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Solar geoengineering reduces atmospheric carbon burden

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Carbon cycle

A limited number of studies have directly addressed the carbon-cycle impact of solar geoengineering under Representative Concentration Pathway (RCP) 8.5[4,5]. Other studies estimate the increase in carbon burden given carbon-climate feedbacks under RCP 8.5 and similar scenarios. Supplementary Table 1 summarizes results from prior literature relevant to assessing solar geoengineering's impact on atmospheric carbon burden over the 21st century.

Supplementary Table 1: Carbon Cycle

Change in burden (GtC)	Reference	Notes
524	Govindasamy *et al*, 2002[1]	Examined carbon-cycle response to geoengineering in an equilibrium simulation using IBIS model with a slab ocean. Geoengineering represented by 1.8% reduction in solar constant to restore surface temperatures to pre-industrial. Land biosphere carbon burden was 524 GtC larger with "2×CO_2" (710 ppm) and geoengineering than with "2×CO_2".
42-420	Friedlingstein *et al*, 2006[2]	Examined carbon cycle feedback in 11 carbon-climate models, comparing coupled model response to the Special Report on Emissions Scenarios (SRES)-A2 forcing scenario to an uncoupled response in which CO_2 does not alter climate. Carbon feedback increased burden by 20-200 ppm over full range of models. Impact of holding 21st century radiative forcing will be smaller than estimates here, as Friedlingstein *et al*. estimates carbon cycle feedback due to warming from pre-industrial levels.

231	Matthews *et al*, 2009[3]	Examined carbon feedback in University of Victoria Earth System Climate Model (UVic ESCM) under a SRES-A2 scenario. Geoengineering was simulated by adjusting solar constant to return radiative forcing to pre-industrial.
251	Keller *et* al, 2014[4]	Examined carbon cycle response to geoengineering in the University of Victoria Earth System Climate Model (UVic ESCM) under an RCP 8.5 scenario.
31.6	Tjiputra *et al*, 2016[5]	Examined carbon cycle response to geoengineering in the Norwegian Earth system model (NorESM1-ME) under an RCP 8.5 scenario.
27-122	Schuur et al, 2015[6]	Reviewed field experiments and models of permafrost carbon loss. Estimates of cumulative carbon release in the 21st century under RCP-8.5 using 8 different models are given in Figure 3 and references therein.

We derive rough estimates for 2100 carbon cycle burden and 21st century permafrost emissions from Supplemental Table 1 for use in Table 1. Our methodology is detailed in the main text. "Uncorrelated error propagation," mentioned in the text, implies that means of ranges are simply added, while errors add in quadrature. For example, when adding $a \pm \sigma_a$ to $b \pm \sigma_b$, the resulting range is: $a + b \pm \sqrt{{\sigma_a}^2 + {\sigma_b}^2}$.

Energy sector

Our calculation for the emissions impact on the energy sector of holding 21st century emissions constant focuses on two parts: (i) estimates on total energy demand due to different heating and cooling demands, and (ii) direct impacts on energy generation.

(i) Energy demand impacts:

One prior study[7] we know of examined the impact of warming on global residential energy demand under a scenario similar to RCP 8.5. It estimated that 21st century emissions would be increased by 7.5 GtC due to the effect of increased temperatures on global residential energy demand. That study used a scenario with about 15% lower carbon emissions than is typical for RCP 8.5, so it may slightly underestimate the carbon emissions' impact. Adding commercial energy demand approximately doubles residential energy demand. We, thus, use double the residential estimate as a lower bound for temperature-driven increases in the global energy demand.

Transportation energy demand is somewhat larger than residential. We are unaware of any study of the impact of temperature on transportation sector energy as a whole, though there are studies of light duty vehicles, about half of transportation energy use, that show a sharp increase in energy use due to vehicle air conditioning load[8]. Given these uncertainties, we choose an upper bound four times the residential estimate yielding a rough overall range of 15-30 GtC for the total amount that carbon emissions might be reduced if solar geoengineering were used to counter surface temperature increases under an emissions scenario corresponding to RCP 8.5.

(ii) Direct impacts on energy generation:
We are unaware of any overall estimate of the impact of warmer temperatures on energy sector emissions. If we assume that fossil fuel generation provides the backup to other sources of energy, there are two effects:

1. A decrease in the efficiency of fossil generation, which causes an increase in emissions for a given demand.
2. A decrease in the supply of low-carbon energy (solar, wind, geothermal, or nuclear) which is, by assumption, made up for by a corresponding increase in fossil emissions.

Supplementary Table 2 provides examples of the temperature coefficient of efficiency of some important energy technologies. Based on these data we assume a range of possible coefficients from 0.1-1%/K. The low estimate assumes the low-temperature response coefficients associated with dry cooling technologies for steam cycle power plants and neglects any effects of reduction of supply of renewables. The high estimate assumes that the supply of carbon-neutral energy is reduced at a rate of 1%/K and that deficit must be made up for by an increased supply of fossil energy.

Supplementary Table 2: Energy temperature coefficients

Energy source	Reference	Temperature coefficient
Thermal power plants (efficiency)	Daycock *et al*, 2004[9]	Efficiency: -0.1%/K
Rankine cycle thermal power plants (wet cooling, efficiency)	Turchi et al., 2010[10]	Efficiency: -0.25%/K
Solar Photovoltaic (PV)	Skoplaki & Palyvos, 2009[11]	-0.5 %/K
Geothermal (typical air-cooled binary cycle geothermal plant)	Wilbanks *et al.*, 2008[12]	Efficiency: -2%/K
Nuclear power (output)	Förster & Lilliestam, 2010[13]	Efficiency: -0.1%/K Capacity: -2%/K at 4 K

The RCP 8.5 scenario assumes temperature increase of 3.7°C by 2100 relative to 1986–2005, and integrated emissions of 1685 GtC. We assume that temperatures increase linearly over the century and ignore the change in emissions rate so that we can use the 21st century average temperature change of 1.8°C. Thus, 1.8 K × 1685 GtC × 0.001 K^{-1} = 3 GtC, whereas, 1.8 K × 1685 GtC × 0.01 K^{-1} = 30 GtC.

Using these assumptions, we roughly estimate that emissions from energy supply would be reduced by 3-30 GtC by solar geoengineering that eliminated the 21st century temperature rise in an RCP 8.5 scenario.

Finally, we add the energy consumption estimate (15-30 GtC) to this energy generation estimate using simple uncorrelated error propagation to yield a combined estimate of 24-54 GtC.

Equivalent Cost of Mitigation

Radiative forcing efficacy of sulfate aerosols. We use a value of 0.55 Wm^{-2} for injection of H_2SO_4 for each 1 million tons per year of sulfur, taken from a rate estimated for a rate of 5 million tons per year[14]. Forcing efficacies of roughly this value are common for studies that have explored the efficient distribution of sulfate aerosols and radiative forcings of less than about 2 Wm^{-2}. Larger radiative forcing may require the direct injection of H_2SO_4 in an aircraft plume to control the particle size distribution[14] or the use of other particles[15]. Injecting $CaCO_3$ would engender roughly similar amounts[16]. For sulfates, we assume that for emission of either H_2SO_4 or SO_2 the aircraft need only carry the equivalent mass of sulfur. Conversion of S to SO_2 can be readily accomplished in compact burners. Conversion to H_2SO_4 is equivalent to conversion to $SO_3 + H_2O$. This is harder because it requires a catalyst, but our unpublished analysis suggests that it can be accomplished with existing technologies.

Cost of transporting material to the stratosphere. We adopt a cost of \$2 billion per Mt/year. Note that this value is deliberately conservative as it is three times larger than the minimum new aircraft estimate for transport to 20km found in the Aurora study[17].

Monitoring costs. We add \$3 billion per year for monitoring this program, an amount roughly equal to the *entire* current budget for described in the US Global Change Research Program[18]. This is several times the minimum cost to fund new satellites, an ongoing suite of in situ observations, and related scientific analysis.

Discount rate. We use a 3% discount rate[19] as our central estimate and explore implications of 2.5 and 5%.

Radiative forcing scenario. We approximate the RCP 8.5 scenario as a linear ramp from 1.75 Wm^{-2} in 2000 to 8.5 Wm^{-2} in 2100, and we assume that sufficient solar geoengineering radiative forcing is used to maintain 1.75 Wm^{-2} radiative forcing over the century.

Discounted costs are then given by:

$$\int_0^{100} \left((RF(t) - 1.75) \frac{LC}{RFE} + MC \right) (1 - discount\ rate)^t\, dt$$

where $RF(t)$ is radiative forcing, increasing from 1.75 to 8.5 Wm^{-2}, LC is the lofting cost to 20km assumed to be \$2 billion/Mt/year, RFE is the radiative forcing efficacy assumed to be 0.55 Wm^{-2}/Mt/year, MC represents monitoring costs equal to \$3 billion/year. For a $discount\ rate$ of 3%, this amounts to \$307 billion in discounted present-value terms. With a $discount\ rate$ of 5%, the number is around \$148 billion, reaching roughly \$385 billion for a discount rate of 2.5%. Given the rough estimates throughout and to avoid the appearance of undue precision, we report estimates of \$300, \$150, and \$400 billion for the central 3%, the 5%, and the 2.5% $discount\ rate$, respectively.

Finally, we use our estimates for the reduction in emissions equivalent of roughly 850 to over 1900 $GtCO_2$ and divide costs by the range of $GtCO_2$ avoided to yield a rough cost effectiveness estimate of solar geoengineering's effectiveness as emissions mitigation. For the central 3% discount rate, that range is \$0.2-0.4/tCO_2. (For a 2.5% discount rate, it is \$0.2-0.5/tCO_2. For a 5% discount rate, it is \$0.1-0.2/tCO_2.)

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