

Frequently Asked Questions

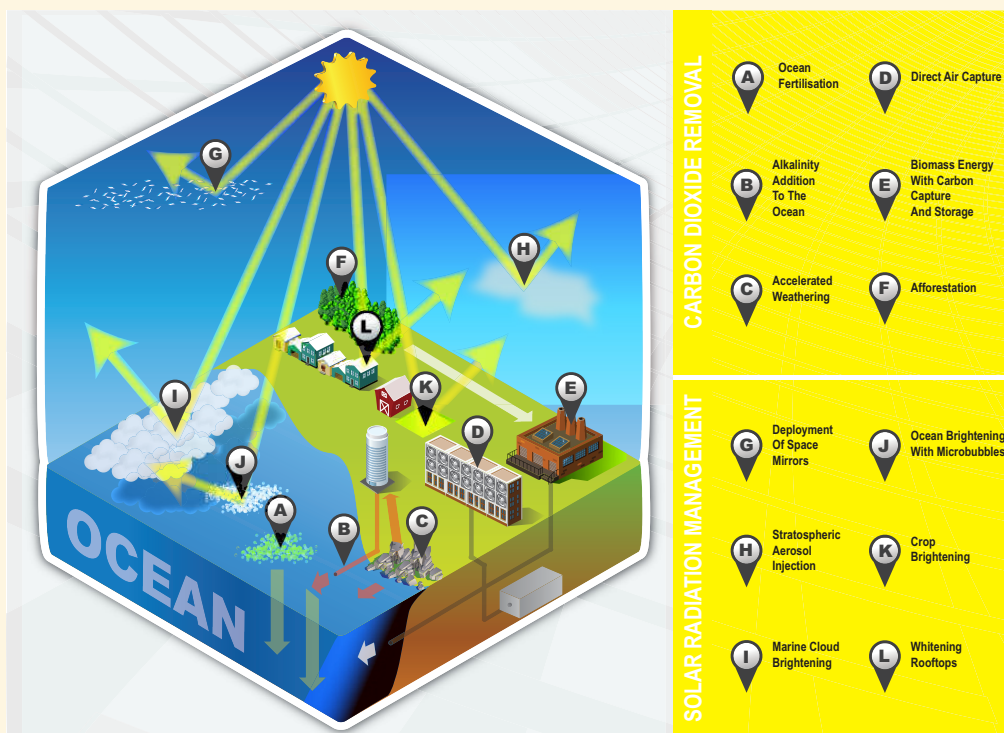
FAQ 7.3 | Could Geoengineering Counteract Climate Change and What Side Effects Might Occur?

Geoengineering—also called climate engineering—is defined as a broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate impacts of climate change. Two distinct categories of geoengineering methods are usually considered: Solar Radiation Management (SRM, assessed in Section 7.7) aims to offset the warming from anthropogenic greenhouse gases by making the planet more reflective while Carbon Dioxide Removal (CDR, assessed in Section 6.5) aims at reducing the atmospheric CO₂ concentration. The two categories operate on different physical principles and on different time scales. Models suggest that if SRM methods were realizable they would be effective in countering increasing temperatures, and would be less, but still, effective in countering some other climate changes. SRM would not counter all effects of climate change, and all proposed geoengineering methods also carry risks and side effects. Additional consequences cannot yet be anticipated as the level of scientific understanding about both SRM and CDR is low. There are also many (political, ethical, and practical) issues involving geoengineering that are beyond the scope of this report.

Carbon Dioxide Removal Methods

CDR methods aim at removing CO₂ from the atmosphere by deliberately modifying carbon cycle processes, or by industrial (e.g., chemical) approaches. The carbon withdrawn from the atmosphere would then be stored in land, ocean or in geological reservoirs. Some CDR methods rely on biological processes, such as large-scale afforestation/reforestation, carbon sequestration in soils through biochar, bioenergy with carbon capture and storage (BECCS) and ocean fertilization. Others would rely on geological processes, such as accelerated weathering of silicate and carbonate rocks—on land or in the ocean (see FAQ.7.3, Figure 1). The CO₂ removed from the atmosphere would

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FAQ 7.3, Figure 1 | Overview of some proposed geoengineering methods as they have been suggested. Carbon Dioxide Removal methods (see Section 6.5 for details): (A) nutrients are added to the ocean (ocean fertilization), which increases oceanic productivity in the surface ocean and transports a fraction of the resulting biogenic carbon downward; (B) alkalinity from solid minerals is added to the ocean, which causes more atmospheric CO₂ to dissolve in the ocean; (C) the weathering rate of silicate rocks is increased, and the dissolved carbonate minerals are transported to the ocean; (D) atmospheric CO₂ is captured chemically, and stored either underground or in the ocean; (E) biomass is burned at an electric power plant with carbon capture, and the captured CO₂ is stored either underground or in the ocean; and (F) CO₂ is captured through afforestation and reforestation to be stored in land ecosystems. Solar Radiation Management methods (see Section 7.7 for details): (G) reflectors are placed in space to reflect solar radiation; (H) aerosols are injected in the stratosphere; (I) marine clouds are seeded in order to be made more reflective; (J) microbubbles are produced at the ocean surface to make it more reflective; (K) more reflective crops are grown; and (L) roofs and other built structures are whitened.

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then be stored in organic form in land reservoirs, or in inorganic form in oceanic and geological reservoirs, where it would have to be stored for at least hundreds of years for CDR to be effective.

CDR methods would reduce the radiative forcing of CO₂ inasmuch as they are effective at removing CO₂ from the atmosphere and keeping the removed carbon away from the atmosphere. Some methods would also reduce ocean acidification (see FAQ 3.2), but other methods involving oceanic storage might instead increase ocean acidification if the carbon is sequestered as dissolved CO₂. A major uncertainty related to the effectiveness of CDR methods is the storage capacity and the permanence of stored carbon. Permanent carbon removal and storage by CDR would decrease climate warming in the long term. However, non-permanent storage strategies would allow CO₂ to return back to the atmosphere where it would once again contribute to warming. An intentional removal of CO₂ by CDR methods will be partially offset by the response of the oceanic and terrestrial carbon reservoirs if the CO₂ atmospheric concentration is reduced. This is because some oceanic and terrestrial carbon reservoirs will outgas to the atmosphere the anthropogenic CO₂ that had previously been stored. To completely offset past anthropogenic CO₂ emissions, CDR techniques would therefore need to remove not just the CO₂ that has accumulated in the atmosphere since pre-industrial times, but also the anthropogenic carbon previously taken up by the terrestrial biosphere and the ocean.

Biological and most chemical weathering CDR methods cannot be scaled up indefinitely and are necessarily limited by various physical or environmental constraints such as competing demands for land. Assuming a maximum CDR sequestration rate of 200 PgC per century from a combination of CDR methods, it would take about one and half centuries to remove the CO₂ emitted in the last 50 years, making it difficult—even for a suite of additive CDR methods—to mitigate climate change rapidly. Direct air capture methods could in principle operate much more rapidly, but may be limited by large-scale implementation, including energy use and environmental constraints.

CDR could also have climatic and environmental side effects. For instance, enhanced vegetation productivity may increase emissions of N₂O, which is a more potent greenhouse gas than CO₂. A large-scale increase in vegetation coverage, for instance through afforestation or energy crops, could alter surface characteristics, such as surface reflectivity and turbulent fluxes. Some modelling studies have shown that afforestation in seasonally snow-covered boreal regions could in fact accelerate global warming, whereas afforestation in the tropics may be more effective at slowing global warming. Ocean-based CDR methods that rely on biological production (i.e., ocean fertilization) would have numerous side effects on ocean ecosystems, ocean acidity and may produce emissions of non-CO₂ greenhouse gases.

Solar Radiation Management Methods

The globally averaged surface temperature of the planet is strongly influenced by the amount of sunlight absorbed by the Earth's atmosphere and surface, which warms the planet, and by the existence of the greenhouse effect, the process by which greenhouse gases and clouds affect the way energy is eventually radiated back to space. An increase in the greenhouse effect leads to a surface temperature rise until a new equilibrium is found. If less incoming sunlight is absorbed because the planet has been made more reflective, or if energy can be emitted to space more effectively because the greenhouse effect is reduced, the average global surface temperature will be reduced.

Suggested geoengineering methods that aim at managing the Earth's incoming and outgoing energy flows are based on this fundamental physical principle. Most of these methods propose to either reduce sunlight reaching the Earth or increase the reflectivity of the planet by making the atmosphere, clouds or the surface brighter (see FAQ 7.3, Figure 1). Another technique proposes to suppress high-level clouds called cirrus, as these clouds have a strong greenhouse effect. Basic physics tells us that if any of these methods change energy flows as expected, then the planet will cool. The picture is complicated, however, because of the many and complex physical processes which govern the interactions between the flow of energy, the atmospheric circulation, weather and the resulting climate.

While the globally averaged surface temperature of the planet will respond to a change in the amount of sunlight reaching the surface or a change in the greenhouse effect, the temperature at any given location and time is influenced by many other factors and the amount of cooling from SRM will not in general equal the amount of warming caused by greenhouse gases. For example, SRM will change heating rates only during daytime, but increasing greenhouse gases can change temperatures during both day and night. This inexact compensation can influence

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the diurnal cycle of surface temperature, even if the average surface temperature is unchanged. As another example, model calculations suggest that a uniform decrease in sunlight reaching the surface might offset global mean CO₂-induced warming, but some regions will cool less than others. Models suggest that if anthropogenic greenhouse warming were completely compensated by stratospheric aerosols, then polar regions would be left with a small residual warming, while tropical regions would become a little cooler than in pre-industrial times.

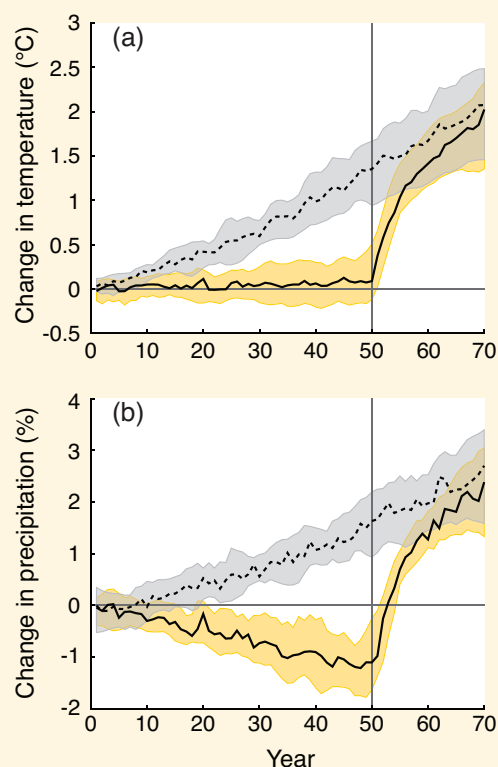
SRM could theoretically counteract anthropogenic climate change rapidly, cooling the Earth to pre-industrial levels within one or two decades. This is known from climate models but also from the climate records of large volcanic eruptions. The well-observed eruption of Mt Pinatubo in 1991 caused a temporary increase in stratospheric aerosols and a rapid decrease in surface temperature of about 0.5°C.

Climate consists of many factors besides surface temperature. Consequences for other climate features, such as rainfall, soil moisture, river flow, snowpack and sea ice, and ecosystems may also be important. Both models and theory show that compensating an increased greenhouse effect with SRM to stabilize surface temperature would somewhat lower the globally averaged rainfall (see FAQ 7.3, Figure 2 for an idealized model result), and there also could be regional changes. Such imprecise compensation in regional and global climate patterns makes it improbable that SRM will produce a future climate that is ‘just like’ the one we experience today, or have experienced in the past. However, available climate models indicate that a geoengineered climate with SRM and high atmospheric CO₂ levels would be generally closer to 20th century climate than a future climate with elevated CO₂ concentrations and no SRM.

SRM techniques would probably have other side effects. For example, theory, observation and models suggest that stratospheric sulphate aerosols from volcanic eruptions and natural emissions deplete stratospheric ozone, especially while chlorine from chlorofluorocarbon emissions resides in the atmosphere. Stratospheric aerosols introduced for SRM are expected to have the same effect. Ozone depletion would increase the amount of ultraviolet light reaching the surface damaging terrestrial and marine ecosystems. Stratospheric aerosols would also increase the ratio of direct to diffuse sunlight reaching the surface, which generally increases plant productivity. There has also been some concern that sulphate aerosol SRM would increase acid rain, but model studies suggest that acid rain is probably not a major concern since the rate of acid rain production from stratospheric aerosol SRM would be much smaller than values currently produced by pollution sources. SRM will also not address the ocean acidification associated with increasing atmospheric CO₂ concentrations and its impacts on marine ecosystems.

Without conventional mitigation efforts or potential CDR methods, high CO₂ concentrations from anthropogenic emissions will persist in the atmosphere for as long as a thousand years, and SRM would have to be maintained as long as CO₂ concentrations were high. Stopping SRM while CO₂ concentrations are still high would lead to a very rapid warming over one or two decades (see FAQ 7.3, Figure 2), severely stressing ecosystem and human adaptation.

If SRM were used to avoid some consequences of increasing CO₂ concentrations, the risks, side effects and shortcomings would clearly increase as the scale of SRM increase. Approaches have been proposed to use a time-limited amount of SRM along with aggressive strategies for reducing CO₂ concentrations to help avoid transitions across climate thresholds or tipping points that would be unavoidable otherwise; assessment of such approaches would require a very careful risk benefit analysis that goes much beyond this Report.



FAQ 7.3, Figure 2 | Change in globally averaged (a) surface temperature (°C) and (b) precipitation (%) in two idealized experiments. Solid lines are for simulations using Solar Radiation Management (SRM) to balance a 1% yr⁻¹ increase in CO₂ concentration until year 50, after which SRM is stopped. Dashed lines are for simulations with a 1% yr⁻¹ increase in CO₂ concentration and no SRM. The yellow and grey envelopes show the 25th to 75th percentiles from eight different models.