Nullius in Verba: Some Thoughts on the Royal Society 2009 Geoengineering Report Relating to Cloud Albedo

Stephen Salter, School of Engineering, University of Edinburgh EH9 3JL.

S.Salter@ed.ac.uk

Reports from The Royal Society of London have strong influence on politicians and funding bodies. In September 2009 they published a report entitled ‘Geoengineering the Climate: Science Governance and Uncertainty’ which compared the various options on slowing and reversing climate change including the idea for increasing cloud albedo proposed by John Latham for which I have been doing the design of engineering hardware.

The description of the cloud albedo approach starting at section 3.3.2 of the Royal Society report is accurate up to the final paragraph and tables 3.3, 3.4 and 3.6 which I have included in this note. This note discusses some later inaccuracies.

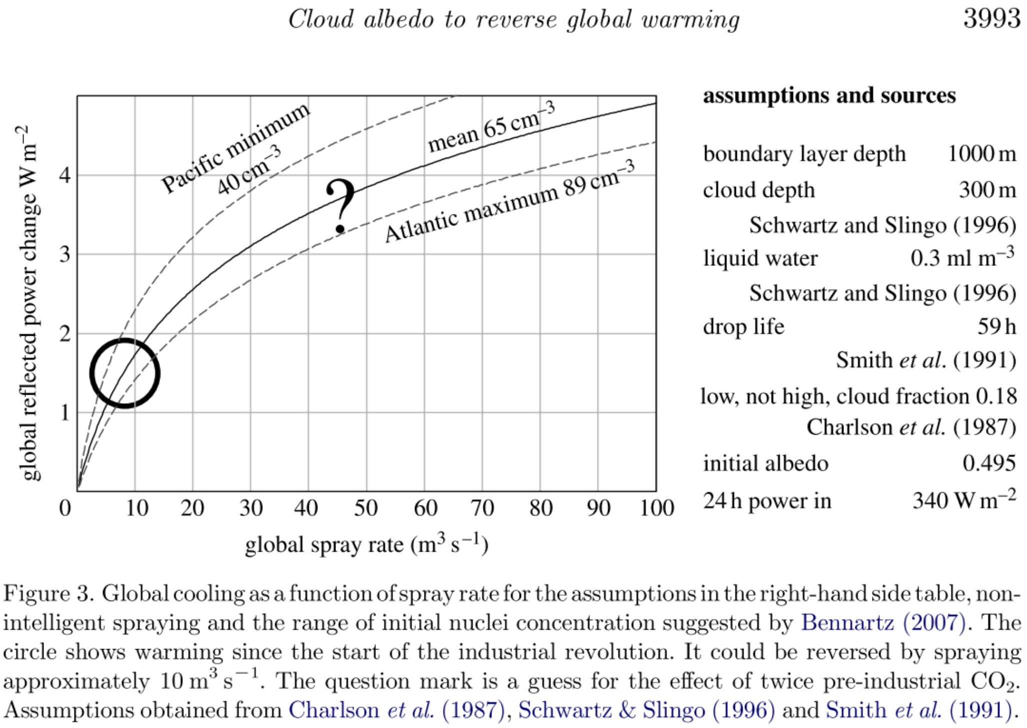
The Royal Society report was split into sections covering

- Effectiveness
- Affordability
- Timeliness
- Safety

Effectiveness

Table 3.3 of the Royal Society report gives cloud albedo **Low** to **Medium** for effectiveness but table 3.4 gives stratospheric sulphur a **High**.

Figure 3 of our Phil. Trans. Roy. Soc. Seagoing Hardware 2008 paper, see below, shows our estimate of cooling against spray rate. It is based on the Schwartz and Slingo 1996 interpretation of Twomey's results. Assumptions are given in the column to the right of the figure. Although I invited suggestions for other assumptions the only challenge to date has been from Kohonen and Carslaw who wanted to use very much higher values for initial CCN concentration despite NASA observations, see the comparison on the final page of this note.



Cloud albedo to reverse global warming 3993

assumptions and sources

boundary layer depth	1000 m
cloud depth	300 m
Schwartz and Slingo (1996)	
liquid water	0.3 ml m^{-3}
Schwartz and Slingo (1996)	
drop life	59 h
Smith *et al.* (1991)	
low, not high, cloud fraction	0.18
Charlson *et al.* (1987)	
initial albedo	0.495
24 h power in	340 W m^{-2}

Figure 3. Global cooling as a function of spray rate for the assumptions in the right-hand side table, non-intelligent spraying and the range of initial nuclei concentration suggested by Bennartz (2007). The circle shows warming since the start of the industrial revolution. It could be reversed by spraying approximately 10 m^3 s^{-1}. The question mark is a guess for the effect of twice pre-industrial CO_2. Assumptions obtained from Charlson *et al.* (1987), Schwartz & Slingo (1996) and Smith *et al.* (1991).

Even though the logarithmic response of the Twomey effect means that returns are diminishing at the higher cooling rates, we are still able to cool more than required for offsetting the thermal effects of double preindustrial CO2. Although we prefer gentle treatment of a wide area Jones Haywood and Boucher show that we can offset 1 watt per square metre by spraying only the most susceptible 3.3% of the oceans. This has been confirmed by several independent climate models. How does this square with '**Low** to **Medium**' for Effectiveness?

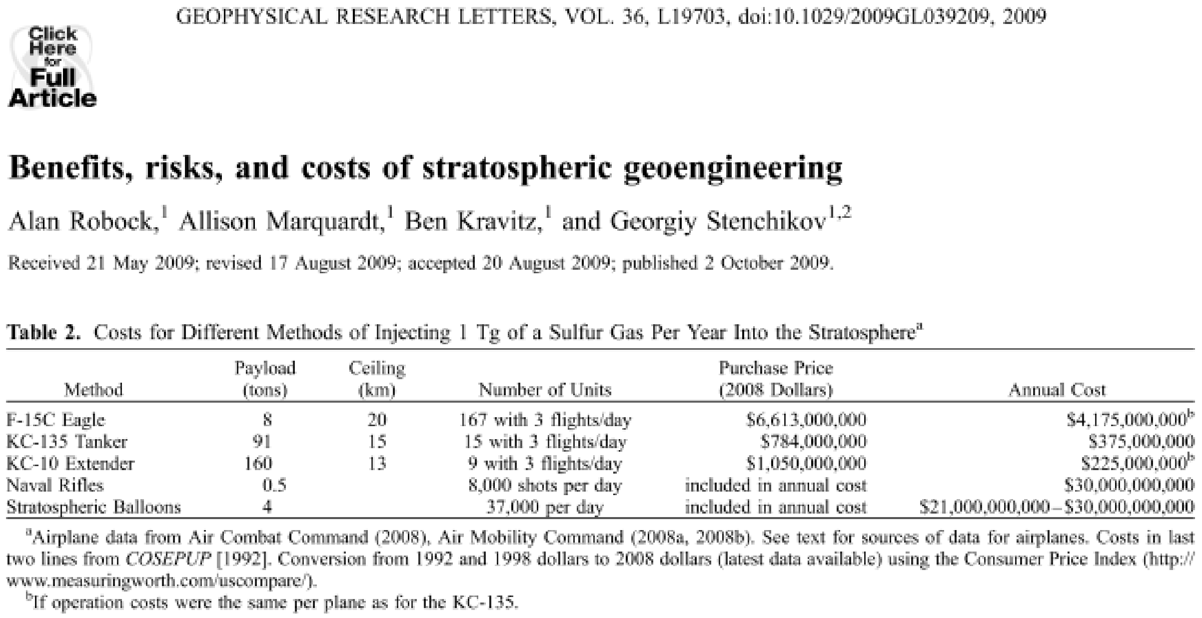
Affordability

Table 3.3 of the Royal Society report gives cloud albedo a **Medium** for affordability but 3.4 gives stratospheric sulphur a **High**.

The 1 watt per square metre of cooling used for table 3.6 could be achieved with a world spray rate of 5 cubic metres a second. The 2008 reference design for a spray vessel was 30 kg a second so we would need only 170 of them in action. Some will be in dock and some in the wrong places but a fleet of 250 ought to be sufficient. We have firm estimates for downhole pumps, Seaguard filters and silicon wafers which amount to £90,000 per vessel. At £4000 per tonne for small ships and £1500 per kW for typical industrial plant, a total cost of £2 million per wind-driven unmanned vessel in steady production looks reasonable. The fleet would cost £500 million. Most ships last 25 years so, allowing a 7% annual charge for capital repayment, the cost of fleet ownership for 250 vessels to achieve 1 watt per square metre of cooling would be £35 million a year, less than the $200 million suggested by the Royal Society in their table 3.6 and less than the cost of world climate conferences and the transfer fees of leading football players.

I am reluctant to comment on technical details of the stratospheric sulphur cooling method but I did check the Robock et al. reference which the Royal Society report uses for its costing of aircraft for dispersing stratospheric aerosols. Robock et al. give the 2008 capital cost of the standard KC-10 Extender as $1.05 billion for each of the 9 that Robock thinks would be needed for three flights each a day. In note (e) of table 3.6 the Royal Society uses the figure of only $200 million a year which Robock et al. give separately in their table 2 column 6 (below) for ‘personnel, fuel, maintenance, modifications and spares’ see top right paragraph of Robock et al. page L19703. This appears to mean that the Royal Society assumes that capital repayment costs for aircraft modified for sulphur spraying are zero.

From



GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L19703, doi:10.1029/2009GL039209, 2009

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Benefits, risks, and costs of stratospheric geoengineering

Alan Robock,[1] Allison Marquardt,[1] Ben Kravitz,[1] and Georgiy Stenchikov[1,2]

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Table 2. Costs for Different Methods of Injecting 1 Tg of a Sulfur Gas Per Year Into the Stratosphere[a]

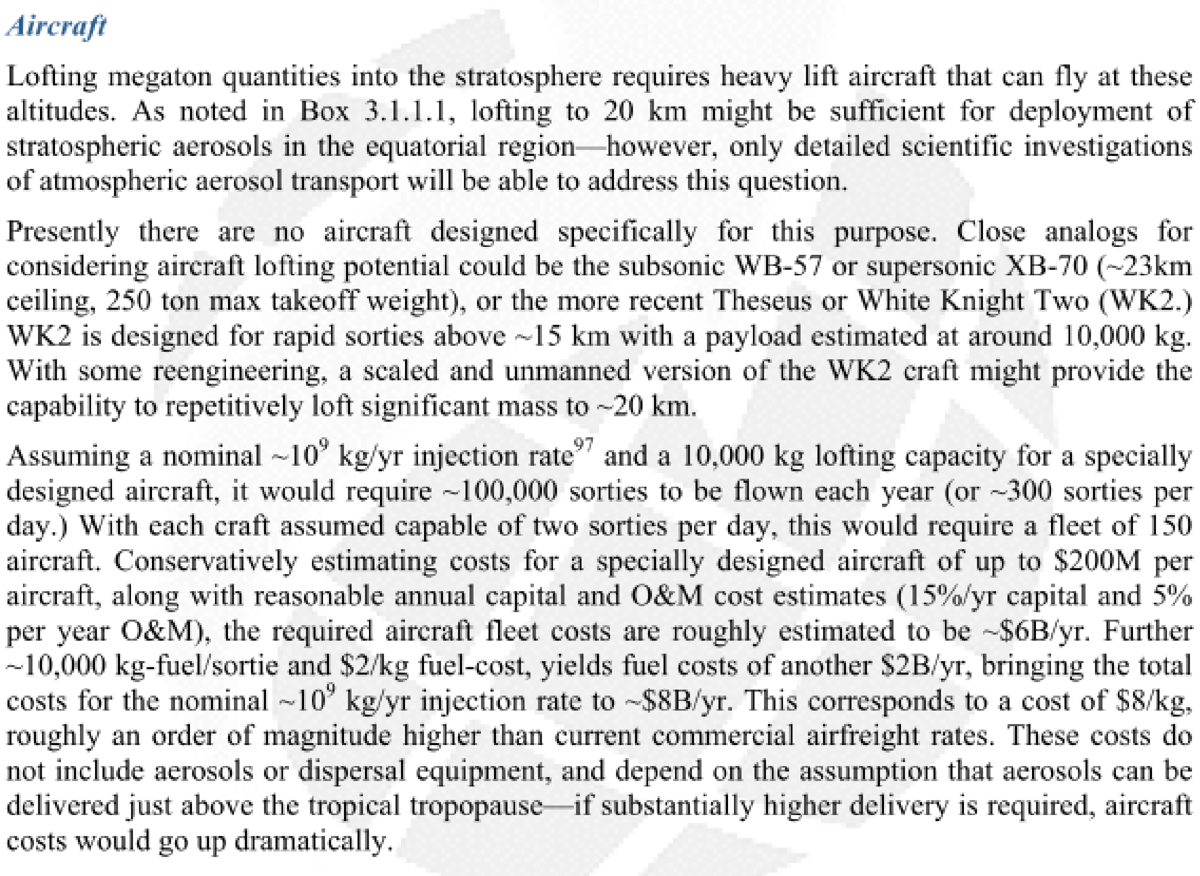
Method	Payload (tons)	Ceiling (km)	Number of Units	Purchase Price (2008 Dollars)	Annual Cost
F-15C Eagle	8	20	167 with 3 flights/day	$6,613,000,000	$4,175,000,000[b]
KC-135 Tanker	91	15	15 with 3 flights/day	$784,000,000	$375,000,000
KC-10 Extender	160	13	9 with 3 flights/day	$1,050,000,000	$225,000,000[b]
Naval Rifles	0.5		8,000 shots per day	included in annual cost	$30,000,000,000
Stratospheric Balloons	4		37,000 per day	included in annual cost	$21,000,000,000–$30,000,000,000

[a] Airplane data from Air Combat Command (2008), Air Mobility Command (2008a, 2008b). See text for sources of data for airplanes. Costs in last two lines from *COSEPUP* [1992]. Conversion from 1992 and 1998 dollars to 2008 dollars (latest data available) using the Consumer Price Index (http://www.measuringworth.com/uscompare/).

[b] If operation costs were the same per plane as for the KC-135.

Another study of the cost of stratospheric sulphur was published by Blackstock et al. in a Novim report in July 2009, before the Royal Society Report in September. Two authors, Caldeira and Keith, were common to both documents. The Novim report page 46 (below) gives a cost of $8 billion a year for aircraft for the one million tonne injection rate needed for a cooling of 1 watt per square metre. A Hadley Centre report mentioned later suggested the 5 million tonnes is needed.

From Blackstock et al July 2009:



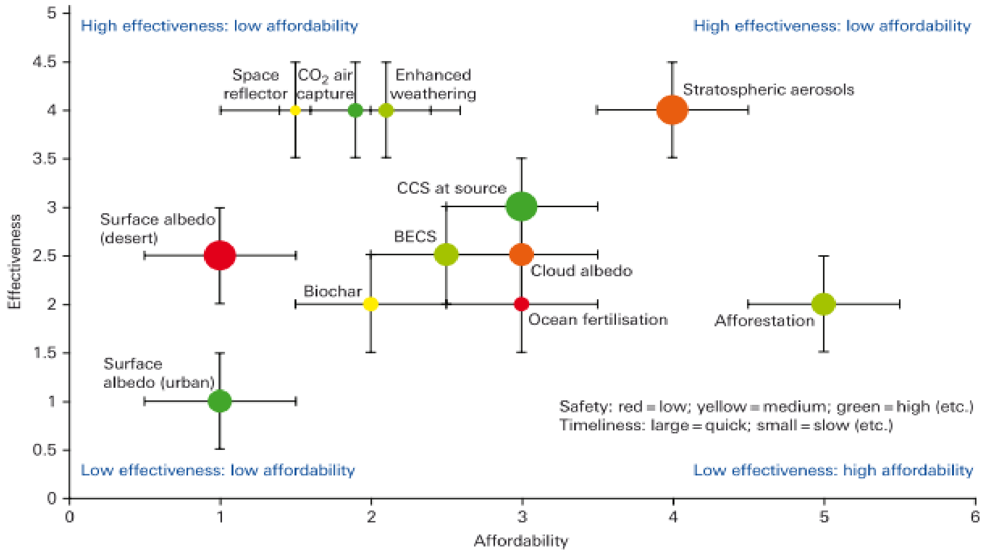
Aircraft

Lofting megaton quantities into the stratosphere requires heavy lift aircraft that can fly at these altitudes. As noted in Box 3.1.1.1, lofting to 20 km might be sufficient for deployment of stratospheric aerosols in the equatorial region—however, only detailed scientific investigations of atmospheric aerosol transport will be able to address this question.

Presently there are no aircraft designed specifically for this purpose. Close analogs for considering aircraft lofting potential could be the subsonic WB-57 or supersonic XB-70 (~23km ceiling, 250 ton max takeoff weight), or the more recent Theseus or White Knight Two (WK2.) WK2 is designed for rapid sorties above ~15 km with a payload estimated at around 10,000 kg. With some reengineering, a scaled and unmanned version of the WK2 craft might provide the capability to repetitively loft significant mass to ~20 km.

Assuming a nominal ~10^9 kg/yr injection rate[97] and a 10,000 kg lofting capacity for a specially designed aircraft, it would require ~100,000 sorties to be flown each year (or ~300 sorties per day.) With each craft assumed capable of two sorties per day, this would require a fleet of 150 aircraft. Conservatively estimating costs for a specially designed aircraft of up to $200M per aircraft, along with reasonable annual capital and O&M cost estimates (15%/yr capital and 5% per year O&M), the required aircraft fleet costs are roughly estimated to be ~$6B/yr. Further ~10,000 kg-fuel/sortie and $2/kg fuel-cost, yields fuel costs of another $2B/yr, bringing the total costs for the nominal ~10^9 kg/yr injection rate to ~$8B/yr. This corresponds to a cost of $8/kg, roughly an order of magnitude higher than current commercial airfreight rates. These costs do not include aerosols or dispersal equipment, and depend on the assumption that aerosols can be delivered just above the tropical tropopause—if substantially higher delivery is required, aircraft costs would go up dramatically.

The difference between an annual cost of $8 billion and one of £35 million does seem large. And yet stratospheric sulphur gets a **High** for affordability while cloud albedo gets a **Medium**. It could be argued that the costs of both techniques are so small in comparison to Stern’s estimates of the cost of uncontrolled climate change that the costs are irrelevant. But why then give it a major axis in the Royal Society graph figure 5.1 shown below? (The caption at the top right must be a misprint).



The summary table of the Royal Society report is below:

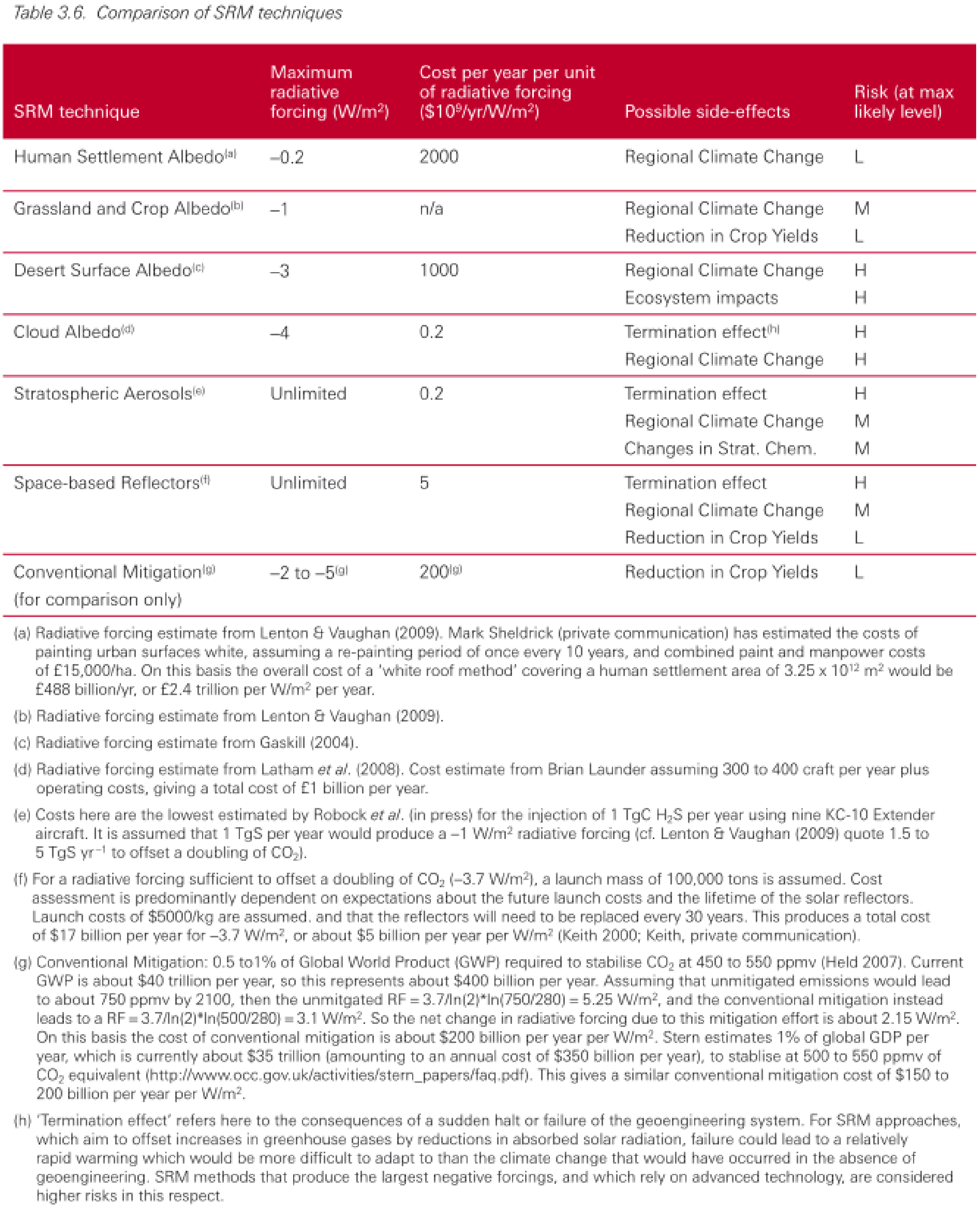


Table 3.6. Comparison of SRM techniques

SRM technique	Maximum radiative forcing (W/m^2)	Cost per year per unit of radiative forcing (\$$10^9$/yr/W/m^2)	Possible side-effects	Risk (at max likely level)
Human Settlement Albedo[a]	–0.2	2000	Regional Climate Change	L
Grassland and Crop Albedo[b]	–1	n/a	Regional Climate Change Reduction in Crop Yields	M L
Desert Surface Albedo[c]	–3	1000	Regional Climate Change Ecosystem impacts	H H
Cloud Albedo[d]	–4	0.2	Termination effect[h] Regional Climate Change	H H
Stratospheric Aerosols[e]	Unlimited	0.2	Termination effect Regional Climate Change Changes in Strat. Chem.	H M M
Space-based Reflectors[f]	Unlimited	5	Termination effect Regional Climate Change Reduction in Crop Yields	H M L
Conventional Mitigation[g] (for comparison only)	–2 to –5[g]	200[g]	Reduction in Crop Yields	L

(a) Radiative forcing estimate from Lenton & Vaughan (2009). Mark Sheldrick (private communication) has estimated the costs of painting urban surfaces white, assuming a re-painting period of once every 10 years, and combined paint and manpower costs of £15,000/ha. On this basis the overall cost of a 'white roof method' covering a human settlement area of 3.25 x 10^{12} m^2 would be £488 billion/yr, or £2.4 trillion per W/m^2 per year.

(b) Radiative forcing estimate from Lenton & Vaughan (2009).

(c) Radiative forcing estimate from Gaskill (2004).

(d) Radiative forcing estimate from Latham *et al.* (2008). Cost estimate from Brian Launder assuming 300 to 400 craft per year plus operating costs, giving a total cost of £1 billion per year.

(e) Costs here are the lowest estimated by Robock *et al.* (in press) for the injection of 1 TgC H_2S per year using nine KC-10 Extender aircraft. It is assumed that 1 TgS per year would produce a –1 W/m^2 radiative forcing (cf. Lenton & Vaughan (2009) quote 1.5 to 5 TgS yr^{-1} to offset a doubling of CO_2).

(f) For a radiative forcing sufficient to offset a doubling of CO_2 (–3.7 W/m^2), a launch mass of 100,000 tons is assumed. Cost assessment is predominantly dependent on expectations about the future launch costs and the lifetime of the solar reflectors. Launch costs of \$5000/kg are assumed. and that the reflectors will need to be replaced every 30 years. This produces a total cost of \$17 billion per year for –3.7 W/m^2, or about \$5 billion per year per W/m^2 (Keith 2000; Keith, private communication).

(g) Conventional Mitigation: 0.5 to1% of Global World Product (GWP) required to stabilise CO_2 at 450 to 550 ppmv (Held 2007). Current GWP is about \$40 trillion per year, so this represents about \$400 billion per year. Assuming that unmitigated emissions would lead to about 750 ppmv by 2100, then the unmitgated RF = 3.7/ln(2)*ln(750/280) = 5.25 W/m^2, and the conventional mitigation instead leads to a RF = 3.7/ln(2)*ln(500/280) = 3.1 W/m^2. So the net change in radiative forcing due to this mitigation effort is about 2.15 W/m^2. On this basis the cost of conventional mitigation is about \$200 billion per year per W/m^2. Stern estimates 1% of global GDP per year, which is currently about \$35 trillion (amounting to an annual cost of \$350 billion per year), to stablise at 500 to 550 ppmv of CO_2 equivalent (http://www.occ.gov.uk/activities/stern_papers/faq.pdf). This gives a similar conventional mitigation cost of \$150 to 200 billion per year per W/m^2.

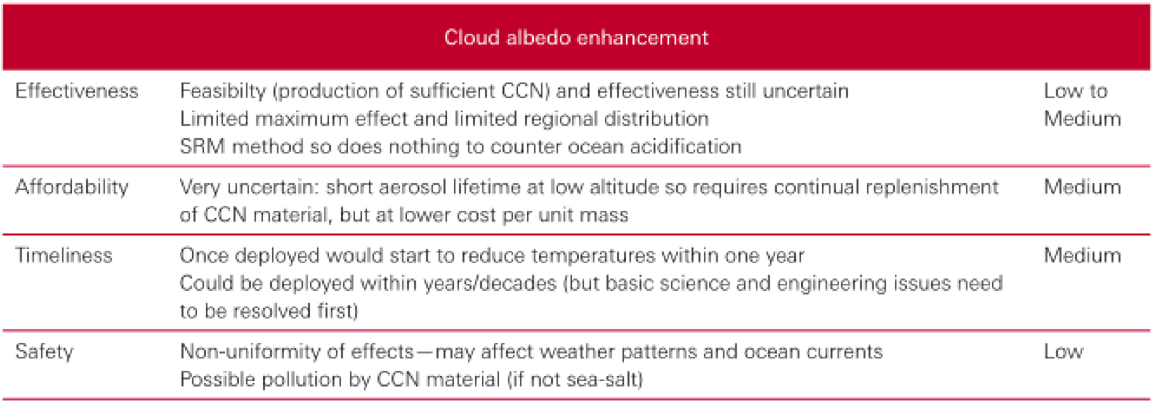
(h) 'Termination effect' refers here to the consequences of a sudden halt or failure of the geoengineering system. For SRM approaches, which aim to offset increases in greenhouse gases by reductions in absorbed solar radiation, failure could lead to a relatively rapid warming which would be more difficult to adapt to than the climate change that would have occurred in the absence of geoengineering. SRM methods that produce the largest negative forcings, and which rely on advanced technology, are considered higher risks in this respect.

Notes (d) and (e) are in dispute. The absence of a termination effect implies 'no going back'.

Timeliness

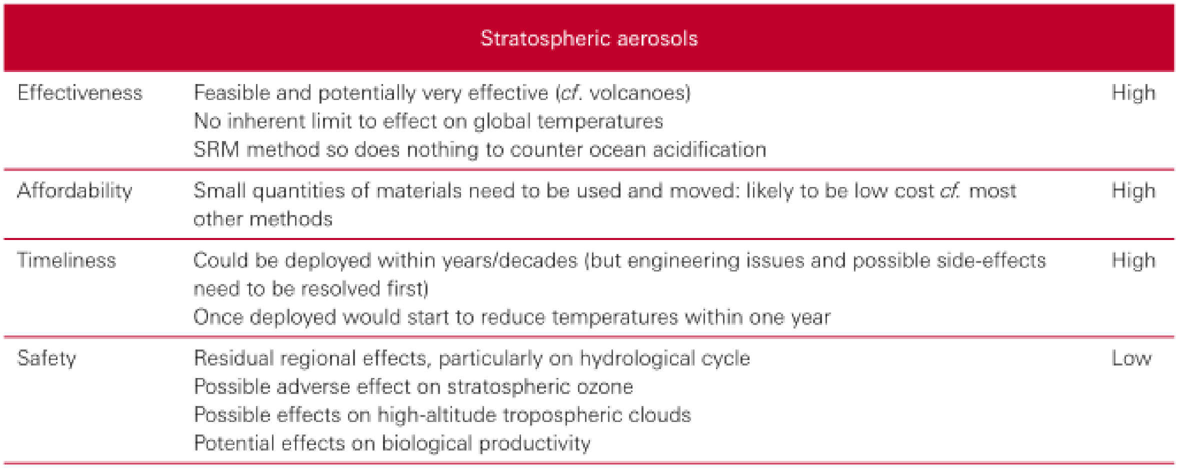
The wording about timeliness for cloud albedo in table 3.3 is almost identical to that for stratospheric sulphur in 3.4, see below. But stratospheric sulphur gets a **High** while cloud albedo gets a **Medium**.

Table 3.3. Summary evaluation table for cloud albedo enhancement methods



Cloud albedo enhancement		
Effectiveness	Feasibilty (production of sufficient CCN) and effectiveness still uncertain Limited maximum effect and limited regional distribution SRM method so does nothing to counter ocean acidification	Low to Medium
Affordability	Very uncertain: short aerosol lifetime at low altitude so requires continual replenishment of CCN material, but at lower cost per unit mass	Medium
Timeliness	Once deployed would start to reduce temperatures within one year Could be deployed within years/decades (but basic science and engineering issues need to be resolved first)	Medium
Safety	Non-uniformity of effects—may affect weather patterns and ocean currents Possible pollution by CCN material (if not sea-salt)	Low

Table 3.4. Summary evaluation table for stratospheric aerosol methods



Stratospheric aerosols		
Effectiveness	Feasible and potentially very effective (*cf.* volcanoes) No inherent limit to effect on global temperatures SRM method so does nothing to counter ocean acidification	High
Affordability	Small quantities of materials need to be used and moved: likely to be low cost *cf.* most other methods	High
Timeliness	Could be deployed within years/decades (but engineering issues and possible side-effects need to be resolved first) Once deployed would start to reduce temperatures within one year	High
Safety	Residual regional effects, particularly on hydrological cycle Possible adverse effect on stratospheric ozone Possible effects on high-altitude tropospheric clouds Potential effects on biological productivity	Low

The engineering design of spray vessels is well advanced to the point where little more can be done without laboratory work to test design assumptions. Most of the general assembly drawings of the full vessel and the more difficult sub-assemblies were complete in 2009. I took a set to the Royal Society Geoengineering meeting and asked for permission to display them. This was refused because drawings for other technologies were not available. I have no knowledge of progress on the design modification of aircraft or balloon spray mechanisms for stratospheric sulphur.

Safety

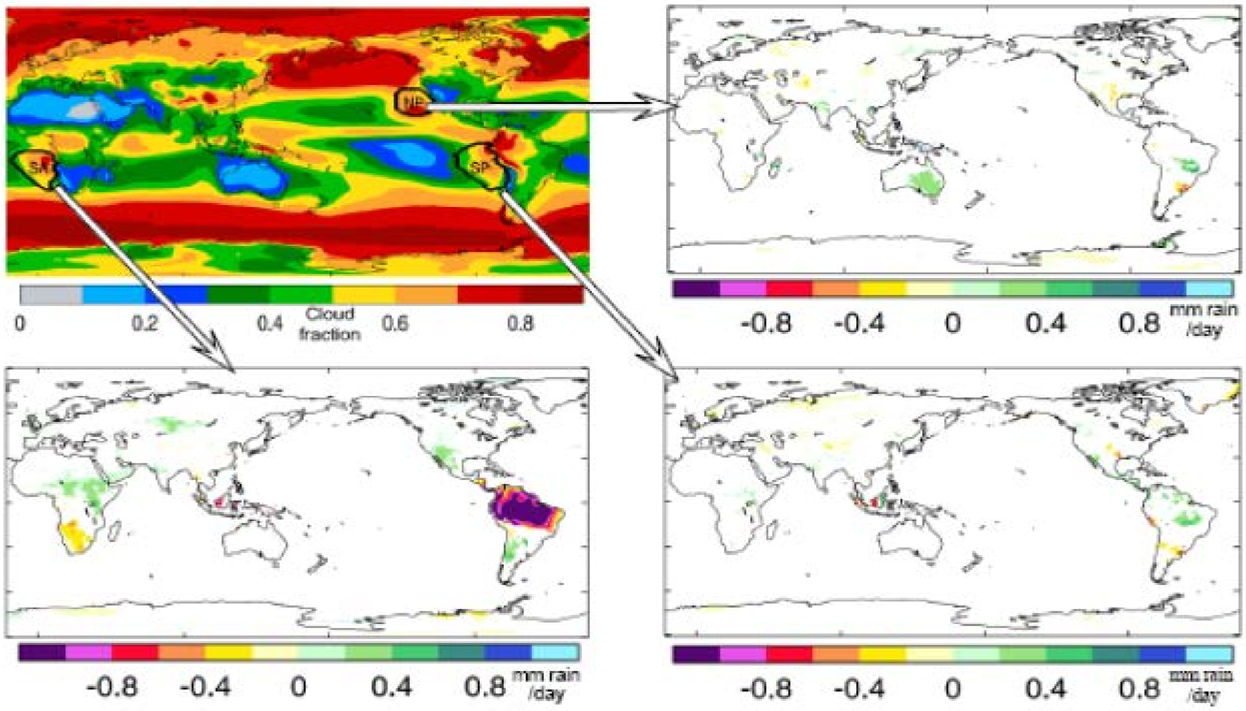
Tables 3.3 and 3.4 of the Royal Society report gives both methods a **Low** for safety. The release of millions of tonnes of sulphuric acid in the stratosphere is much less than the amount released from coal generation and is therefore a public relations matter rather than a safety problem. I would argue similarly that cloud albedo adds a small increase (about 1%) to the present transfer of salt from sea to air even if we had to offset double preindustrial CO2. Most of our salt will fall back into the sea before the treated air masses reach land. The only difference between the sprays is that we pick the best diameter to trigger nucleation of drops while the natural salt transfer has a very wide range of drop sizes. The smallest are too small for nucleation and the larger ones fall too fast or work in the wrong direction. We (and many Victorian doctors) know that our salt nuclei are good for asthma and general lung diseases. Computer models show that if spraying stops there is a rapid return to the conditions that would have existed with no spraying. This is presented as an undesirable ‘termination effect’ in note (h.) of the Royal Society table 3.6 shown above. In fact rapid reversibility is a highly desirable feature. The simultaneous failure of hundreds of spray vessels dispersed world wide has a vanishingly low probability. Spray can be slowed with reduced carbon emissions or if we need to avert the next ice age.

The potentially dangerous features of stratospheric sulphur are

- The two-year half life means we cannot turn it off rapidly following another Pinatubo.
- We have little local tactical control.
- It is difficult to detect the effects of very small-scale tests.
- There may be a reduction of stratospheric ozone which is needed for UV protection.
- One high resolution climate model, discussed later, shows a general reduction but temperature *increases* in the Arctic Ocean.

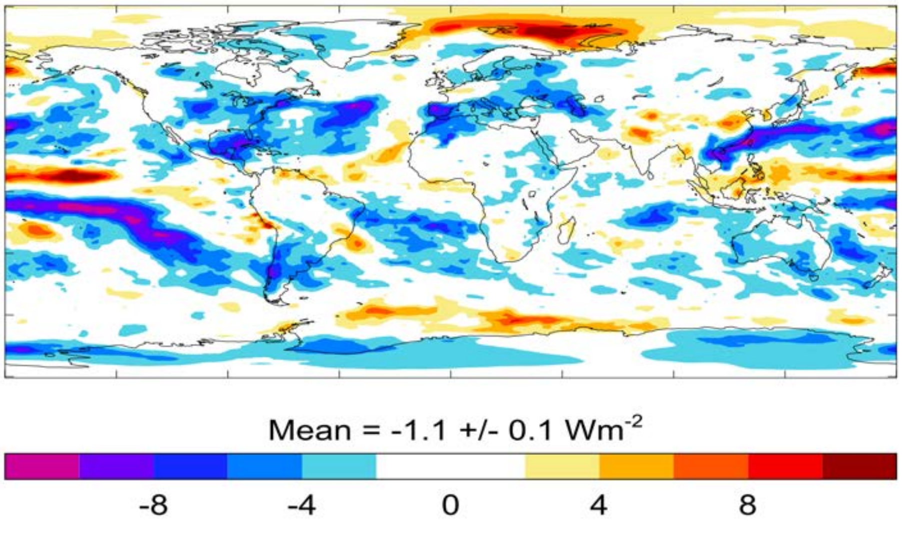
Control engineers like systems with high-frequency error-sensing and fast correcting mechanisms. They fear multiple phase shifts which can lead to oscillations. They also know that small amounts of a damping force in phase with velocity can have large effects on the growth and decay of the amplitude of oscillating systems. Satellites can give frequent measurements of sea-surface temperatures. We know that these are strong drivers of weather and climate. Steering sea surface temperatures to values we know were historically desirable should be good. We can change spray rates within minutes and move spray vessels in days or weeks. We can choose times and places much faster than the response system of the climate, so although the laws of thermodynamics mean that eventually results will diffuse through the world, we have full control of where and when the initial correction takes place. The suggestion that in some places extra CCN concentration can work in the opposite direction to produce warming (presented as a flaw in the proposal on page 28) is excellent news, allowing corrections in both directions if we know when and where these places are.

The most obvious concern is about precipitation. Climate change with no geo-engineering is already producing extremes of flood in Pakistan and Queensland with droughts in South Australia and the Horn of Africa. From the first results of Jones, Hayward and Boucher of the Hadley Centre on spray from a very small fraction of the oceans we know that albedo control can both increase and reduce precipitation far from the spray source. Steady spray from California (NP) can nearly double rainfall in South Australia while spray off Namibia (SA) gives a 15% reduction over the Amazon along with a useful increase in the Horn of Africa, see lower-left image. Brazilians watching recent television footage of dying children in Kenya camps would be glad to have their rainfall reduced to 2000 mm a year when necessary. Lyon and DeWitt (2012) have linked the reduction of rain in East Africa to a rise in sea-surface temperature in the Pacific

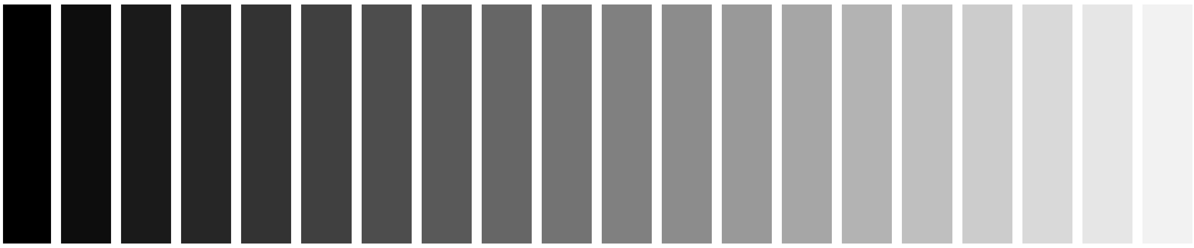


Jones et al. did not test other source positions, spray rates or seasonal variations relative to the monsoons. Ongoing work by Gadian and Parkes at Leeds using the pseudo-random modulation of the nuclei concentration of 89 spray sources round all the oceans shows that, as well as the two Pacific spray sources used by Jones et al., there are many other spray sources which will both increase and reduce precipitation in the Amazon. The technique can produce an everywhere-to-everywhere climate transfer function and so let us steer towards beneficial precipitation and temperature patterns if only we can agree what these are.

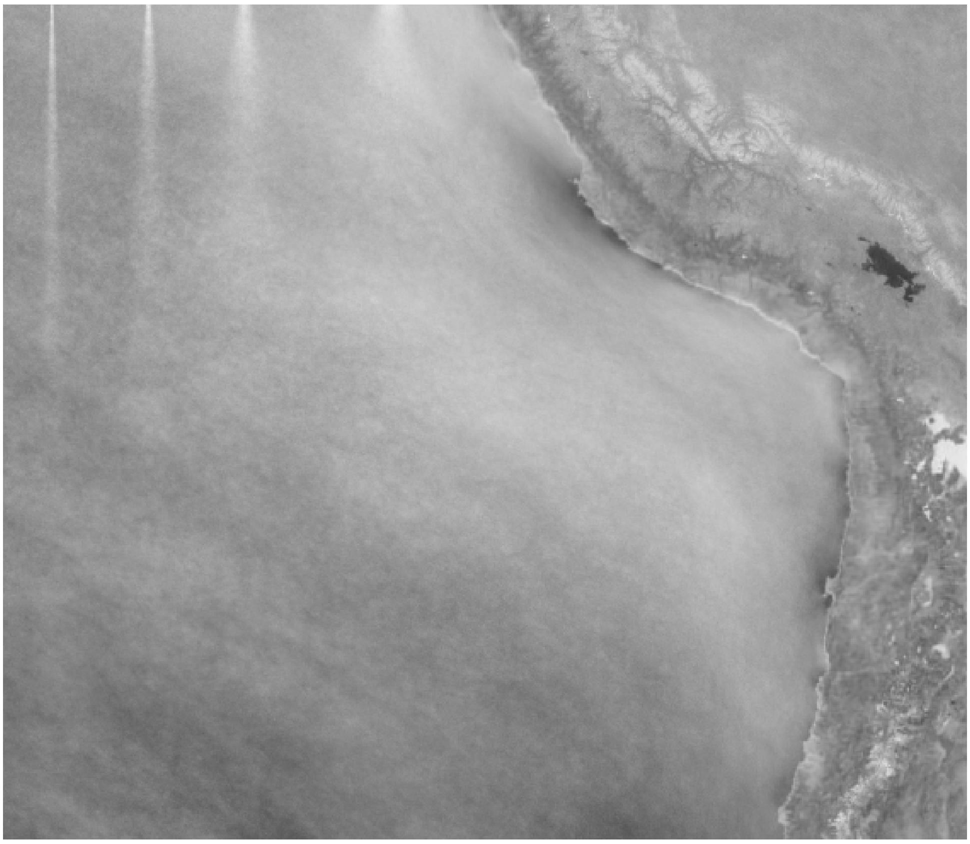
In figure 2 of a later paper Jones et al. produced results for the effect of stratospheric sulphur shown below. The injection of 5 megatonnes a year gave a mean overall reduction of 1.1 watts per square metre in short-wave radiation but a local large and unwelcome increase of 6 to 10 watts per square metre in the Arctic Ocean. This would have serious effect on methane release from the sea bed and permafrost. This is shown in results from some but not all models but HadGEM2 has a particularly high resolution. The reason might be that in summer high altitude aerosol is deflecting sideways energy that might have missed the earth. John Egil Kristjansson has shown that in winter cloud will send back energy that might have radiated out to cold space. Reflecting aerosol cannot tell up from down. The short life of tropospheric sea salt means that Arctic warming can be avoided.



Small scale tests are a desirable safety feature. It is useful to calculate the smallest geo-engineering perturbation that could be detected. The 20-bar grey-scale below shows that change of cloud contrast needed to reverse the thermal effect of double preindustrial CO2 is well below the detection threshold, 15 to 20%, of the human eye.



The mathematical addition of the contrast change downwind of one spray vessel is not detectable in a single satellite image. But if we know the position of a spray source and the wind directions to leeward we can align, rotate and add multiple satellite images to make the spray wakes appear in an averaged cloud field as shown below.



The ability to use tactical local spray with fast corrections and this image superposition technique to study the results of very small quantities and the rapid removal of anything which produces unwanted results should allow cloud albedo control to claim a **High** in the safety category.

The only challenge to the assumptions of cooling to spray rate so far is from Kohonen and Carslaw who say that much higher spray rates are needed. Their numbers for nuclei concentration are higher than NASA MODIS data shown below and may have been based on near-shore conditions.

Korhonen H, Carslaw KS,
Romakkaniemie S.

Atmos. Chem. & Phys. 15 Jan. 2010

	CDNC (cm^{-3})
North Pacific	171
South Pacific	133
South Atlantic	177
Indian Ocean	134

Cloud droplet concentration for warm clouds over the global oceans estimated using MODIS

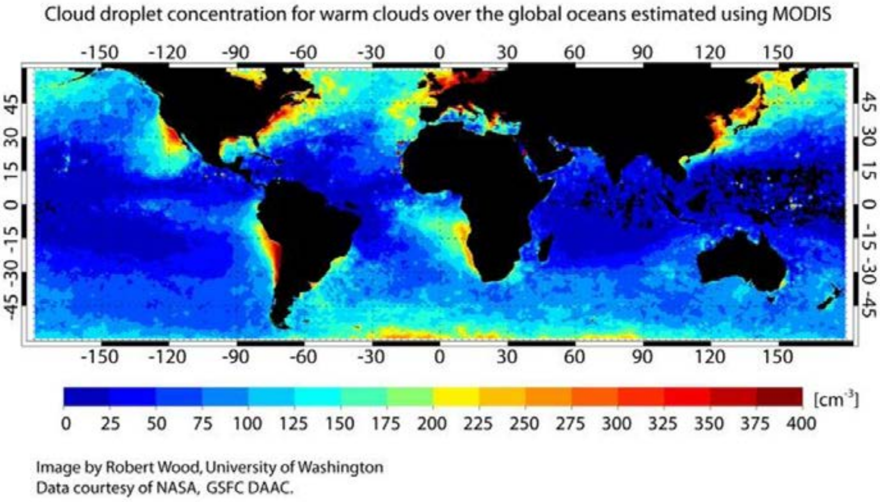


Image by Robert Wood, University of Washington
Data courtesy of NASA, GSFC DAAC.

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Also available from www.see.ed.ac.uk/~shs by browsing to

/Climate change/Pseudo random explanation
/Climate change/Field trial simulation
/Climate change/DEFRA Collection
/Climate change/Data sources/Twomey 1977