Practicality of stratospheric geoengineering with black carbon aerosols

Ben Kravitz and Alan Robock

Ben Kravitz, Department of Global Ecology, Carnegie Institution for Science, 260 Panama Street, Stanford, CA 94305, USA. (bkravitz@stanford.edu) (Corresponding Author)

Alan Robock, Department of Environmental Sciences, Rutgers University, 14 College Farm Road, New Brunswick, NJ 08901, USA. (robock@envsci.rutgers.edu)

1Department of Global Ecology, Carnegie Institution for Science, Stanford, California, USA.

2Department of Environmental Sciences, Rutgers University, New Brunswick, New Jersey, USA.
We calculate costs and emissions factors for two methods of producing 1 Tg per year of black carbon aerosols in the stratosphere as a means of geo-engineering the climate. The cheapest investigated idea of combusting diesel fuel in the stratosphere to produce the aerosols would require an initial investment of US $1.4 trillion and would incur an annual operating cost of approximately US $540 billion, or 2.0% and 0.8% of worldwide GDP, respectively. Costs are reduced by 1-2 orders of magnitude if the aerosols are produced on the ground and transported to the stratosphere. Using carbon black would be much cheaper, with both fixed and annual costs of approximately US $1 billion. Additional emissions dependent upon the means of production and transport would mostly be negligible, with the exception of large amounts of NO\(_x\) from diesel combustion. The amount of NO\(_x\) produced could cause catalytic ozone destruction by approximately 3-10%. The current worldwide oil production and refining capacity cannot support diesel fuel combustion to produce 1 Tg of black carbon aerosols, but producing this much carbon black would be cheap and relatively easy with current technology. The cost of using black carbon for stratospheric geoengineering may not be a limiting factor, but there are other reasons why this technique is impractical, including massive ozone depletion.
1. Introduction

Stratospheric geoengineering with black carbon (BC) aerosols has been proposed as a potential means of alleviating some amount of anthropogenic warming [Crutzen, 2006; Kravitz et al., 2011]. Should this be deemed a viable geoengineering option, one of the most immediate questions is how one can produce a large amount of black carbon aerosols in the stratosphere. We adapt some of the methods and calculations of Robock et al. [2009], who performed similar investigations for sulfate aerosols.

We look at two methods of BC aerosol production: diesel combustion and carbon black. Soot production is a particularly sensitive marker of diesel exhaust [Fruin et al., 2004]. Diesel combustion has the significant advantage of a vast infrastructure currently in place, including transportation and regulation, which would lend this technology particularly well to geoengineering purposes. Carbon black results from furnace combustion of heavy fuel oil in low oxygen [Crump, 2000]. It is generally an agglomeration of mostly elemental carbon particles, whereas black carbon aerosols often have adsorbed organic particles, depending upon the source of the emission [Watson and Valberg, 2001], but the mechanisms of formation of the two compounds are quite similar [Medalia et al., 1983], so we can assume the particle density and refractive indices are similar. However, a typical radius of black carbon aerosol is approximately 0.1 µm [Rose et al., 2006], but a typical carbon black agglomerate can have a diameter on the order of millimeters [Gandhi, 2005]. A larger diameter means a greatly increased fall speed as well as a reduced radiative efficiency, so the same mass of carbon black might be significantly less effective, or possibly ineffective, for geoengineering.
2. Logistics and costs of using diesel fuel

The black carbon emissions for heavy-duty diesel vehicles are approximately 1 g black carbon emitted per kg of fuel used [Kirchstetter et al., 1999], but the highest emitting 10% of all heavy-duty diesel trucks produce 42% of black carbon emissions [Ban-Weiss et al., 2009]. Assuming diesel engines could be tuned to produce 10 g black carbon per kg of fuel, the largest value reported by Ban-Weiss et al. [2009], and assuming an average density of 0.84 kg L$^{-1}$ of diesel fuel [Brown, 1999], producing 1 Tg of black carbon would require combustion of $1.19 \times 10^{11}$ L of diesel fuel, or approximately 10.8% of current worldwide production [EIA, 2010a]. Refineries in the United States are operating at approximately 90% capacity [EIA, 2010b], so extrapolating this value worldwide implies geoengineering by combustion of diesel would require additional expansion of the current refining capacity, especially since this capacity is likely a theoretical maximum. We do not have estimates of cost for this expansion. We assume the cost of obtaining the oil, refining it into diesel, and transporting it to its desired destination, which would be the geoengineering deployment site, is included in the at-the-pump fuel cost. For each US $0.01 increase in the market price of diesel fuel, the annual cost of geoengineering increases by US $314 million.

Industrial diesel engines are designed to run continuously at 100% capacity and need to be maintained relatively infrequently [USPE&E, 2010]. As the central model for our calculations, we use specifications of the Caterpillar 3516B industrial engine [Caterpillar, 2010a]. Average costs for this particular engine are not available, but several auctions reported the sold price at US $395,000 (used), which we adopt as our price estimate. Assuming the engine is in operation for 2920 hours a year (365 days a year, 8 hours per
day - the case for 24 hour per day operation is discussed in Table 1), this would require
75,100 engines at a capital cost of approximately US $30 billion. We do not include
estimates of the cost of replacing the engines when they reach the end of their operational
lifetime, but average diesel engine lifespans are in the range of 10-22 years [MacKay &
Co., 2003; Lyon, 2007].

The maintenance costs are twofold: actual cost to maintain the engine and replacement
engines to operate during the equipment’s downtime. Maintenance requirements for the
Caterpillar 3516B mean each engine will be inoperative 3.4% of the time [Caterpillar,
2010c]. To meet the required black carbon production rate, an additional 255 engines are
required at a capital cost of US $100 million.

Maintenance estimates for the Caterpillar G3520 industrial gas engine are approximately
US $0.008 per kW-h, which is likely more expensive than maintaining a diesel engine
[USP&E, 2010]. Using this as an upper bound, given that the 3516B runs at a maximum
of 1492 kW of power generation [Caterpillar, 2010a], the total annual maintenance cost
is US $2.6 billion.

A natural solution for getting the black carbon aerosols to the stratosphere is to place
these diesel engines and diesel fuel in the cargo hold of airplanes and fly them to the
stratosphere. Robock et al. [2009] evaluated several choices of aircraft that would be
suitable for geoengineering (their cost estimates were similar to those of McClellan et al.
[2010]), but we base our calculations here on the KC-10 Extender [USAF, 2010a]. It has
a payload of 76,560 kg, a ceiling of 12.7 km, and a unit purchase price (2010 dollars) of
US $116 million. This maximum altitude is only suitable for reaching the stratosphere at
high latitudes, but because the aerosols self-loft, getting them to the upper troposphere is sufficient, resulting in rain-out of about 20% [Mills et al., 2008; Robock et al., 2007; Fromm et al., 2010].

Each airplane is capable of carrying more than one engine, so we decompose our calculations into units consisting of an engine and 8 hours of diesel fuel. The 3516B engine weighs up to 8028 kg and can consume 4339.12 L of fuel in 8 hours for a total unit weight of 11,977.0 kg [Caterpillar, 2010b]. Each KC-10 Extender can hold 6 units per airplane, meaning 12,342 airplanes would be required at a total purchase price of US $1.4 trillion.

Curtin [2003] gives an estimate of US $3.7 million in annual cost, based on 300 flying hours per year, for personnel, fuel, maintenance, modifications, and spare parts for the KC-135 airplane. As Robock et al. [2009] state, the KC-10 is a newer airplane and would likely be cheaper, so we use this value as an upper limit for our estimations. Scaling these maintenance costs, annual maintenance and personnel costs will be approximately US $36 million per plane, for a total annual operating cost of approximately US $450 billion.

This combination results in a fixed cost of US $1.4 trillion and an operating cost of approximately US $540 billion. This is the cheapest of the methods shown in Table 1, which include calculations for the Caterpillar 3406C engine [Caterpillar, 2010a], the KC-135 Stratotanker airplane [USAF, 2010b], and geoengineering in three 8-hour shifts per day instead of a single shift.

The world gross domestic product (purchasing power parity) in 2009 was US $69.98 trillion [CIA, 2010]. The initial investment for geoengineering would be 2.0% of worldwide GDP, with an additional 0.8% each year. Stern [2006] states the cost of climate change for
2-3°C of warming could be a permanent loss of up to 3% of GDP, so geoengineering with black carbon aerosols is slightly cheaper than the damage that would be caused by climate change and is vastly more expensive than geoengineering with sulfate aerosols [Robock et al., 2009]. IPCC [2007] calculates that mitigation to reach a stabilization of 535-590 ppm CO$_2$-eq would result in a GDP reduction by 0.2-2.5%, with a median reduction of 0.6% and an annual reduction of GDP growth rate by less than 0.1%. Compared to the cost of black carbon geoengineering by diesel fuel combustion, mitigation either costs the same or is cheaper by as much as an order of magnitude.

The largest source of cost in this method is using airplanes to fly the diesel fuel and engines up to the stratosphere. If the black carbon aerosols were produced on the ground, collected, and then flown into the stratosphere to be dispersed, the fixed costs could be reduced to about US $31 billion, and the annual costs could be reduced to about US $97 billion [Robock et al., 2009].

Thus far we have not considered the potential benefit of generation of a large amount of electricity from diesel fuel combustion. Using the Caterpillar 3516B engine would create approximately 330 TW-h of energy per Tg of BC aerosols produced, which could possibly be used to power the airplanes, reducing the associated costs and resources of operating the fleet. For comparison, in 2008, the worldwide energy consumption was approximately 132,000 TW-h [British Petroleum, 2009].

3. Logistics and costs of using carbon black

Carbon black feedstock is produced from fractional distillation of petroleum and is generally extracted as a heavy or residual fuel oil [Dow, 2010a, b; ICBA, 2004]. The
yield of carbon black from the oil furnace process is 35-65%, depending upon the chosen
feedstock and the desired particle size, with smaller particles resulting in lower yields
[EPa, 1995]. Small particles are more efficient for geoengineering, so we use the lowest
value in this range. Assuming an average density of carbon black feedstock of 1.08 kg L$^{-1}$
[Dow, 2010b] and that suitable feedstock (residual fuel oil) comprises approximately 8%
of refinery yields [EIA, 2010b], producing 1 Tg of carbon black will require 3.18 × 10$^{10}$ L
of oil, or an additional 0.8% of current worldwide production [EIA, 2010b].

Available furnace black production capacity in the United States (1998) is 1.6 × 10$^9$
kg, more than sufficient to produce 1 Tg [Crump, 2000]. Annual production costs for all
carbon black produced in the United States (1998) was US $625 million, or approximately
US $0.33 per kg, with the finest grade having a 1998 cost of approximately US $1.03 per
kg. Therefore, using current infrastructure, producing 1 Tg of carbon black would cost
approximately US $1 billion.

The costs of ferrying 1 Tg of carbon black to the stratosphere are similar to those
reported in Robock et al. [2009]. The cheapest transportation option has fixed costs of US
$1 billion and annual costs of about US $320 million. Including the cost of manufacturing
the carbon black, the total per-Tg cost of geoengineering with carbon black is US $1
billion fixed and US $1.3 billion annually. We do not include the cost of transporting the
carbon black to the geoengineering site in these estimates.

4. Emissions factors

Table 2 summarizes the various emission factors for the most abundant products of
aerosol production, some of which we examine in more detail.
Carbon dioxide, the chief contributor to climate change, is the largest emissions factor in Table 2 [IPCC, 2007]. The total worldwide emissions of CO$_2$ are approximately 30 Pg of CO$_2$ per year [IEA, 2010], so this would constitute an additional 1.1% of emissions. The additional CO$_2$ produced from jet fuel combustion as part of the geoengineering process would be less than 1% of current aviation emissions, which are already only 2-3% of current worldwide emissions [Enviro Aero, 2009].

Diesel combustion produces NO$_x$ from high temperature dissociation of ambient nitrogen [EPA, 1996]. Creating 1 Tg of black carbon aerosols from diesel combustion would produce $8.5 \times 10^9$ kg of NO$_x$. Total worldwide NO emissions in 1990 were 49.6 Tg [Stevenson et al., 2004], so this source of NO$_x$ would be an additional 17%. NO$_x$ is an effective catalyst for destruction of stratospheric ozone [Crutzen, 1970]. This mechanism competes with reactions between other species, depending upon altitude [Finlayson-Pitts and Pitts, 2000]. Based on an experiment by Stolarski et al. [1995] simulating ozone destruction from a stratospheric fleet of high speed civil transport aircraft and extrapolating from a linear fit to their results, we roughly estimate that combustion of diesel fuel for geoengineering could cause a -10 to -3% change in total ozone column due to NO$_x$ alone.

CO is by far the predominant emissions factor of carbon black manufacturing, although the CO emissions can be reduced by up to 99.8 percent by controlling with CO boilers, incinerators, or flares [EPA, 1995]. Without these controls, producing 1 Tg of carbon black would result in the emission of $1.4 \times 10^6$ kg of CO. Diesel combustion would result in a larger amount of $1.8 \times 10^9$ kg of CO. Carbon monoxide is naturally produced at a rate of $5 \times 10^{12}$ kg annually in the troposphere [Weinstock and Niki, 1972], so the additional
CO from producing this large amount of aerosols would be negligible. The stratosphere is a natural sink for carbon monoxide, due to reaction with the hydroxyl radical [Pressman and Warneck, 1970], so we anticipate this emissions factor would not cause any noticeable adverse effects.

Sulfur compounds resulting from diesel fuel combustion are due to sulfur content of the fuel. During the combustion process, nearly all of the sulfur is oxidized to SO$_2$, which is a precursor to sulfate aerosols [EPA, 1996]. Using the emissions factor given in Table 2, creating 1 Tg of black carbon aerosols would result in the production of approximately 0.57 Tg of SO$_2$, which would cause small climate effects but would still significantly impact the planetary radiation budget [Robock et al., 2008; Kravitz and Robock, 2011; Solomon et al., 2011]. It is an insufficient amount to produce damaging acid rain [Kravitz et al., 2009]. Since the reporting of the year 1996 emissions factors given in Table 2, ultra-low sulfur diesel has been introduced to the market and is the only readily available diesel fuel in the United States [EPA, 2009], so this emissions factor would likely be lower than the values reported here. The chemistry effects of this increase in SO$_x$ may not be trivial, especially when considering the effects on ozone. Simulations of 2 Tg a$^{-1}$ injections of S into the stratosphere showed a delay in the recovery of the ozone hole by approximately 30 years [Tilmes et al., 2009], suggesting the additional SO$_x$ from our diesel fuel combustion calculations has the potential to cause ozone destruction.

Methane is a powerful greenhouse gas, 23 times more effective than CO$_2$ on a 100-year time scale [IPCC, 2007]. From the emissions factor reported in Table 2, producing 1 Tg of carbon black would result in the production of $2.5 \times 10^4$ kg of methane, or
an increase in atmospheric concentrations by significantly less than 1 part per trillion.

Current concentrations of methane are on the order of 1 ppm [IPCC, 2007], so this is a
negligible contribution.

5. Discussion and Conclusions

A comparison of all of the discussed means of geoengineering, as well as the calculations
for SO$_2$ performed by Robock et al. [2009] are in Figure 1. Based on our calculations, if
black carbon aerosols were to be used for geoengineering, producing 1 Tg of aerosols via in
situ diesel combustion would be prohibitively expensive and potentially greater than the
cost of mitigation, which would actually directly address the problem of anthropogenic
climate change. Producing the aerosols on the ground and transporting them to the
stratosphere would be much cheaper.

This study does not address side effects of black carbon geoengineering. The climate
effects would likely be adverse and severe [Kravitz et al., 2011]. Moreover, diesel fuel,
black carbon aerosols, carbon black, and their respective byproducts of manufacture and
combustion are hazardous to human health [CDC, 1999; Baan et al., 2006]. This poses
a risk to all those in the employ of the geoengineering program, as well as those affected
by deposition of the particulate matter. In combustion of diesel fuel, a small portion of
the emissions (2-3%) are through the crankcase instead of the exhaust, which could pose
a hazard to the airplane pilots and the maintenance crews [EPA, 1996]. Despite these
unknowns and negative impacts, most emissions factors from black carbon geoengineering
would be negligible from a climate impact standpoint, although the chemical effects would
need to be evaluated.
The calculations presented here are one aspect of many that should be carefully evaluated. Geoengineering is a complex problem with multiple facets, all of which must be considered before society decides whether to geoengineer.

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Table 1. Fixed (one-time) and annual costs for geoengineering by combustion of diesel fuel for each considered combination of diesel engine, airplane, and daily shift number. Included in the annual costs are an estimate of fuel consumption with an at-the-pump price of US $3.00 per gallon, for a total of US $94.3 billion. Values reported are rounded to two significant digits.

<table>
<thead>
<tr>
<th>Engine/Airplane</th>
<th>2920 hours per year</th>
<th>$7600 hours per year</th>
</tr>
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<tbody>
<tr>
<td>3516B, KC-135</td>
<td>US $1.3 trillion</td>
<td>US $990 billion</td>
</tr>
<tr>
<td>3516B, KC-10</td>
<td>US $1.4 trillion</td>
<td>US $540 billion</td>
</tr>
<tr>
<td>3406C, KC-135</td>
<td>US $1.6 trillion</td>
<td>US $1.2 trillion</td>
</tr>
<tr>
<td>3406C, KC-10</td>
<td>US $1.8 trillion</td>
<td>US $650 billion</td>
</tr>
</tbody>
</table>

Table 2. Significant emissions factors for diesel fuel combustion and carbon black production. Emissions factors for diesel fuel are from EPA [1996, 2005] and for carbon black from EPA [1995]. All emissions factors are in total number of kg emitted for producing 1 Tg of black carbon aerosol (diesel fuel combustion) or carbon black. 95% of all carbon black is created by the furnace black process [Crump, 2000], so we use those emissions factors here. Only emissions factors which were deemed to be significant products are included.

<table>
<thead>
<tr>
<th>Emissions factor</th>
<th>Diesel fuel</th>
<th>Carbon black</th>
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<tbody>
<tr>
<td>CO₂</td>
<td>3.2 × 10¹¹</td>
<td></td>
</tr>
<tr>
<td>NOₓ</td>
<td>8.5 × 10⁹</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>1.8 × 10⁹</td>
<td>1.4 × 10⁶</td>
</tr>
<tr>
<td>organics (exhaust)</td>
<td>6.8 × 10⁸</td>
<td></td>
</tr>
<tr>
<td>organics (crankcase)</td>
<td>1.9 × 10⁷</td>
<td></td>
</tr>
<tr>
<td>PM-10</td>
<td>6.0 × 10⁸</td>
<td></td>
</tr>
<tr>
<td>SOₓ</td>
<td>5.7 × 10⁸</td>
<td></td>
</tr>
<tr>
<td>aldehydes</td>
<td>1.4 × 10⁸</td>
<td></td>
</tr>
<tr>
<td>H₂S</td>
<td>3 × 10⁴</td>
<td></td>
</tr>
<tr>
<td>CS₂</td>
<td>3 × 10⁴</td>
<td></td>
</tr>
<tr>
<td>OCS</td>
<td>1 × 10⁴</td>
<td></td>
</tr>
<tr>
<td>CH₄</td>
<td>2.5 × 10⁴</td>
<td></td>
</tr>
<tr>
<td>C₂H₂</td>
<td>4.5 × 10⁴</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Fixed and annual per-Tg costs of stratospheric geoengineering with black carbon aerosols. Sulfur gas calculations are repeated from Robock et al. [2009] and are included for comparison.