrm{m/mi})^2 = 1.5 \times 10^{14}\ \mathrm{m}^2.$$

The annual cost for painting roofs in 1% of this area is then:

$$\$0.30/\mathrm{m}^2/\mathrm{year} \times 0.01 \times 1.5 \times 10^{14}\ \mathrm{m}^2 = \$4.5 \times 10^{11}/\mathrm{year}.$$

In other words, \$450 billion per year!

Estimates of the effectivity of roof painting conclude that the net effect would reduce the radiative impact of a doubling of CO_2 in the atmosphere by only about 0.25%.

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[11] This exercise is based on an estimate in The Royal Society, Geoengineering the climate: science, governance and uncertainty. London, UK (2009).

4. Geoengineering Choices

This section did not review all geoengineering proposal discussed in the literature. Omissions include reflective structures in space to block sunlight before it even reaches Earth's atmosphere, technologies that can remove CO_2 directly from the air, and biofuel production and use combined with carbon capture and sequestration technology. Several of the footnotes in this chapter give references which provide more detail on these methods.

Geoengineering proposals have varying but generally high degrees of uncertainty in their effectivity and impacts. They must be evaluated based on financial cost, land area used, energy required, potential for environmental degradation, effectivity, time scales for implementation and effect, and social and political barriers. For many approaches, their implementation has risks that we don't currently know how to evaluate. For these reasons, almost all reviews of geoengineering methods emphasize that our primary focus today should be on reducing greenhouse gas emissions.

See Chapter 7: Climate Change Mitigation.

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RESOURCES

An article about an innovative approach to climate intervention that could also simultaneously produce biofuels and food: *Marine Microalgae: Climate, Energy, and Food Security from the Sea* by C.H. Greene et al., *Oceanography* 29(4):10–15 (2016). https://tos.org/oceanography/assets/docs/29-4_greene.pdf.

Two 2015 reports on climate intervention from the US National Research Council, along with links to media coverage of their release: https://nas-sites.org/americasclimatechoices/other-reports-on-climate-change/climate-intervention-reports/.

The website of the Oxford Geoengineering Programme at Oxford University, UK, contains brief overviews of geoengineering methods: http://www.geoengineering.ox.ac.uk/.