Peter Davidson explains how using balloons to lift and disperse stratospheric aerosols that scatter the sun's light back into space could work as a 'plan B' for climate remediation

Up and away!

ATMOSPHERIC carbon dioxide levels are higher than they have been in the last 400,000 years (see Figure 1a), as a result of mankind producing CO_2 at an ever increasing rate. Predicting the impact of these levels of CO_2 is a massive task, but there is a broad consensus amongst climate scientists that we have embarked on a large planetary experiment which will have dire consequences if we do not reduce CO_2 emissions.

Current models are predicting more-severe, more-frequent droughts, hurricanes and tornadoes, and rising sea levels inundating some low-lying lands.

There's also a (somewhat contentious) possibility that the climate system may 'flip' from one stable state to another – for example the collapse of Arctic Sea ice or a massive release of methane from permafrost.

Simulations based on carbon balance and assumptions of human production of CO_2 suggest that we'll have to live with a world stressed with high levels of CO_2 for at least 50–100 years (see Figure 1b).

Such analyses have encouraged researchers to think about an 'insurance policy' – a 'plan B.' This isn't intended to replace efforts to reduce greenhouse gas emissions, but to have in reserve, to be switched on quickly if matters go badly wrong. CO_2 removal (CDR) though worth researching, would be too slow to make an impact this century.

The only contender may be solar radiation management (SRM), scattering the sun's light back to space by means such as:

- seeding more clouds above the oceans where nuclei to form clouds are lacking; or
- lofting particles into the stratosphere, where they could remain for 1–2 years.

The first approach, although worth exploring, risks altering global precipitation patterns. This article focuses on the second strategy.

mimicking volcanoes

Paul Crutzen (the 1995 Nobel laureate for chemistry related to CFC/ozone depletion) gave credibility to the second strategy by suggesting that we need to investigate putting an artificial sulphuric acid aerosol into the stratosphere to cool the planet – mimicking the effect of large volcanic eruptions near the equator. These occur several times a century and provide global cooling of up to 1°C for a few years. For example, in 1991 Mount Pinatubo in the Philippines threw 20m t of SO_2 into the stratosphere, which via hydrolysis and oxidation, resulted in a

The Pinatubo aerosol cloud caused mean global temperatures to drop by ~0.5°C for two years.

Artist's impression of a NASA superpressure balloon (at ~30 km altitude); they are regularly launched for earth observation and astronomy.

sulphuric acid aerosol. Reaction rates are low in the dry, cold stratosphere (<5 ppm H_20, -50°C); the sulphuric acid aerosol took several weeks to form and consisted of particles of around 1 µm effective diameter.

Light is best scattered by particles having a circumference comparable to the wavelength of the incoming light and a high refractive index. This size, fortuitously, allows residence in the stratosphere for a couple of years (see Figure 2).

While particle sizes after the Pinatubo eruption were possibly larger than optimum (solar illumination is greatest at 0.5 µm wavelength or green light), its aerosol cloud spread over the globe in the stratosphere within 3–6 months, driven by natural circulation, and caused mean global temperatures to drop by ~0.5°C for two years. This matched scattering simulations well.

So far so good; if you could get enough SO_2 up into the stratosphere (any lower and it gets washed out quickly), you could, in theory, lower the temperature and precipitation impacts of global climate change. Unfortunately, there are at least four significant technical issues with this:

- a risk of reducing ozone concentrations in the stratosphere, and hence our planet's defence against UV light. Sulphuric acid aerosols can promote ozone destruction. After Pinatubo, mean global ozone concentrations fell by around 2–3% over two years;
- sulphuric acid aerosols absorb light as well as scattering it. This absorption heats the upper atmosphere, changing circulation patterns in the stratosphere, and between the troposphere and stratosphere, altering regional weather patterns. The South-East Asian monsoon may have been weaker in the two years following the Pinatubo eruption; and there's also some evidence that precipitation south of the Sahara was lowered;
- lofting the quantities of SO_2 needed (up to 10m t/y) to the stratosphere (above 20 km) is difficult: only very advanced aircraft of limited capacity can fly that high; other means considered prior to this work look to be at least as expensive;
- it's hard to envisage meaningful small-scale field trials. After injection of an aerosol precursor (SO_2 or H_2S), it takes 2–4 weeks to generate sulphuric acid aerosols. With horizontal wind speeds of ~20 m/s, the precursor will have travelled around the planet before it has had time to form an aerosol. Background variability will mask differences unless the injected amounts have a measurable effect on the whole planet.

from SO_2 to TiO_2

The obvious question is could we use a more benign particle than sulphuric acid, with a higher refractive index, with a better way of lifting and dispersing it into the stratosphere? Following work carried out (and subsequent patent application[1]) at Davidson Technology, the answer is, possibly yes.

Titanium dioxide (TiO_2) is one of the most commonly-used pigments: it has the highest refractive index (~2.5) of any known material that is stable in air and non-toxic, which compares well with that of stratospheric sulphuric acid aerosols (~1.5). It's around seven times more effective at backscattering light than sulphuric acid (see Figure 3). It is one of the commonest elements in the earth's crust, so there's no problem with its supply: global production is ~5m t/y of sub-micron TiO_2 particles. Well-established coating technologies provide nanometer-thick organic and inorganic coatings. TiO_2 particles are used wherever light scattering is needed: in paints, plastics, inks, fabrics, UV screens, on skin to protect against sunburn, and even in foods.

To minimise ozone destruction a TiO_2, or other manufactured particle surface has the potential to be tailored, as is already done for many industrial applications. The effect of different surfaces is being researched in the UK at Cambridge University[2]. It may be that a suitable organic hydrophobic surface will reduce the rates of two of the key reactions in the stratosphere:

$N_2O_5 + H_2O \rightarrow 2HNO_3$ and

$HCl + ClONO_2 \rightarrow Cl_2(g) + HNO_3$

Or a suitable inorganic coating could minimise the less significant direct reaction:

$2O_3 \rightarrow 3O_2$.

Such coatings would need to be stable for several years under the harsh UV illumination in the stratosphere. Hydrophobicity may also help to avoid ice nucleation on the TiO_2 particles.

novel lofting technologies

Conveying bulk materials by pumping (rather than conveying in discrete packages) provides energy savings. To deliver material to the stratosphere, the concept of a pipe supported by a balloon (at 20+ km) has already been considered by Nathan Myhrvold.

Figure 1a: CO_2 levels (ppm)

CO_2 levels from ice core data (blue) and atmospheric measurements (red). Only in the last 50 years have levels exceeded 300 ppm.

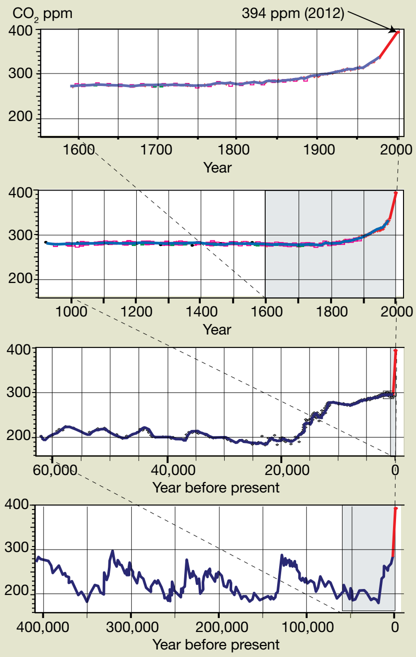


Figure 1b: Forecasts of human CO_2 production

Both models assume CO_2 production increases at current rates (2.3% annually), until 2040, when rates fall at 6% annually (dashed lines), or 2.3% annually (continuous lines). CO_2 levels are over twice preindustrial levels for 50–100 years (blue lines).

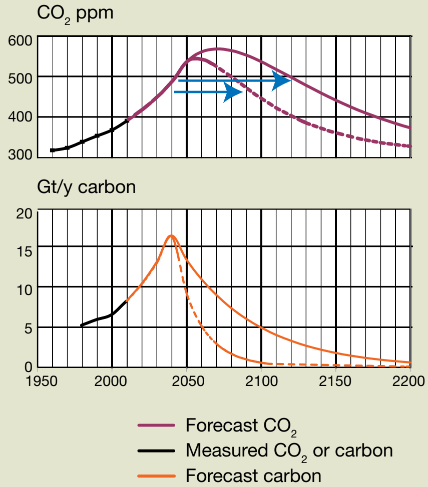
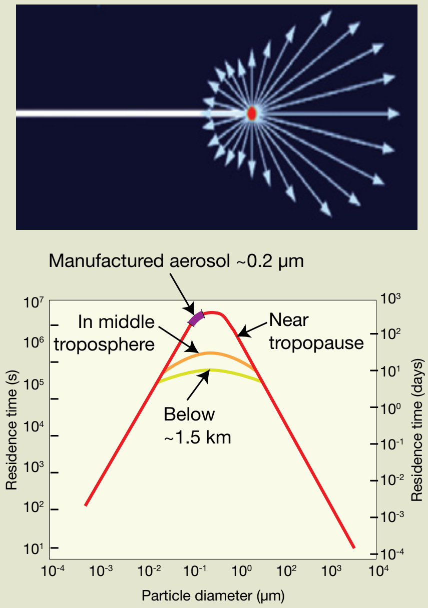


Figure 2: Impact of particle size and refractive index

Light scattering (Mie) by a particle of comparable diameter to that of incoming light showing significant backscattering as well as forward scattering.



Small particles agglomerate through Brownian motion and impact, large particles settle. Lifetimes just above the tropopause can be 1–2 years for particles of 0.1–1 µm diameter, but only weeks at low altitude. The diagram is for water densities; for higher densities the optimum particle size to increase residence time becomes smaller, so a TiO_2 particle at ~0.2 µm diameter is close to the optimum size for long residence.

Adapted from PV Hobbs

At current levels, supplying 1.5m t/y of TiO_2 would cost around £3bn/y – that's 50p per head of population, or around 0.1% of the world's energy expenditure.

The new lofting concepts described here (see Figure 4) consider wind drag, and reduce costs and balloon size dramatically. At an altitude of 20 km, at the bottom of the stratosphere, peak wind strengths are minimum, and so the ratio of balloon lift to drag (ρ/ ρv²) is also at a minimum. A supercritical nitrogen/hydrogen/TiO_2 slurry (which creates neutral buoyancy for the ejected plume) is used as a conveying fluid for particulate TiO_2. A hypersonic nozzle design related to those used in conventional pigment production is used to disperse this at altitude.

The balloon tether acts both as a tension element and contains a pipe carrying fluid at pressures of up to 6,000 bar to allow all pumping equipment to be ground-based. For minimum weight designs, static head and frictional pressure drops are comparable. The tether has to withstand high longitudinal tensile stresses and high hoop stresses – suitable materials of construction for it are aramid fibres such as Kevlar or Twaron. Aramids have a short-term strength of about 2,700 MPa, and a density of 1,440 kg/m³, implying that a self-supported length of about 190 km would be feasible. Even stronger materials may be available, such as the commercially produced but less commonly used poly-p-phenylenebenzobisoxazole (PBO).

The balloon must generate enough lift to prevent 'blow-over' by the wind forces on the tether. Initial concepts required huge balloon sizes (~300 m diameter), but using a novel aerodynamically-shaped tether (hopefully stable) and intermittent lifting surfaces (like gliders) might allow for a much more feasible balloon size of ~90 m diameter, larger it is true, than current high altitude balloons (of 80 m diameter) but not outrageously so (see Figure 5). Launching tethered balloons needs calm conditions, not just at ground level but also at the 'jet stream' level of 10 km. Internal ballonets, progressively deflated when the balloon gains altitude, can avoid a partially-inflated balloon being shredded in cross-winds.

how much TiO_2 is needed?

The solar energy flux at the Earth, the 'solar constant' is ~1368 W/m², or 342 W/m² averaged over the Earth's surface. Of this, more than 30% is already reflected or scattered back to space. The reduction in illumination needed to offset, say, a doubling of atmospheric CO_2 concentrations is affected by climate system feedbacks but is ~4 W/m² over the Earth's surface – or 1.2% of the average (IPC 2007a).

If the scattering cross section is comparable to the particle cross section, then just over 1% of the earth's surface at stratospheric heights needs to have particle coverage, requiring a 800,000 m³ particle volume for 0.2 µm diameter particles. At a coated particle density of ~4000 kg/ m³, that gives us 3m t of particles. If the particles remain in the stratosphere for 2 years then 1.5m t/y must be lofted, equivalent to an annual average coating of 1 nm on the earth's surface. Sea-level concentrations would be around a million times lower than those routinely present in TiO_2 factories.

More elaborate scattering calculations indicate that using suitable TiO_2 particles could reduce the mass of aerosol by a factor of three and the volume by a factor of seven compared with a sulphate aerosol, with a two-fold reduction in surface area. However, the lofted mass of material is comparable if H_2S is used as a precursor, since this reacts with O_2 and water vapour already at altitude.

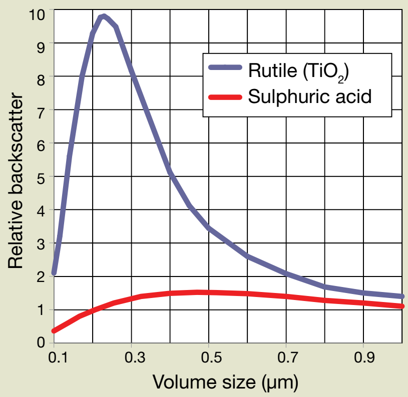
TiO_2 has lower absorption of light in the relevant wavelengths than sulphate aerosols. Preliminary analysis by Ferraro *et al*[3] suggests that there would be 10% of the temperature change (pole to equator) in the stratosphere due to injection of TiO_2 to achieve the same amount of scattering as a sulphate aerosol, if 0.2 µm TiO_2 particles are compared to natural 0.6 µm sulphate particles, and 33% if the particles are of the same size.

what would it cost?

At current prices, supplying 1.5m t/y of TiO_2 would cost around £3bn/y (US$4.8bn/y) – that's 50p per head of population, or around 0.1% of the world's energy expenditure. Other costs are small by comparison: development might cost <£2bn; in the short-term, key research £3m/y rising to £10m/y in 5 years if good progress continues to be made.

Figure 3: Effect of particle size on lifetime & scattering

Relative backscattering of visible light at 0.55 µm wavelength TiO_2 (blue curve) is ~seven times more effective on a volume basis for scattering than sulphuric acid mists (red curve). A smaller particle size is needed for TiO_2



Davidson Technology. Scattering analysis Grainger and Temperley

Improving climate modelling capability would be one of the main costs after this. Total UK government expenditure on geoengineering research is about £1.5m/y, which compares with a Royal Society recommendation in 2009 of £10m/y.

It appears that a balloon supporting a pressurised pipe is likely to be less expensive, perhaps by more than an order of magnitude, than any likely alternative[4].

next steps

While it's essential that we work on reducing CO_2 emissions now, it would be wise to have a tested emergency system in reserve as an alternative – a 'plan B,' if you like.

Technical issues are likely to be more manageable than political, legal, social and ethical considerations: who should control the 'thermostat,' how do you prevent being sued by every farmer in the world with a poor crop? Arbitrating who would be the winners and losers is a huge ethical challenge.

A system with multiple injection points would be robust against terrorist attack, but probably not be capable of implementation against the wishes of any of the great powers, being vulnerable to airborne munitions. Leaving aside political questions, injection sites should be in equatorial regions, in areas of low lightning frequencies, minimal icing potential and a reasonable frequency of balloon launch windows. There are many suitable candidates.

A crash 'Manhattan Project'-style programme might take only five years but would risk untoward planetary effects. A much lower risk approach would involve 20 years for R&D and governance development with perhaps another 15 years for implementation if needed. Previously, investigation of sulphate aerosols has ruled out meaningful small-scale field trials because of the time taken for sulphate aerosols to form. A tethered balloon with a TiO_2 plume, however, allows (with suitable governance) concept testing on a gradual, progressively larger scale with careful checks on atmospheric chemistry, agglomeration and opacity.

While it's essential that we work on reducing CO_2 emissions now, it would be wise to have a tested emergency system in reserve as an alternative. Much research is still needed, but a vision is now on offer for debate and development.

Figure 4: Novel tethered balloon concept

A novel tethered balloon concept is shown for lofting manufactured particles in a conveying supercritical (N_2/H_2) fluid or particle precursors (eg H_2S) to 20 km altitude, above the tropopause. The design shown is for five balloons lofting a total of 1.5m t/y TiO_2. Equipment at altitude is a relatively simple microniser or impact jet mill (with no moving parts) and a hypersonic letdown system which entrains sufficient air to avoid significant particle agglomeration through Brownian motion. The balloon size is far larger than any balloon launched to date to avoid 'blow-over' from wind forces on the tether at 10 km. Estimates of ~£20–100bn development and capital have previously been suggested for high performance aircraft, artillery, multiple balloon systems, airships and even tall towers for stratospheric particle injection systems.

For this concept the total cost of the balloons, tethers, pumps and other ground-based equipment (excluding H_2S or TiO_2 production and transport) has been estimated at ~£500m capital and £600m annual operating cost for the injection system[4].

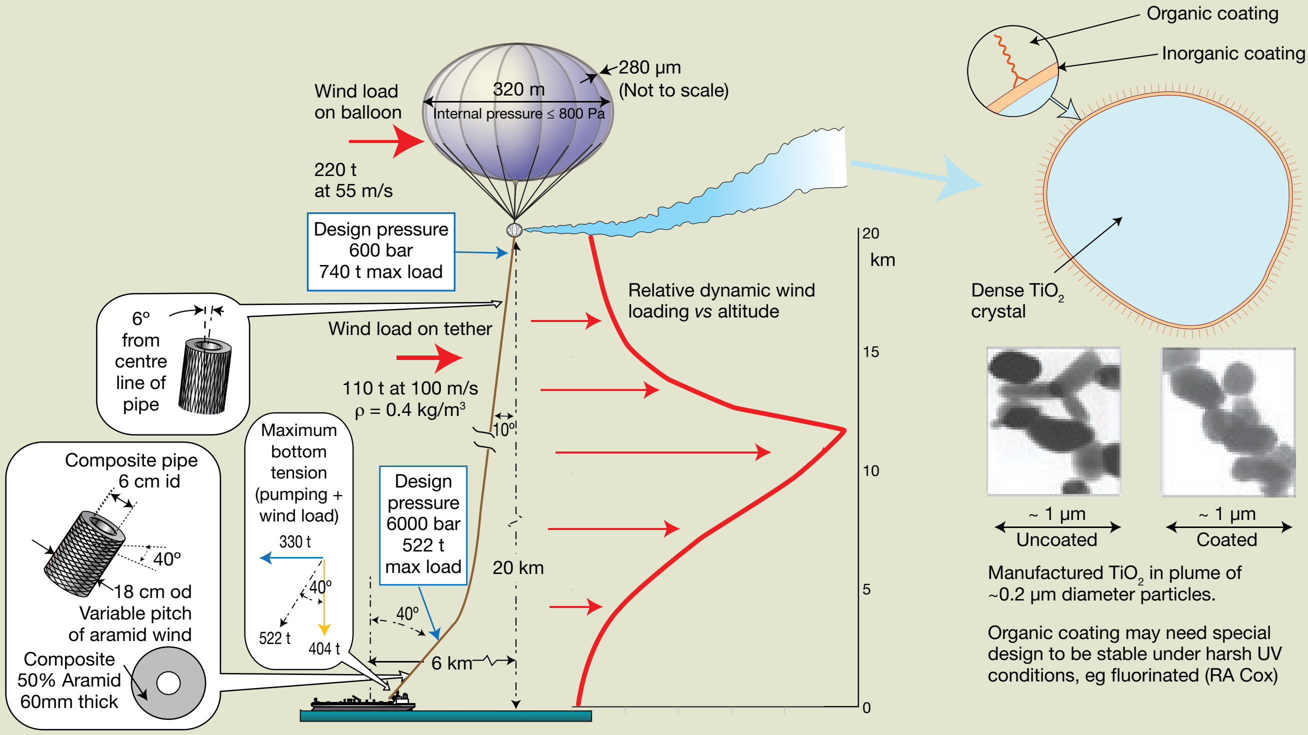
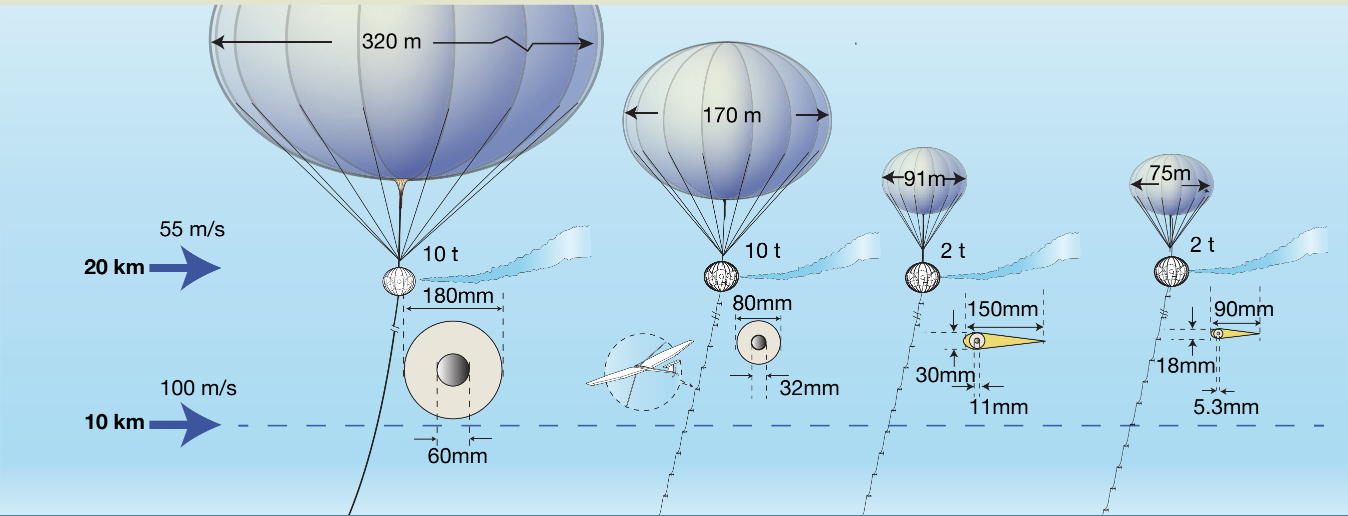


Figure 5: Developing a practical balloon size for the concept

Early concepts (see Figure 4) needed an enormous balloon to provide stability against wind drag on the tether. Progressively more feasible concepts have been developed with smaller balloons. For a circular tether there is a minimum size which will be stable in high cross winds. A balloon of less than 300 m diameter will 'blow over' in the extreme winds encountered at 10 km altitude for current tether materials. However, if the side winds are used to provide lift (for relatively low drag) on glider type lifting surfaces, the balloon size can be dramatically reduced. If in turn an aerodynamic tether turns out to be stable, and can be manufactured, the balloon size can be reduced further. The impact on this design of a higher strength material (PBO) is shown last. At a moderate cost (< £10m) this concept could be tested, first with nitrogen pumping for mechanical integrity and vibrational stability, prior to any small scale field experiments with manufactured particles or sulphate aerosol precursors, after suitable governance is developed.



Case	1	2	3	4
kt/y TiO_2/balloon	300 kt/y	75 kt/y	1.5 kt/y	1.5 kt/y
Tether	Circular Aramid 180 mm od	Circular Aramid 80 mm od	Aerofoil Aramid 150 mm x 30 mm	Aerofoil PBO 90 mm x 18 mm
Bore	60 mm id	32 mm id	11 mm id	5.3 mm id
Intermediate lifting devices	No	Yes	Yes	Yes
Balloon volume (m^3)	17,000,000	2,600,000	400,000	220,000
Net lift (t)	1250	180	25	15

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The most important short-term research questions are whether a coated particle can increase scattering while minimising ozone depletion and atmospheric heating, and whether the tethered balloon concept at 20 km altitude can be stable in high cross-winds at 10 km and can be launched at suitable sites.

In the long term, a very significant improvement of our climate models is required for regional environmental impact assessment. Creating a suitable insurance policy for climate remediation is a vital task. It will not do to underestimate the challenges. Much research is still needed, but a vision is now on offer for debate, and development where potential means of solving some of the most difficult technical challenges have been identified. **tce**

Peter Davidson is a consultant at Davidson Technology. He was formerly senior innovation advisor to the UK's Department of Business Enterprise and Regulatory Reform and the Department of Innovation Universities and Skills.

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