

Lifting options for stratospheric aerosol geoengineering: advantages of tethered balloon systems

Peter Davidson, Chris Burgoyne, Hugh Hunt and Matt Casurier

Phil. Trans. R. Soc. A 2012 **370**, 4263-4300

doi: 10.1098/rsta.2011.0639

References

This article cites 24 articles, 3 of which can be accessed free

<http://rsta.royalsocietypublishing.org/content/370/1974/4263.full.html#ref-list-1>

Article cited in:

<http://rsta.royalsocietypublishing.org/content/370/1974/4263.full.html#related-urls>

Subject collections

Articles on similar topics can be found in the following collections

[atmospheric science](#) (43 articles)

[environmental engineering](#) (21 articles)

[structural engineering](#) (6 articles)

Email alerting service

Receive free email alerts when new articles cite this article - sign up in the box at the top right-hand corner of the article or click [here](#)

Lifting options for stratospheric aerosol geoengineering: advantages of tethered balloon systems

BY PETER DAVIDSON¹, CHRIS BURGOYNE^{2,*}, HUGH HUNT²
AND MATT CAUSIER²

¹*Davidson Technology Limited, 8a Village Walk, Onchan, Isle of Man*

²*Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK*

The Royal Society report ‘Geoengineering the Climate’ identified solar radiation management using albedo-enhancing aerosols injected into the stratosphere as the most affordable and effective option for geoengineering, but did not consider in any detail the options for delivery. This paper provides outline engineering analyses of the options, both for batch-delivery processes, following up on previous work for artillery shells, missiles, aircraft and free-flying balloons, as well as a more lengthy analysis of continuous-delivery systems that require a pipe connected to the ground and supported at a height of 20 km, either by a tower or by a tethered balloon. Towers are shown not to be practical, but a tethered balloon delivery system, with high-pressure pumping, appears to have much lower operating and capital costs than all other delivery options. Instead of transporting sulphuric acid mist precursors, such a system could also be used to transport slurries of high refractive index particles such as coated titanium dioxide. The use of such particles would allow useful experiments on opacity, coagulation and atmospheric chemistry at modest rates so as not to perturb regional or global climatic conditions, thus reducing scale-up risks. Criteria for particle choice are discussed, including the need to minimize or prevent ozone destruction. The paper estimates the time scales and relatively modest costs required if a tethered balloon system were to be introduced in a measured way with testing and development work proceeding over three decades, rather than in an emergency. The manufacture of a tether capable of sustaining the high tensions and internal pressures needed, as well as strong winds, is a significant challenge, as is the development of the necessary pumping and dispersion technologies. The greatest challenge may be the manufacture and launch of very large balloons, but means have been identified to significantly reduce the size of such balloons or aerostats.

Keywords: geoengineering; climate change; tethered balloons; stratospheric particle injection

*Author for correspondence (cjb@eng.cam.ac.uk).

One contribution of 12 to a Discussion Meeting Issue ‘Geoengineering: taking control of our planet’s climate?’.

1. Introduction

Lord Rees commented in the foreword to the Royal Society report on geoengineering, ‘many proposals for geoengineering have already been made—but the subject is bedevilled by much doubt and confusion. Some schemes are manifestly far-fetched; others are more credible, and are being investigated by reputable scientists; some are being promoted over-optimistically’ [1].

At an Engineering and Physical Sciences Research Council/Natural Environment Research Council workshop in March 2010, proposals were invited for preliminary research into geoengineering by various methods including solar radiation management (SRM) by particle injection into the stratosphere. At the workshop, the idea of a high-altitude tethered balloon delivery system, with ultra-high pressure pumping to elevate fluids or particle slurries, appeared to offer significant advantages over other delivery options. A proposal to investigate the desired particle properties, the method of their delivery and modelling their impact on the climate was funded. The dispersion at altitude of particles manufactured at ground level, with tailored size distributions and coatings may provide benefits, such as reduced or negligible ozone impact, not readily available to other delivery options. This paper reviews the merits of this idea alongside those of other delivery options.

Previously, Blackstock *et al.* [2] considered the scientific and engineering requirements of various technologies but did not consider costs. Others have provided cost estimates for certain technologies such as aircraft and naval artillery but did not consider as many delivery options [3–5]. Consideration has also been given by some of the authors to the use of tethered aerostats, manufactured particles, drag reduction strategies and dispersion technologies [6].

The lead time required for implementation of any injection system is a particularly important criterion if the real value of SRM options is to provide an insurance policy against global warming and its effects: rising greenhouse gas concentrations may trigger significant transients such as runaway methane emission from melting arctic permafrost, major acceleration of ice sheet melting, or methane clathrate release from the ocean floor. Should any of these ‘tipping points’ be encountered then immediate measures will be required to reduce global temperature quickly in order to avoid unprecedented social, environmental and economic costs. For this reason, it is important to assess the time needed for a candidate geoengineering strategy to have any significant impact on global temperature. Modifying greenhouse gas concentrations is likely to take far too long: time constants for natural processes to reduce greenhouse gases in the atmosphere are hundreds of years, and the time constant for man-made emissions to fall to insignificant levels is likely to be similar. Carbon dioxide removal techniques might possibly have an impact in 50 years [7], but SRM technologies would appear to be the only options capable of achieving global temperature stabilization, or reduction, on a time scale of a few years commensurate with the uncertainties of predicting significant transients. Two general arguments against all SRM techniques are that they do not directly retard ocean acidification, and their regional impact is difficult to assess with current climate models, but they might at least buy time and allow the world to avoid some of the more extreme temperature or precipitation scenarios.

2. Particle choice and properties

The choice of particle is receiving close attention; hitherto, it had been assumed that aerosols would be sulphuric acid mists similar to those produced by volcanoes. Such natural mists are efficient scatterers of visible light from the Sun and very inefficient scatterers of infrared radiation from the Earth, even though they are slightly smaller than optimum [4]. However, it may be possible to consider using other particles with better properties. The Royal Society report on geoengineering comments [1]

Various other types of stratospheric aerosol particles have also been suggested (Teller *et al.* 1997; Blackstock *et al.* 2009; Keith 2009; Katz 2009) [2,8–10]. Engineered aerosols might enable scattering that did not produce so much diffuse illumination, potentially circumventing a significant side-effect of sulphate aerosols. Alternative materials might also avoid the coagulation and vaporisation problems that will be significant for sulphate aerosols. Finally, it is possible that advanced engineered particles could be designed that had longer lifetimes, or that were lofted out of the lower stratosphere, so reducing the impact of the aerosol on ozone chemistry, or enabling radiative forcing to be concentrated in special locations such as the polar regions.

If other particles are to be designed and manufactured for use in a suspended pipe system, they will need particular properties to be attractive alternatives to the use of a sulphuric acid aerosol. As well as having a high refractive index and suitable particle size to maximize solar radiation scattering, they should, for a given amount of scattering,

- minimize stratospheric ozone destruction by having a lower heterogeneous reaction rate than sulphuric acid aerosols for the following reactions:
 - (i) $2\text{O}_3 \rightarrow 3\text{O}_2$
 - (ii) $\text{N}_2\text{O}_5 + \text{H}_2\text{O} \rightarrow 2\text{HNO}_3$
 - (iii) $\text{HCl} + \text{ClONO}_2 \rightarrow \text{Cl}_2(\text{g}) + \text{HNO}_3$
- minimize regional changes in precipitation by reducing stratosphere heating through having a lower absorption of solar radiation than for sulphuric acid aerosols.

The particle surface coating technology needs also to:

- Provide dispersion of the particles in the chosen carrier fluid both in the pipe at very high pressures (at up to 6000 bar), and at the point of discharge under low pressure (less than 0.1 bar, -50°C). Electrical field gradients are likely to be significant at the start of the plume and may be used to reduce coagulation. The carrier fluid composition must ensure an unreactive, buoyant plume at 20 km altitude even with significant particle loading. Nitrogen might be a suitable candidate carrier gas, with added hydrogen to ensure necessary buoyancy.
- Be stable for at least two years in the cold but high UV conditions of the upper atmosphere.
- Be designed to minimize nucleation effects in the troposphere after the particles have left the stratosphere.

Manufacture of the particles should be low cost, with a low environmental impact, and the particles must have negligible toxicity. Ideally, there should be a sufficient supply of the relevant raw materials to ensure availability for at least a century.

Various high refractive index particle systems could be considered but titanium dioxide (TiO_2) is a promising candidate. No other particle comes anywhere close to its properties: it has a high refractive index, its safety has been well researched and it is produced in industrial quantities. Coated TiO_2 particles of a size approximately 0.15–0.25 μm in diameter would be suitable. They are only slightly smaller than those already produced for most paints and for providing opacity in many other applications, e.g. in paper, plastic films, inks, some foodstuffs. A much smaller particle size (approx. 0.05 μm) is already made to scatter UV in sunscreens. Titanium dioxide has the highest refractive index of any pigmentary substance currently manufactured on a relevant scale which is stable in air and non-toxic. It also has a low visible light absorption, and there is a vast experience in manufacturing nanometre thickness coatings on titanium dioxide to control surface properties [11,12].

The use of different coatings allows the possibility of minimizing atmospheric chemistry effects. Current TiO_2 particle sizes are optimized for light scattering in close-packed systems, but the existing manufacturing units could easily be modified to produce the slightly smaller sizes for light scattering in a dispersed environment [11]. The inorganic/organic coating systems have the potential to be modified to give stable hydrophobic surfaces with a variety of chemistries that may reduce ozone destruction to a lower level than that of sulphuric acid mists. Other potential high refractive index particle systems should also be considered.

By conveying the particles up the pipe in a supercritical fluid, and making use of existing compact and lightweight micronizing technologies employing the conveying fluid for motive power, there is the potential to create a well-dispersed aerosol system at 20 km altitude.

Early experiments could be carried out from free-flying balloons or fast jets, possibly followed in due course with a high-pressure pipe supported from a relatively small (approx. 100 m diameter) balloon. The latter system would be able to create progressively larger plumes at altitude to enable the atmospheric chemistry, dispersion scattering and electrical effects to be studied. Much of the technology to examine such plumes is available from existing atmospheric science studies using satellites, free-flying balloons, aircraft and ground-based equipment.

Notwithstanding all of the above, the use of H_2S as a precursor system for sulphuric acid aerosols has the great advantage of generating almost five times the mass of the material lofted, through the supply of oxygen from the stratosphere, i.e. $\text{H}_2\text{S} + 2\text{O}_2 \rightarrow \text{H}_2\text{SO}_4$. A particulate system also needs a conveying gaseous material to be lofted. Scattering calculations and process flow analyses indicate that the conveying material mass flow and the extra mass provided by the ‘free oxygen’ are likely to negate mass reduction through higher scattering per unit volume. However, creating an appropriate sulphuric acid mist at altitude in a representative environment poses significant problems. Without that capability, the slowness of the reaction of SO_2 to H_2SO_4 means that local, small-scale experiments would be impossible: atmospheric circulation would disperse precursor material (SO_2 or H_2S) around the planet before sulphuric acid mists would form, and also before suitable measurements could be carried out on their effects [4].

3. Costing and development times of delivery technologies

A rational comparison of the technologies for delivery of aerosols into the stratosphere must include outline estimates for the financial costs involved. Any such estimates will be based on various assumptions and preconditions.

Assumptions

- (i) Each technology requires at least four delivery sites around the globe in non-polar regions, i.e. at latitudes within approximately 20° of the equator, for effective dispersal of albedo-enhancing aerosols with a mass of around 10 million tonnes per year at above 20 km altitude.

To support this conjecture, it has been observed that volcanoes in the tropics (e.g. Pinatubo, 1991, 15° N) have a greater effect on temperature than those at higher latitudes (e.g. Katmai, 1912, 58° N). Preliminary modelling suggests that this is because of a higher solar radiation flux near the tropics and stratospheric (Brewer–Dobson) circulation lofting particles injected near the equator to high altitudes, whereas particles injected nearer the poles remain close to the tropopause and are removed more rapidly [13]. Atmospheric currents distribute the injected particles east–west within weeks, but more slowly (months) north–south as shown, for example, in Pinatubo observations [14]. The amounts of SO_2 released by Pinatubo (18 ± 4 megatonnes SO_2 equivalent) [15] can be used to compare theory with actual events, and information is available on the optical depth [16].

Pierce *et al.* give an overview of some of the uncertainties in estimating the amount of material needed if SO_2 is used as the aerosol precursor [17]. Some models suggest that 2 million tonnes of sulphur per year, or 4 million tonnes of SO_2 per year, would be sufficient to counter a doubling of CO_2 levels by the use of a smaller particle size than Pinatubo [18]; others say 10 million tonnes of SO_2 per year might be needed [19]. Estimates for the amount of material required vary with particle size, refractive index, coagulation rate and stratosphere/troposphere mixing rate. If the feed is SO_2 , hydrolysis takes place to form a sulphuric acid mist with a droplet size in the light-scattering range, with an e-folding time of around 35 days in the relatively dry stratosphere [20], much as in the natural processes of volcanoes with SO_2 or H_2S , so dispersion is known to be relatively straightforward. (H_2S oxidizes to SO_2 and water relatively quickly, followed by the slow reaction to H_2SO_4 .)

The cost of producing the aerosol feed is assumed to be independent of the delivery technology and is omitted from the comparisons, as have the costs of basic infrastructure facilities for transporting materials to the launch sites and intermediate storage. Personnel costs associated with running the various facilities are generally ignored except when they become material to the comparisons, although some personnel costs are implicitly included in the costs of the various components. Costs quoted in references in US\$ have been converted at the rate $\$1.6 = \pounds 1$. Significant rounding has been applied given the tolerance of the estimates.

- (ii) Weather, particularly wind speed in the troposphere, has an appreciable effect on most of the delivery systems under consideration. Lightning, icing and turbulence can play a part in choosing the injection locations.

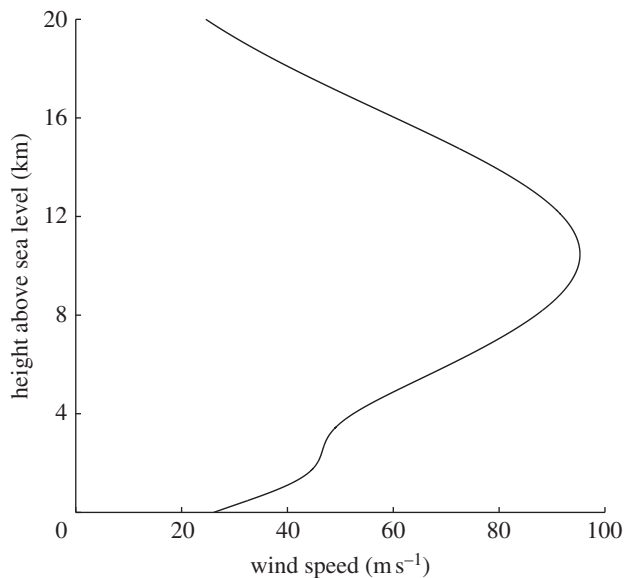


Figure 1. Variation of wind speed with height (maximum of 6 hourly data at 33°N).

The wind speed shown in figure 1 is taken from the maximum of the 6 hourly ‘instantaneous’ data for the wind (ERA-Interim) at 33° N [21]. The effect of the jet stream at an elevation of about 11 km is clearly visible, as is the reduction to relatively steady conditions at 20 km. The figures used reflect extremes in the tropics if very dry (low storm intensity) regions are used for the injection points. Surface drag reduces the wind speed at the Earth’s surface. For some calculations the figures will need to be increased; very short gusts have structural effects, and these figures do not include the effect of tropical storms that can cause very large wind speeds at low levels. The peak wind speed at 20 km is only about 50 m s^{-1} , while the maximum peak wind speed measured in a year (1953) over North America was 136 m s^{-1} [22]. While these data are relatively old, it remains the most consistent dataset available for peak wind speeds and provides a useful semi-continuous wind velocity function for optimizing engineering design.

The density variation (figure 2) is also important, falling to about a 14th of its surface value at 20 km.

- (iii) The systems considered below can be classified in various ways. Two criteria are of particular importance: the length of time the delivery device remains in the stratosphere and the reusability of the components.

It is assumed that:

- those systems where the delivery device follows a ballistic trajectory will remain in the stratosphere for a very short time (of the order of seconds) and will therefore require an extremely rapid dispersal process, either by means of detonations or by using a system where the liquid or solid will naturally disperse without mechanical assistance and
- those systems with a dwell time in the stratosphere measured in minutes or hours, such as aircraft or cruise missile technology, could use some form of mechanical dispersion.

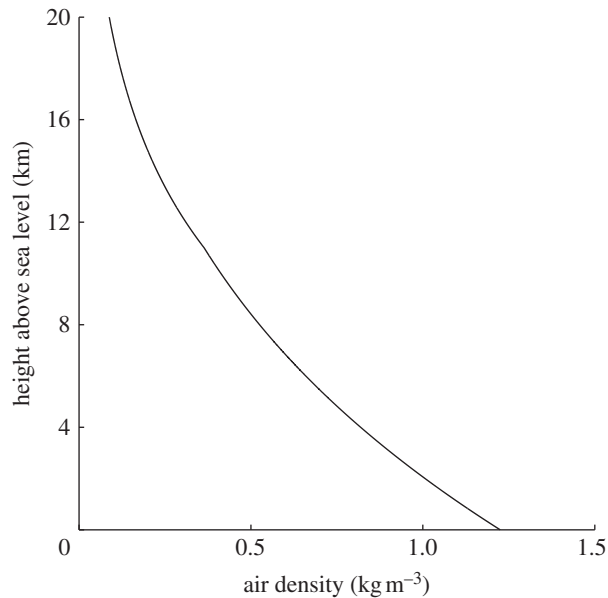


Figure 2. Variation of air density with height.

These short residence time systems are effectively batch processes. It is also assumed that:

- those systems with a time in the stratosphere of many days or months, such as tethered balloons or airships, could use quite sophisticated dispersal technology and can be expected to give a much more controlled dispersion. There will be a weight penalty since the machinery would have to be carried to an altitude of 20 km, and powered continuously at this height.

These long residence time systems are effectively continuous delivery processes.

(iv) The options for reusability raise different issues.

- For ‘one-shot’ systems, the multiple delivery elements have to be cheap. The environmental cost of the redundant components must be considered, both in terms of safety (heavy pieces falling back to Earth or the possibility of noxious materials being strewn around) and appearance (litter).
- Systems with limited reusability allow components to be recovered and either used again immediately or refurbished. In this way, many of the drawbacks of one-shot systems are removed. However, the costs of recovery must be taken into account, or at least an allowance made for the difficulty of making the system components return to base autonomously. The cost of regularly providing replacements for damaged components must also be considered.
- Systems with complete reusability. Systems that provide for continuous use, or reuse over a long period, may justify high initial costs and complexity.

- (v) The development times discussed assume a ‘Manhattan project approach’ where ‘political will’ ensures almost unlimited access to relevant resources: people, finance, facilities. Such a position might develop when obvious societal stress was arising from global warming, but would have greater attendant risks.

(a) *Free-flying balloons*

The concept of using cheap latex balloons, similar to weather balloons, to lift a payload of particles has been considered by a number of authors [1,2,4]. The analysis given here closely follows that in COSEPUP [5] but uses different values for some parameters. A 20 m diameter balloon has been assumed to be the maximum practicable.

By application of Archimedes’ principle, a payload of around 250 kg can be lofted to 20 km (where the density of air is around 0.08 kg m^{-3}) by a single hydrogen-filled balloon of 20 m in diameter. A latex or nylon balloon, typical of those routinely used for scientific purposes, would weigh around 25 kg, and 20 kg is allowed for a canister and valve needed to release the payload. It follows that 40 million balloon flights per year are required to loft 10 million tonnes of aerosol.

The price of latex in July 2010 was $\text{£}1.4 \text{ kg}^{-1}$ [<http://www3.lgm.gov.my/mre>, date accessed: 1 July 2010] and in July 2008 the hydrogen price stood at around $\text{£}1.6 \text{ kg}^{-1}$ [<http://www.hydrogencarsnow.com/blog2/index.php/hydrogen-fuel-production/global-hydrogen-inc-lowers-price-of-hydrogen-to-247-per-gallon>, date accessed: 31 October 2010]. The cost for a canister and valve in bulk production is estimated at $\text{£}30$.

The use of a premixed hydrogen/ H_2S or SO_2 system as the lifting gas has been proposed [4]; this is entirely feasible but would increase the volume and therefore the number of balloons by a factor of 5 with a consequential increase in cost.

(i) *Single-use balloons*

If individual balloons are not reused, one balloon is required per flight. The total cost of hydrogen is $\text{£}1.4$ billion, that of balloon fabric is $\text{£}4$ billion (with fabrication costs on this scale being minimal when compared with material costs), and that of canisters is $\text{£}1.2$ billion per year.

These numbers imply a total cost of approximately $\text{£}7$ billion per year, and would be expected to increase in line with energy prices.

Global annual production of latex and hydrogen is 21 million tonnes [<http://www.lgm.gov.my/nrstat/T1.htm>, date accessed: 31 October 2010] and 70 million tonnes [<http://www.azom.com/news.asp?NewsID=20711>, date accessed: 31 October 2010] respectively, so these requirements represent 11 and 1.4 per cent of current global production. The largest delays in producing a single-use balloon system are likely to be the difficulties of scaling up production and the provision of ground facilities, so a system should be deployable within 5 years in extremis.

Latex is naturally biodegradable but the mechanism is not well understood [23]. It would need to be made more rapidly biodegradable, without affecting its strength, otherwise the environmental impact of balloons littering the Earth’s surface would be severe, particularly to marine life. The social impact would be moderate, mostly affected by the extensive effect on air traffic given the unpredictability of the flight path and the frequency of balloon launches. The spent hydrogen would combine with oxygen in the atmosphere to release about

10 million tonnes of water into the stratosphere each year; i.e. far less than the 500 million tonnes threshold at which significant effects on stratospheric circulation might be expected [24].

(ii) *Reusable balloons*

Compared with the single-use balloon case, the number of balloons required falls if they can be retrieved and reused. However, the cost and environmental impact of retrieving the spent balloons is likely to be significant, and could be greater than for single-use balloons since greater care would be needed in retrieval to ensure reuseability. Horizontal wind components of approximately $30\text{--}40\text{ m s}^{-1}$, averaged over a 20 km column, are typical. If a balloon flight lasts between 1 and 3 h, with a rate of ascent around $4\text{--}12\text{ m s}^{-1}$, then the balloon will travel around 150–450 km, which if all directions are equally probable, equates to a retrieval area of up to 600 000 km² around each launch station. In practice, the area over which the balloons would fall would be somewhat less, at least over short time scales, since the wind direction is not random.

Environmental damage and wear-and-tear are likely to restrict the lifetime of each balloon. A modern hot air balloon has a lifetime of approximately 700 flight hours. Time on the ground or in the sea would add to wear-and-tear. Keeping time on the ground down to an average of 24 h, with 25 000 launches per day per site to meet the four-site, 40 million balloon launches per year criterion, requires around 4000 retrieval teams per site if each can pick up six balloons per day and cover approximately 10–75 km² in unpopulated terrain such as the Australian outback. If a larger number of sites were used, the number of teams would probably increase since the balloons would typically be spread over a wider area.

A retrieval truck or boat with two operators might cost around £750 per day including fuel and depreciation. This would amount to an expenditure of 16 000 teams \times 365 \times 750 \approx £4.4 billion per annum (p.a.) plus launch costs for the worst case and perhaps one quarter of this if high speed ascents and descents are used. Assuming a round trip time from launch to launch of 3 days, at least 300 000 balloons would be needed. If the balloons last an average of 20 flights, then 1.3 million new balloons are needed each year, and if each reusable balloon costs twice as much as a throw-away one, the cost would be about £400 million p.a. It is assumed that the hydrogen cannot be reused.

The total cost is thus approximately £1–4.4 billion p.a. for recovery + £4 billion p.a. hydrogen + £0.4 billion p.a. balloons, giving a total between £6 billion and £9 billion p.a., which is at least as high as the cost of throw-away balloons, largely because of the costs associated with recovery.

The technology is mostly available today, but there would probably need to be a large investment in establishing the necessary supply routes to the launch sites, which would probably mean a delay of 5–10 years before such a system could be deployed effectively. Although the pollution associated with discarded balloon fabric of one-shot balloons would not be incurred, the effects of the release of large amounts of hydrogen at high altitude would remain. There would be the same issues associated with interference with air traffic, so social impacts would be similar to single use balloons.

The idea of using superheated sulphur dioxide itself as both the buoyant gas and the payload of the balloon was rejected on the grounds that it would require

temperatures of around 600°C, well above the melting point of any low cost balloon fabric.

When considering the dispersal of aerosols other than those derived from a precursor gas, both balloon options become more expensive on account of the dispersion equipment that has to be carried to high altitude.

(b) *Towers*

It is difficult to conceive of any tower option being achievable in the foreseeable future, but they have been proposed and should be considered. Both environmental and social costs can perhaps be considered to be moderate rather than high but would be overwhelmed by the effects of the massive financial investment needed for towers.

(i) *Conventional towers*

Tall towers have been mentioned as potential options for elevating and dispersing material to stratospheric altitudes [4,25]; they would have the advantage that they could operate continuously while providing human access to the dispersal equipment, but the simple analyses described below show that such a tower built with any materials currently available is not practicable and would certainly be expensive (£250 billion in materials alone for each tower). Some savings could be obtained if a 15 km tower (rather than a 20 km tower) were built on a high plateau, for example, in the Andes or Himalayas.

A tall tower, to carry only its self-weight and wind loading, must satisfy two basic criteria. It must be strong enough that the structural materials do not reach their limiting stresses and it must be stiff enough that it will not buckle. In the first instance, these criteria can be considered separately and, for illustration, the designs have been carried out in steel and in carbon fibre reinforced polymer (CFRP) with the material properties listed in table 1.

Strength design

A straight tower, of uniform cross section, will fail in compression when the height is equal to $\sigma/\rho_m g$, where σ is the strength of the material in compression, ρ_m the density and g the acceleration owing to gravity. This is a limiting factor for steel, giving a maximum height (without any safety factor) of approximately 6.5 km. However, as will be seen below, this height can be exceeded if the tower tapers.

The predominant wind forces will be horizontal, so the tower will act primarily in flexure as a vertical cantilever. Two tower cross sections are considered: one formed from a single hollow tube as shown in figure 3a, rather like a continually tapering cooling tower; the other from four legs with bracing, figure 3b, like the Eiffel Tower or a UK electricity pylon. Most tower configurations can be approximated to one or other of these cross sections.

The single tube will be thin walled and it is assumed that the wall thickness t is $R/50$. Thin-walled tubes in compression are at risk from local buckling where the thin wall crumples. For this failure mechanism to be avoided stiffeners in the form of internal bracing will probably be required but it is assumed that the stiffeners are light enough to be neglected in the calculation of tower mass. For

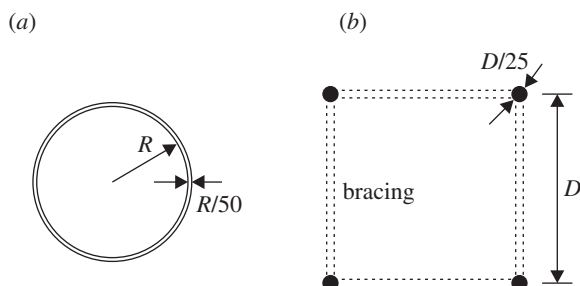
Figure 3. Alternative tower cross sections. R and D vary with height.

Table 1. Comparisons of 20 km tower designs.

	steel	CFRP
material properties		
density (kg m^{-3})	7800	1500
allowable stress (MPa)	500	1500
Young's modulus (GPa)	200	120
cost (£ t^{-1})	800	4000
cylindrical tower to resist wind only		
diameter at base (m)	134	52
total weight of material (t)	18.3×10^6	657×10^3
g_{cr} (m s^{-2})	0.166	0.104
4-legged braced tower to resist wind only		
leg spacing at base (m)	256	53
total weight of material (t)	15.4×10^6	217×10^3
g_{cr} (m s^{-2})	0.017	0.0131
uniform cylindrical tower to resist buckling		
diameter (m)	—	1000
total weight of material (t)	—	942×10^6
uniform 4-legged braced tower to resist buckling		
leg spacing (m)	—	1000
total weight of material (t)	—	302×10^6
shaped cylindrical tower to resist wind and buckling		
diameter (m)	1030	508
total weight of material (t)	1.09×10^9	62×10^6
material cost (£billion)	872	248
4-legged braced tower to resist buckling		
leg spacing (m)	6130	1460
total weight of material (t)	8.88×10^9	163×10^6
material cost (£billion)	7040	652

the truss, a significant amount of bracing would be required, as in an electricity pylon. It will be assumed that this bracing weighs as much as the four main legs and attracts the same amount of wind load. The diameter of each leg d is related to the overall tower width D by taking D/d fairly arbitrarily as 25.

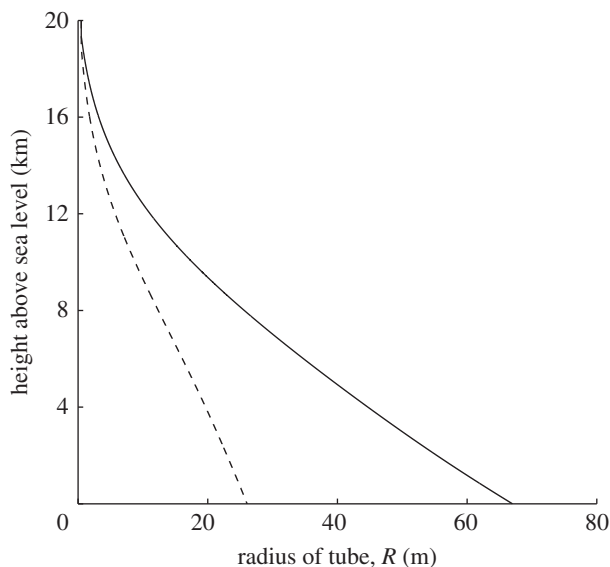


Figure 4. Variation of principal diameter of single tube to resist wind loads only (solid line, steel; dashed line, CFRP).

The steady wind load on the tower is given by $F = (1/2)\rho_a C_D v^2 A$, where F is the force, ρ_a the air density, C_D the drag coefficient, A the area facing the wind and v the wind speed. The wind speeds in figure 1 certainly underestimate the maximum 3 s gust normally used for structural design but are used here in the absence of better data. The drag coefficient depends on Reynolds number (Re), but for the structures and wind speeds being considered Re is greater than 8×10^4 so C_D can conservatively be taken as 0.5 (e.g. [26]).

To determine the section dimensions the loads are integrated from the top of the tower downwards, giving a vertical moment (from the wind) and an axial force (from the self-weight). The top of the cylindrical tower is assumed to have a radius R of 0.5 m and the truss a width D of 1 m. By computing the sum of the axial stress and the bending stress and comparing this total with the limiting material stress σ_y , the required diameter at each level can be found. No allowance has been made for the deflection of the tower above the point in question, which would increase the forces and hence increase the size of the tower cross section. For the hollow tube design, the variation of R with height is shown in figure 4. For steel, the radius at the base is about 68 m with a total weight of steel of about 19 million tonnes. Using a lighter material such as CFRP the width increases less rapidly, thus reducing the wind load, so R at the base is only 26 m with a total weight of 0.66 million tonnes.

Similar effects are observed for the trussed form, with the variations shown in figure 5. The width of the steel truss increases quite rapidly towards the base, indicating that the self-weight of the tower is starting to be a much more significant part of the load, although it is still possible to build a tower 20 km tall. The trussed steel tower would have a total weight of 16 million tonnes, half of which is assumed to be in some kind of bracing. There is much less weight in the CFRP tower (218 000 tonnes).

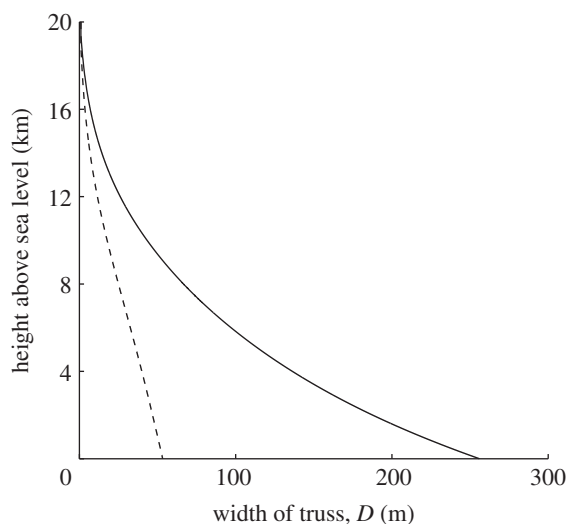


Figure 5. Variation in width of trussed form with height (solid line, steel; dashed line, CFRP).

Stability design

These dimensions, although large, give structures that are very slender. Even for the steel tube, the ratio of the height to the width at the base is about 150, which is comparable to a very slender flag pole; such structures are very susceptible to buckling under their own self-weight. In the first instance, buckling will be computed on the assumption that the towers are of uniform cross section for their entire height. Later, tapered towers will be considered.

The well-known formula for Euler buckling load of a uniform pin-ended strut under externally applied axial load is $P_{\text{cr}} = \pi^2 EI/L^2$, where E is the Young's modulus of the strut material, I its second moment of area and L its length. For a cantilever column, this buckling load must be divided by 4 to reflect the different boundary conditions. When the buckling load comes from the tower's own self-weight, the classical analysis of a uniform cantilever column gives a value for the critical load as

$$(qL)_{\text{crit}} = \frac{7.837EI}{L^2}, \quad (3.1)$$

where q is the weight per unit length [27]. The 7.837 factor can be compared with $\pi^2/4 = 2.467$ for the end-loaded column; clearly, more load can be carried if it is distributed evenly along the length rather than being carried at the end. But the self-weight is related to the material density and its cross-sectional area so the formula above can be rearranged to give

$$L_{\text{crit}} = 7.837 \left(\frac{E}{\rho_m g} \right) \left(\frac{r}{L} \right)^2, \quad (3.2)$$

where r is the radius of gyration of the tower cross section. This formula conveniently separates the buckling load into a material factor and a shape factor. For a thin circular tube, the radius of gyration r is $R/\sqrt{2}$ (and notably

is independent of the tube thickness). Even for a solid cylinder r only decreases to $R/2$, so the values determined below apply to a wide range of cross-section options. For the truss $r = D/(2\sqrt{2})$, allowing for the fact that half of the material is in the bracing that contributes to the weight but not to the overall stiffness of the tower.

For steel, the required dimensions for the uniform tube at 6.5 km tall would give $r = 116$ m whence $R = 163$ m for the tube or $D = 327$ m for the truss. For a 20 km tower in CFRP, the radius of the uniform tube is 500 m. These dimensions are clearly much larger than the values given by the strength analysis, but do not take account of the reduction in section at the top: these values do not include any safety factor.

For a tapered tube there is typically no closed-form solution. An approximate Rayleigh analysis for the self-weight buckling load can be performed by assuming the shape of the buckling mode and equating the strain energy of flexure to the work done by the load. The exact analysis would predict a lower buckling load because the assumed shape will need more strain energy than the correct form. A commonly assumed buckling mode is to calculate the shape the tower would adopt if it were mounted *horizontally* and subjected to a gravity load [27]. By this approximation, the Rayleigh analysis for a uniform section (for which an exact solution *is* available) overestimates the critical length by only 0.1 per cent, so it is reasonable to use the same approximation for a tapered tower.

A Rayleigh analysis indicates that the tapered steel tube tower, with $R = 68$ m at the base designed to resist the wind load in flexure, and with a mode predicted as above would buckle if the gravitational acceleration g_{cr} were 0.166 m s^{-2} . Since the buckling load will vary as R^2 , in order to make the tube buckle when g_{cr} is 9.81 m s^{-2} , the tube dimensions would have to be increased by a factor of about 7.6, giving a diameter at the base just over 1 km—which is a tube into which a large football stadium would fit, complete with its carpark.

Similar analyses have been carried out for tubes and trusses in both steel and CFRP. The results are given in table 1. The ‘cheapest’ of these options (shown in bold in the table) is the shaped cylindrical tower in CFRP, at about £250 billion each. If four such towers are required, the cost would be of the order of £1 trillion with 250 million tonnes of CFRP needed. No allowance has been made for the difficulty of working at the altitudes needed. Figure 6 shows these towers in comparison with some well-known landmarks to give some sense of scale.

The choice of materials for illustration was determined by material properties: since buckling is the governing condition, it is the specific modulus (E/ρ) that matters. Steel is stiff but heavy, so E/ρ is low, although it has the advantage of being plentiful and relatively cheap. Carbon fibre has a similar modulus but is lighter, so E/ρ is higher, but it is much more expensive. Most other structural materials fall within this range; aluminium, for example, has both a modulus and a density that are about one-third those of steel, so the same amount of material would be needed, but at a much greater cost. The only way to make a significant improvement would be to increase E , but this is limited (at least for organic materials) to the stiffness of the C–C bond, which is about 600 GPa, while at the same time decreasing the density. Even if materials like graphene were available in industrial quantities, they could only increase the specific modulus by at most a factor of 2.

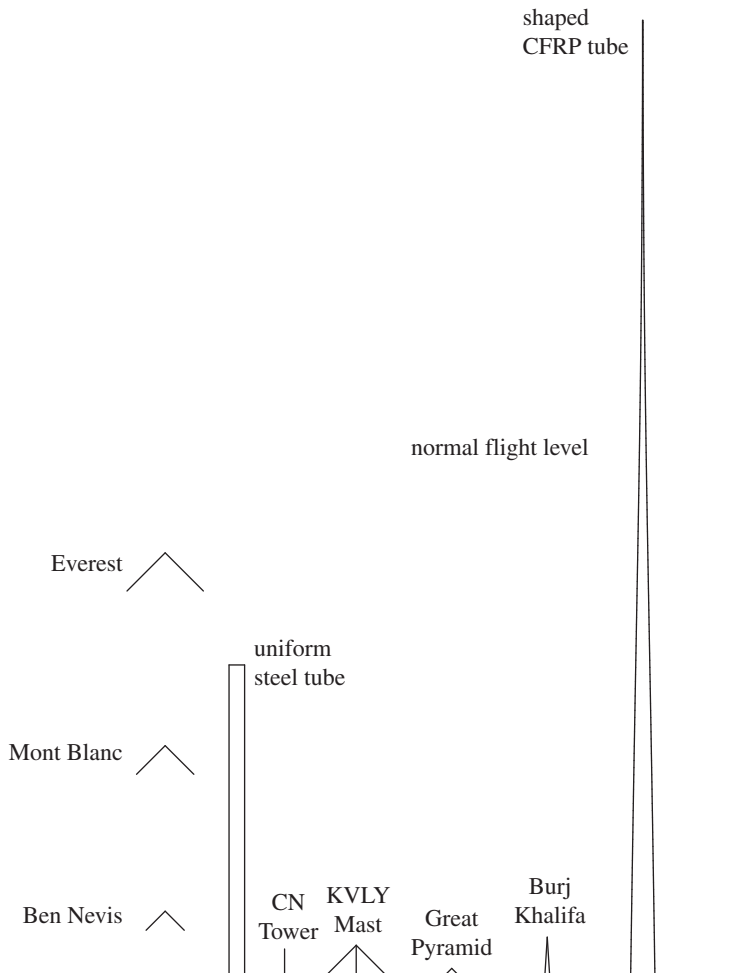


Figure 6. Comparison with notable tall structures (to scale).

Cost

There would be major supply issues for carbon fibre; current world production is of the order of 50 000 tonnes p.a. [<http://www.prnewswire.com/news-releases/reportlinker-adds-global-and-china-carbon-fiber-industry-report-2010-101893378.html>, date accessed: 31 October 2010] with around \$460 million for a 4800 tonne p.a. marginal increase including impregnation facilities [<http://pubs.acs.org/cen/news/85/i08/8508notw2.html>, date accessed: 31 October 2010]. At £60 000 per tonne p.a., a few trillion pounds would be needed to increase carbon fibre production to the 10+ million tonnes p.a. needed to make the materials for these towers (approx. 100 million tonnes of carbon fibre) over a 10 year period. Even if economies of scale meant that the cost of providing new plant reduced by 20 per cent each time production was doubled, scaling up production gives a cost (£1–2 trillion) that is comparable to the material cost quoted above, which neglects erection and fabrication costs. This approach would clearly need a very long time

to scale up production, followed by another very long time for the actual building; 50–100 years does not seem unreasonable.

Significant savings could be achieved if the CFRP tower were founded on a 5 km plateau; the base diameter would reduce to 350 m, and both the material weight and its cost would reduce by 70 per cent to give a cost of £77 billion per tower. Access to infrastructure would have to be provided, but the 1000 km railway to Lhasa at 6000 m is reputed to have cost about \$4 billion in 2006 [<http://news.bbc.co.uk/1/hi/4345494.stm>, date accessed: 31 October 2010]. Given the costs of a tower it would be worth constructing a road up Mt Everest and building a tower there!

The analysis presented above is simple, but reasonable. A more extensive variational analysis to choose the optimal shape of the tower, to resist both global buckling and flexural stresses, could be carried out, which might reduce the total weight of the tower. However, allowance would have to be made for reductions in stability caused by wind-induced deflections (a full wind load on the CFRP tube gives a deflection at the top of about 0.35 km). The ability to resist local buckling effects, distortions of the cross section and vibration of the tower when subject to gusting winds, all of which have been ignored here, would add weight to the tower. The foundations would need careful consideration, as would the tower's susceptibility to earthquake and even possibly local effects of applying a very high point load to the Earth's crust.

(ii) *Guyed masts*

Many of the existing studies of very tall towers, for example, Bolonkin [28], who proposes towers 100 km tall, and others [29], avoid the problem of buckling by assuming that the tower can be guyed. This is also the normal form of construction for tall unoccupied structures such as transmitter towers. However, the guys at the top of a 20 km tower would need to be about 30 km long. Depending on the degree of sag the designer chooses to allow, the tension in a cable hanging as a catenary between two supports, without any external load, can be many times its own weight [30]. The analysis is highly nonlinear [31], so it is difficult to come up with a simple factor without defining a very specific set of conditions, but if the ratio of the cable tension to the cable weight were a factor of 10, which would not be unreasonable, a material capable of supporting 300 km of itself in simple tension would be required, even before taking into account a safety factor, difficulties of anchorage, or creep. The only material commercially available at present would be poly-*p*-phenylenebenzobisoxazole (PBO); graphene and nanotubes might be possible if the strengths observed on minute quantities in laboratories could be reproduced in bulk but this has yet to be demonstrated. There are other issues: allowing more sag reduces the tension, but in turn reduces the effectiveness of the guys and allows the mast more freedom to move. The vertical component of the guy forces adds to the weight of the mast, thus exacerbating the very problem they are designed to solve. Inclined stay cables in bridges are known to be susceptible to wind-induced vibration [32] and are often themselves guyed with counter-cables and provided with dampers.

The guys would impose very large lateral loads at the top of the tower; once in place, the tower should be in equilibrium, but during erection it would not be in balance unless very complex rigging schemes were devised. It is no coincidence

that the world's tallest radio mast collapsed while an individual guy was being replaced [http://en.wikipedia.org/wiki/Warsaw_Radio_Mast, date accessed: 31 October 2010].

It is believed that the complexities of design, construction and maintenance would make the erection of a guyed tower impossible.

(iii) *Inflatable towers*

The construction of towers from inflatable tubes made from lightweight materials has been proposed [33]. That idea was used as the basis for a tower designed to reach an altitude of 20 km from a mountain-top plateau at a height of 5 km.

Unfortunately, no account is taken of sideways loads because of even moderate winds, to say nothing of jet streams, and a cursory analysis shows such a proposition is impracticable with any currently known construction materials. In addition, there is an error in the original concept, which assumes that the prestress from the internal pressure counteracts the structure's own weight, thereby preventing buckling, which is then ignored. But the prestress is part of a set of purely internal, self-equilibrating, forces, and although they might prevent local buckling of the skin they cannot prevent global buckling. Inflatable towers would be subject to exactly the same buckling conditions as have been described above. There is a direct analogy (although in reverse) with a bicycle brake cable; no matter how hard the cyclist applies the brake, the cable does not buckle because the compression in the cable sheath is equilibrated by an equal and opposite tension in the brake cable.

(c) *Aircraft*

Systems based on aircraft have the advantage of using modified military vehicles; they can loiter in the stratosphere long enough to disperse the particles effectively and would be reusable. They have the disadvantage that there would be a significant energy cost in getting to the required height, and there would be a significant modification cost. The analysis below is adapted from that given by Robock *et al.* [4].

(i) *Fast jets (F-15)*

The F-15 has a maximum payload of around 10 tonnes [<http://www.aerospaceweb.org/aircraft/fighter/f15>, date accessed: 31 October 2010] so injecting 10 million tonnes of aerosols into the atmosphere requires around a million flights per year. If each plane is capable of performing three 2 h flights per day, or roughly 1000 flights per year, a fleet of 1000 planes should be able to deliver the intended annual payload. The cost per plane is about £25 million. A fleet of 1000 modified planes would therefore incur a total capital cost of £25 billion. As the F-15 has a lifetime of only around 16 000 flight hours [<http://www.fas.org/programs/ssp/man/uswpns/air/fighter/f15.html>, date accessed: 31 October 2010] the planes would need to be replaced every 8 years, the annualized average replacement cost would therefore be around £3 billion.

The operating costs are classified, but for tanker planes such as the KC-135 a figure of \$4.6 million is quoted for 435 flight hours in 2003 dollars, which translates to about £8000 per flight hour today [<http://www.gao.gov/new.items/d03938t>].

pdf, date accessed: 31 October 2010]. It is assumed that costs for fast jets are at least as high. The annual operating costs for 1000 planes performing 2000 flight hours work out at £16 billion. The total cost for fast jets is thus £25 billion initial capital + £3 billion replacement p.a. + £16 billion operating costs p.a.

(ii) *Tanker jets (KC-10 and KC-135)*

The analysis is similar to the section above but the maximum altitude the tanker jets can reach is below that needed to get above the tropopause except in polar regions where injection is less effective. The payload of the KC-10 is around 80 tonnes [<http://www.af.mil/information/factsheets/factsheet.asp?fsID=109>, date accessed: 31 October 2010], so with 1000 flights p.a. a total of 125 planes would be required. In 1998, the KC-10 unit cost was \$88 million, corresponding to a cost today of £70 million or £9 billion for a fleet of 125. At 40 000 flight hours [<http://www.fas.org/programs/ssp/man/uswpns/air/fighter/f15.html>, date accessed: 31 October 2010], the lifetimes are considerably longer than those of the F-15 and thus a fleet replacement would only be necessary every 20 years. On average, therefore, replacement capital costs for planes amount to £440 million p.a. For 125 planes operating costs are $125 \times 2000 \text{ flight hours} \times £8000 = £2 \text{ billion}$. The total cost for tanker jets would be £9 billion capital + £0.44 billion replacement p.a. + £2 billion operating costs p.a.

Older KC-135 tankers have a lower payload of around 40 tonnes [<http://www.aerospaceweb.org/aircraft/transport-m/c135>, date accessed: 31 October 2010], requiring a fleet of 250 planes. The unit cost is about £32 million leading to a capital cost of £8 billion; if replaced every 20 years the annualized cost would be £400 million. With twice as many planes the operating costs would be doubled to about £4 billion p.a.

A hybrid system, in which the tanker carries both fuel and payload to 12 km height, and then transfers both to an F-15 using air-to-air refuelling techniques could also be considered but has not been costed.

The costs, particularly for the small jets, are related to high-performance military units; it could be expected that in the next 20–30 years the capital costs might reduce somewhat. It would also be possible to consider designing a new plane tailored to the role of stratospheric particle injection [3]. However, the operating costs would be likely to increase substantially in line with projected increases in energy costs. It should be possible to deploy a system such as this relatively quickly in an emergency, since a significant number of military jets are available now and would need relatively little modification, but there would almost certainly need to be new production if a permanent deployment were required. However, the political will required would be extreme reflecting the costs and environmental impacts: these are roughly equivalent to about 5 per cent of the current world wide passenger air traffic. It is presumed that the airbases would be located away from populated areas, to minimize noise pollution, and would be kept away from normal flight routes to avoid air traffic problems, giving a high environmental but moderate social cost.

(d) *Artillery*

The largest naval artillery shell that could be fired in the twentieth century weighed 1510 kg using the 18 inch (0.457 m) barrel designed for HMS *Furious* in

the First World War [34]. The size of the gun was effectively limited by the size of the ship needed to support it; the barrel itself weighed 151 tonnes and had a very complex form of construction. Such guns had a muzzle velocity of 738 m s^{-1} and a horizontal range of about 37 km. Air drag ($F_D = (1/2)C_D\rho v^2 A$) is significant; equating the change in kinetic and potential energy with the frictional drag for a shell moving vertically gives

$$-\frac{dv}{dh} = \left(\frac{g}{v} + \frac{1}{2} \frac{C_D A}{m} \rho v \right). \quad (3.3)$$

The drag coefficient for a streamlined projectile is reasonably constant in the subsonic and trans-sonic regions at around $C_D = 0.5$ and if it is assumed that air density decreases linearly with altitude from 1.2 to 0.1 kg m^{-3} at 20 km, then a simple numerical integration shows that if a 1510 kg shell were fired vertically it would need to have a muzzle velocity of about 800 m s^{-1} (Mach 2.6) just to reach 20 km. Smaller or heavier shells travel further.

It is assumed here that a similar gun, firing a 1500 kg shell, of which 800 kg is the aerosol payload, could be (re)developed relatively easily, and that it could be mounted on land, or on a specialized barge. The shells would need to be robust in order to withstand the accelerations when firing, and they would have to be intelligent to disperse the payload at the right time: requirements that might be difficult to achieve simultaneously. To lift 10 million tonnes p.a. would require 12.5 million shots a year. Inflation-adjusted estimates based on [5] for a slightly smaller shell give a 2009 cost of £15 000 per shot, or about £200 billion for shells per year. Gun barrels would need to be replaced at least every 3000 shots, because of wear and the effects of the very hot gases, at a cost of £1 million per barrel, and this rate of replacement assumes that relatively low accuracy is required for stratospheric lofting. Total annual expenditure on barrels would therefore be about £4.2 billion.

At a firing rate of 5 shots per hour, with continuous firing throughout the year, some 290 barrels would be required at any one time, and each barrel would need replacing every 25 days. There would be large setup costs but these would be small by comparison with the annual cost of shells (£200 billion) and barrels (£4 billion).

These cost estimates may be considered too high because no account has been made that the shell price might be expected to reduce given the scale of the operation but this will be offset by the environmental costs associated with recovery and clean up of the spent shells. There would probably be public opposition to the establishment of such a large arsenal of 'weapons', and this option has been classified with a moderate environmental and moderate social cost.

Although a system such as this would make use of 100-year-old technologies, there remain difficulties of making large gun barrels to withstand the very high pressures from the propellant, and it is probable that it would take many years and a large investment in heavy manufacturing facilities before an artillery system could be deployed.

(e) Missiles

Missiles differ from artillery in that they possess their own means of propulsion and guidance. There is no longer a need for the gun barrels that made up a large proportion of the cost of the artillery option.

(i) *Single-use missiles*

'Battlefield range ballistic missiles' (BRBMs) such as the Pakistani Hatf-1 have a range of 70 km, a weight of 1500 kg and a payload of 500 kg [<http://www.fas.org/nuke/guide/pakistan/missile/hatf-1.htm>, date accessed: 31 October 2010]. If this could be modified without incurring too much expense to yield a stratospheric rocket with a weight of approximately 2000 kg capable of lofting 1 tonne of aerosols into the stratosphere, delivering 10 million tonnes of aerosols per year would require 10 million flights per year. If particles are dispersed explosively and missiles are not retrieved, then this is also the annual number of rockets required. As a possible point of reference for the price, a sophisticated long-range cruise missile such as the Tomahawk has a unit cost of around £300 000 [<http://www.fas.org/man/dod-101/sys/smart/bgm-109.htm>, date accessed: 31 October 2010], thus one might assume that the short range, technologically less complex missiles required for stratospheric lofting might be procurable at a far reduced unit cost of £20 000. To inject the required amount of aerosol into the stratosphere would therefore cost $2 \times 10^4 \times 10^7 = \text{£}200$ billion annually.

The technology is available today, but the systems are complex, so it is assumed that it would take several years before production could be increased sufficiently for such a system to be deployed effectively. There would also be significant pollution from the exhaust gases, and expended missile casings. As with artillery, it is to be expected that there would be public objections to the significant expansion in the production of war-like systems, resulting in a classification of high environmental and moderate social impact.

(ii) *Retrievable missiles*

The cost of missiles can be significantly reduced if individual missiles are reused, in which case they would have to make a controlled landing. They would thus need to be powered after dispersing the payload so might be much more closely based on cruise missiles or a new generation of high performance UAVs. They would be expected to carry a more sophisticated particle dispersion technology and a landing mechanism, potentially doubling the unit cost to £40 000. In addition, individual missiles would need to be refuelled before each flight. If, as with balloons, one assumes 20 flights a year for each missile, then once retrieval and refuelling have been taken into account, about 500 000 missiles would be required. The initial expenditure on missiles would be £20 billion, one-tenth of the cost of one-shot missiles. However, the lifetime of the missiles can be expected to be of the order of one year, so this is probably also the annual replacement cost.

Although BRBMs generally use solid rocket fuel the price of jet fuel is used here as a first approximation. If 1000 kg of a missile weighing 2000 kg is fuel, and the price of jet fuel is $\text{£}0.42 \text{ kg}^{-1}$ [http://www.iata.org/whatwedo/economics/fuel_monitor/Pages/index.aspx, date accessed: 7 July 2010], then the fuel cost for 10 million flights per year is £4.2 billion. Total costs are thus of the order of £25 billion p.a. As with single-use missiles, the technology largely exists today, although the rate of production would need scaling up very rapidly, and there would be the same concerns about exhaust gases. Overall, retrievable missiles are classified with a lower environmental impact than single use missiles with a comparable social impact.

(f) Electrical systems

Electrical technology has developed to the extent that it is now feasible to use it to accelerate an object to the speeds needed by weapons. For stratospheric injection, the projectile would not need to be steered, so the system could be a fixed-axis device mounted inside a shaft in the ground, either vertically or, more probably, slightly inclined towards an area where the debris could safely fall. The naval gun discussed above achieves a muzzle velocity of 800 m s^{-1} with $1800 g$ acceleration in an 18 m barrel, whereas if the system consisted of a 1 km long tube in the ground, the acceleration would reduce to about $35 g$, which would then allow a much lighter casing to be used. Two technologies can be considered—railguns and coilguns.

(i) Railguns

Railguns are under development for use as weapons [<http://en.wikipedia.org/wiki/Railgun>, date accessed: 31 October 2010]. Two rails carry a large current that passes through the projectile; the interaction between these currents generates a propulsive force. In essence, it is a conventional electric motor with a single winding. The requirement for electrical contact between the rails and the projectile would lead to friction and wear, especially for systems such as those envisaged here that will be fired frequently. The very high current would also cause heating within the projectile, which would almost certainly impose constraints on the type of payload.

A railgun can provide energies of the order of 50 MJ and seems feasible for SRM operations in the near future [<http://www.defenseindustrydaily.com/bae-producing-scaled-down-rail-gun-naval-weapon-01986>, date accessed: 31 October 2010] but the use of coilguns presents a more suitable alternative and for this reason the railgun option has not been costed.

(ii) Coilguns

Coilguns use linear motor technology [<http://en.wikipedia.org/wiki/Coilgun>, date accessed: 31 October 2010]. By surrounding a tube with a series of annular coils that are switched on and off in sequence, a ferromagnetic projectile can be accelerated. As for the railgun, lower accelerations are experienced if the tube is very long. Long tubes mean that less steel is needed both to provide electromagnetic coupling and to resist the inertial forces, but more material is required for the tube and more coils are needed. One of the most significant design considerations for such a gun would be the difficulty of switching the coils on and off fast enough.

If it is assumed that the projectiles are of a similar weight to the artillery shells discussed above (1500 kg), but with only 250 kg of steel and 1250 kg of payload, then 8 million shots will be needed each year or about 1000 shots an hour. Each shell would contain less steel but, unlike conventional guns where the barrel is rifled to make the shell spin to achieve stability, it is probable that the projectiles would have to be provided with deployable fins, adding to the cost. It is assumed that each shell would be cheaper than an artillery shell at about £10 000, which would give an annual cost of £80 billion. Without the need to constrain very hot high-pressure gases, the lifetime of the tubes is expected to be much longer than

that of conventional gun barrels. If each gun can be fired once every 5 min, only about 80 coilguns would be needed. If it is assumed that each tube is mounted in a separate shaft drilled into the ground that costs £10 million to build, with another £10 million for the electrical equipment, then the capital cost is under £2 billion.

The kinetic energy of each 1500 kg shell at the muzzle velocity of 800 m s^{-1} is 480 MJ giving a total annual energy requirement of about 4×10^{15} J. As a rough guideline, consumer electricity prices in July 2010 were around £0.1 per kWh or $\text{£}3 \times 10^{-8}$ per J, giving total annual energy costs of £120 million. If the efficiency of the coilgun is 20 per cent, this would entail annual costs of £0.6 billion, which is small by comparison with the cost of the projectiles.

The overall costs are thus £2 billion setup costs plus £80 billion p.a., mainly for the shells themselves. The use of fins opens the possibility of making a reusable system, since it is conceivable that the shells could be programmed to glide back unpowered to a landing site downrange. This would significantly add to the cost and complexity of the system but would save on the number of shells that would be needed. The recovery option has not been costed because of the large number of unknown factors, but as with balloons it is expected that recovery will be a substantial contribution to the overall cost. It is assumed here that it would take about 10 years to develop a working system and to construct the required infrastructure, and there would be pollution issues associated with the spent casings falling back to Earth. These systems have been classified as having a moderate environmental impact as a result, but a low social impact.

(g) *High altitude airships*

Airships have the advantage, over free-flying balloons, of being powered and able (weather permitting) to navigate back to given launch points. In 2006, Lockheed Martin was granted a \$150 million contract by the US Army to construct high altitude airships capable of reaching the stratosphere for battlefield surveillance purposes [<http://www.defenseindustrydaily.com/lockheed-wins-1492m-contract-for-high-altitude-airship-updated-01607>, date accessed: 31 October 2010] but the project was delayed in 2008, before being re-launched in 2010 [<http://remixxworld.blogspot.com/2010/09/lockheed-martins-high-altitude-airship.html>, date accessed: 31 October 2010]. These airships are designed to loiter for long periods in the relatively low wind speeds at 20 km (compared with the higher wind speeds at lower altitudes) rather than shuttling up and down frequently. Basing costs on such a design probably gives a lower bound on the cost of an aerosol deployment system. The prospective cost per unit has been estimated at ‘tens of millions of dollars’, so £6 million is assumed here [http://www.usatoday.com/tech/science/space/2005-07-05-air-force-balloons_x.htm, date accessed: 31 October 2010].

The payload of each airship (150 m in length with a diameter of 46 m) is only 2 tonnes, so to loft 10 million tonnes of aerosols requires 5 million flights each year. If each airship is capable of performing two flights per day, including ascent, dispersal, descent and refuelling, then 7000 vessels are required, amounting to an initial £42 billion for airships. Very extensive ground handling facilities would be required, for which a similar amount probably needs to be added. Each airship carries around $135\,000 \text{ m}^3$ of helium (chosen for safety purposes) for

buoyancy [<http://www.globalsecurity.org/intell/systems/haa.htm>, date accessed: 31 October 2010]. In order to return to the ground after dispersing 2 tonnes of aerosol the airship will need to discard 2 tonnes worth of lift and this is most easily achieved by dumping roughly 20 per cent of the helium in the airship. At a crude helium price of £1500 per million m^3 [[http://www.blm.gov/pgdata/etc/medialib/blm/nm/programs/0/helium_docs.Par.50876.File.dat/FY2011 Posted Price final.pdf](http://www.blm.gov/pgdata/etc/medialib/blm/nm/programs/0/helium_docs.Par.50876.File.dat/FY2011%20Posted%20Price%20final.pdf), date accessed: 31 October 2010], £40 is required on each balloon per flight, amounting to £200 million for 5 million flights. However, there are significant concerns about the rate at which helium supplies are being depleted [35] and the cost is unlikely to remain so low for long. If each airship is designed to remain in the air for a year that gives a lifetime of approximately 9000 flight hours. If, as with multiple balloons, the average flight time is around 3 h and two flights are performed each day that gives a lifetime of 3000 flights a ship, or around 4 years. If the fleet is renewed at this frequency, the average annualized replacement cost would be about £10 billion.

The total is therefore about £80 billion startup costs, plus about £11 billion p.a. It is assumed that this project would take 10–20 years to reach practicality as a delivery system, and the side effects would be relatively small, apart from the significant amount of helium jettisoned during descent, giving a low social and environmental impact.

(h) Mixing aerosols into the fuel supplies of commercial flights

It has been suggested that sulphur compounds could be added to the fuel on commercial airliners to permit the deployment of albedo-enhancing aerosols without needing to expend large amounts of additional energy and resources on specifically constructed aerosol lofting mechanisms [<http://groups.google.com/group/geoengineering/web/jet-fuel-additive>, date accessed: 31 October 2010]. Commercial airliners only reach the stratosphere when flying over the poles. Elsewhere, the tropopause is above normal flight levels.

No modifications to the aircraft would be necessary and aerosols could be dispersed as part of jet engine exhaust. The practicality of such a scheme hinges on the amount of aerosol that could be delivered. There are four polar flight routes over the North Pole and none over the South Pole, accommodating about 10 000 cross-polar flights per year [http://www.icao.int/icao/en/assembl/a36/wp/wp144_en.pdf, date accessed: 31 October 2010; <http://travel.usatoday.com/flights/legacy/item.aspx?ak=68495594.blog&type=blog>, date accessed: 31 October 2010]. Most of these flights operate between the eastern United States and eastern Asia, corresponding to a distance of roughly 10 000 km. A Boeing 747 consumes some 17.5 l of fuel per km [<http://www-personal.umich.edu/~murty/planettravel2/planettravel2.html>, date accessed: 31 October 2010] corresponding to 175 000 l or 140 tonnes. Assuming that 5 per cent of this fuel payload could be allocated to transporting SO_2 aerosols then this accounts for only about 70 000 tonnes of SO_2 per year, or around 0.7 per cent of the necessary 10 million tonnes required. In addition, as discussed earlier, aerosols injected at the poles are believed to be much less effective for SRM than aerosol injection at mid-latitudes.

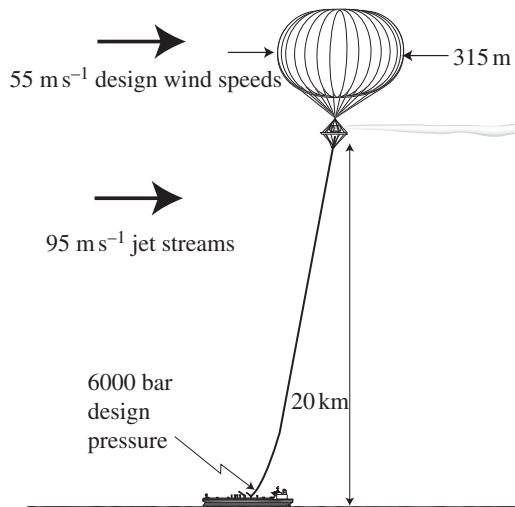


Figure 7. Tethered balloon concept. SO_2 flow of 96 kg s^{-1} or approximately $2\,500\,000 \text{ t yr}^{-1}$, per pipe and balloon system. Pipe: 200 mm o.d., 100 mm i.d., 21.5 km length.

(i) *Balloon-supported high-pressure pipes*

Pumping precursors to aerosols such as H_2S or SO_2 via a pipe elevated by a balloon or aerostat or has been suggested by a number of authors [36].

The concept that is described here was developed in 2009 by one of us and has been refined with the help of the co-authors: a large high-altitude balloon or aerostat located at around 20 km altitude of sufficient size can provide enough lift to support its own weight as well as the weight of a fibre-reinforced pipe, lifting devices intermittently spaced along the tether, and the weight of the fluid being pumped through the pipe [6] (figure 7).

The balloon system has a low cost and only moderate difficulty of manufacture, provided structural and stability considerations are satisfied. Some degree of streamlining can also be considered, but this is outside the scope of the current work.

However, the pipe needs considerable additional lift from aerodynamic surfaces providing a high lift to drag ratio. These need to be attached at a variety of altitudes to prevent the pipe from having too great an inclination to the vertical when exposed to jet streams and also to ensure suitable launch and recovery trajectories (see the forthcoming sections).

The analysis below is similar to that of Badesha *et al.* [37], where the wind profile was shown to be the most significant design driver for both the balloon size and tether tensions, and hence cost. Others also mention wind but do not factor its significant effect in their detailed analysis [3].

A design altitude of around 20 km was chosen to be just within the stratosphere, above the tropopause, in near-equatorial regions, allowing the majority of the material injected to circulate within the stratosphere and not immediately be lost to the troposphere. A higher altitude might be preferable to reduce losses further but a far larger balloon would be required to provide the necessary lift. The other great advantage of the 20 km altitude is that the wind strengths are at their

lowest at this altitude, typically being of the order of 20 m s^{-1} or less (see figure 1). However, the balloon needs to tolerate winds whose mean velocity is as much as 45 m s^{-1} at this altitude (P. Davidson 2010, personal communication). The wind speeds in figure 1 are taken from the ERA database and do not reflect short duration (2 min or more) gust speeds. These must be taken into account to prevent ‘blow-over’: in this scenario, the wind load on tether and balloon is sufficient to cause the balloon to be dragged sideways and downwards, leading to a pronounced fall in altitude of the balloon. This can drag the balloon into the higher wind speeds encountered at lower altitudes resulting in balloon failure. A wind speed of 55 m s^{-1} (continuous + 20%) has been used for ‘semi-static’ design purposes to prevent blow-over. For blow-over calculations, only winds of duration of at least 2 min need be considered to generate sufficient changes of height. Two minutes at approximately 45 m s^{-1} implies a vertical or horizontal eddy size of at least 5 km, which is unlikely at an altitude of 20 km, if the balloon is sited away from large mountain ranges.

Still shorter time-constant transient gusts must be considered in analyses of the dynamics of the system, and when ensuring the structural integrity of the tether and the balloon. Analyses for balloons at 6 km altitude suggest that stress peaks show relatively modest transients [38,39]. Extension of this analysis to 20 km will require some additional turbulence data for suitable sites. Predictions have been made about the response to severe turbulence of a smaller diameter tethered balloon at 20 km altitude for a thunderstorm propagating across the system with a core updraft and microburst. A benign balloon temporal response is reported, with the tether length scale (diameter) reacting to a comparatively narrow part of the turbulence energy spectrum that has very little energy. The model used 101 nodes to represent the balloon and tether, and a time duration of 2000 s with a time step of 0.01 s [40].

Balloon launch and recovery present particular problems for a tethered balloon. Free-flying balloons move with the wind in ascent or descent and are only affected by variations with a length scale similar to the balloon diameter, but a tethered balloon is subject to cross winds (with a maximum dynamic load at around 10 km altitude), so the balloon surface must be under tension from the launch level to operating altitude, to avoid the possibility of waves developing on its surface that could tear the fabric.

A conventional ballonet arrangement allows an internal air-filled balloon to be deflated on ascent and inflated by fans (which must be powered) on descent to accommodate a factor of 14 volume change in the lifting gas between 20 km altitude and ground level. This restricts the maximum rate of descent because of limitations on fan size and power. A similar problem has been described in trajectory simulation of the descent of a tethered balloon [41].

Another issue is that of vortex-induced oscillations of tethered balloons in directions both inline and transverse to the flow [38]. The drag on the balloon is less significant than the tether drag, and furthermore active oscillation control may be possible both with control surfaces on the tether and adjacent to the balloon.

Twisting and kinking of the tether have been raised as potential issues with variable wind direction and speed over the height of the tether. For kinking to occur, the longitudinal tension in the tether would need to fall transiently to zero which is not what is observed in the analyses described above. Three

thousand barrage balloons in the Second World War were successfully deployed in the most turbulent part of the lower atmosphere over the UK alone. This gives encouragement that such issues will not give material problems.

The particle injection does not need to be continuous, allowing operation for between 200 and 300 days of the year, given that the time constants of the upper atmosphere are of the order of 1–2 years (as seen with the Mt Pinatubo eruption). Jet streams occur at an altitude of around 10 (± 3) km and the design accommodates a peak jet stream velocity of around 95 m s^{-1} with 55 m s^{-1} winds at 20 km in the same direction. The maximum pipe angle under these conditions is between 10° and 35° to the vertical, so the tether length needs to be around 21.5 km. A large tethered balloon would best be deployed from a ship or an island, or possibly in desert regions with low population densities but with good rail transport links.

Siting considerations (leaving aside political questions) should preferably be in equatorial regions, with dry tropospheric conditions for at least six months of the year, leading to low lightning frequencies and minimal icing potential. Tether surfaces that are hydrophobic may also help in this regard. The vertical altitude over which ice can build up if suitable locations are chosen is likely to be small (approx. 2 km) compared with the tether length (approx. 20 km), with typical lapse rates of 6 K per thousand metres.

The tether acts both as a tension element and as a pipe carrying liquid at very high pressures. It thus has to withstand very high longitudinal tensile stresses *and* very high hoop stresses. Aramid fibres appear to be the most probable candidate materials from which to fabricate the tether. They are made on an industrial scale by a number of manufacturers; world production is of the order of 30 000 tonnes annually. They have a short-term strength of about 2700 MPa, and a density of 1440 kg m^{-3} , giving a free length (the length of itself that it will support) of about 190 km, which at first sight appears more than adequate. However, aramid fibres are susceptible to creep rupture, which is a thermally activated process [42] and allowance must be made for a 60 per cent fill factor, the weight of the product being delivered, fibres to resist the high hydrostatic pressures in the pipe, possible temperature effects from the product and from the environment, the need to anchor the tether, and a safety factor. A design stress of 750 MPa has been used here [42]. Although aramids are suited to this application, their capabilities will be pushed to the limit. A potentially much stronger alternative is PBO [43] with an allowable design stress of around 1500 MPa, and it has been successfully anchored, in the same way as aramids, without the use of resin. Such a doubling of design stress would allow the balloon volume to be halved. However, there are no published data on its creep and creep-rupture properties, which are currently being studied. Neither aramids nor PBO can carry axial compression since they form kink bands (essentially buckles at the sub-filament scale), which is another reason why the tether should be designed to be under tension at all times.

Alternative materials have been considered. Carbon fibres have strength comparable to that of aramids, and can be stiffer, but they are always used with resin (thus adding about 30% to the weight of the tether) and are difficult to anchor [44]. Their use would also make the tether electrically conducting. A lightning strike passing down the tether might destroy it. Another alternative would be ultra high modulus polyethylene (UHMPE) fibres, which are widely

used in the marine industries for ropes and cables, and have the advantage of being cheap. But they have the disadvantage that they creep which discounts their use in a pressure pipe.

The design pressure of 6000 bar allows all pumping requirements to be satisfied at ground level. The pumping power is determined by the hydrostatic head (of the order of 3000 bar) and additional frictional pressure drop, which for a low total system cost (pump + pipe + balloon) design is comparable to but lower than the hydrostatic head. With a mean supercritical SO_2 density of around 1400 kg m^{-3} throughout the pipe, and a maximum velocity inside the pipe of under 9 m s^{-1} , the frictional pressure drop is in the region of 2000 bar, leaving a maximum total operating pressure at the pipe base of less than 6000 bar. Water-jet pumps at 6000 bar, with a capacity of around 71 min^{-1} , have a cost of around £70 000 (manufacturer's quotation, 2011), compared with the required flow of the order of 4000 l min^{-1} , but a scale-up in flow rate of the order of 10–100 seems entirely practical even if this requires a number of parallel pumps. If high pressure positive displacement pumps have a cost versus capacity exponent of around 0.65, 25 pumps with a capacity of 160 l min^{-1} will cost around £630 000 each, and the whole pump assembly will cost around £16 million. Tripling this cost to allow for different materials and ground level pipe work gives a cost per installation of around £50 million or £200 million for the four installations.

As a cross-check, these numbers were compared with American data. The capital cost for a 4000 bar, 100 hp (75 kW) water-jet pump with all infrastructure is \$62 500 [<http://news.directindustry.com/press/jet-edge/jet-edge-introduces-low-cost-100hp-waterjet-pump-11866-333796.html>, date accessed: 31 October 2010]. Scaling up using a 0.65 power rule gives the cost of a 6 MW pump as $(6/0.074)^{0.65} \times \$62\,500 = \$1$ million each. Ten of these would be needed in each location. So, for four locations, the cost would be \$40 million. Allowing for more sophisticated technology than simple water pumps might cost 200 per cent more, suggesting a total capital of £75 million for the pumps for all four locations.

The energy required to lift the materials is only greater than the thermodynamic minimum to the extent that the design incurs frictional pressure drop, pump inefficiencies and dispersion power requirements. It is thus unlikely to be bettered by any design that involves high-speed delivery (artillery, rockets, etc.) or the use of intermittent carriers such as weather balloons or jet aircraft, where the additional payloads to be carried to altitude, or the energy costs of throwing away the carrier gases (either H_2 or He) are relatively prohibitive. For a pipe the pumping power is given by $500 \times 10^6 \text{ (Pa)} \times (100 \text{ (kg s}^{-1})/1400 \text{ (kg m}^{-3})) / 0.6$ (60% efficiency) = 60 MW. Assuming power costs of $\text{£}0.1 \text{ kW h}^{-1}$ and with an 85 per cent motor efficiency, the cost is about $\text{£}7000 \text{ h}^{-1}$.

A tether of outer diameter (o.d.) 200 mm with an inner diameter (i.d.) of 100 mm would weigh around 800 tonnes (with a composite density of 1600 kg m^{-3} and with an additional weight of fluid of around 250 tonnes). The sales price of aramid fibres is currently in the range $\text{\$}20\text{--}\text{\$}30 \text{ kg}^{-1}$, so assuming a fabricated cost of around $\text{\$}40 \text{ kg}^{-1}$ and a tether length of 21.5 km the cost of each tether would be in the range of £18 million.

Lifting devices comparable to small gliders attached to the tether mostly at between 7 and 13 km in altitude dramatically reduce the size of the tether and

balloon system. Approximately 4200 m^2 of wing area is needed with an associated cost (based on quoted prices for small commercial gliders) of £9 million.

Previous studies have considered smaller pipes for a 'slurry system' of 40 mm o.d. and 20 mm i.d. (for liquid), or 210 mm o.d. and 200 mm i.d. (for gas) [3]. The cost comparisons are very different from those calculated here. A material cost for pipes is given as \$2.5 million, which seems reasonable, but a development cost of \$10 billion, just for the pipes, is used in their cost estimates which seems excessively high. Those figures were based on the assumption that a balloon system would be as complex as a deep-water offshore oil production platform, which seems unreasonable. Many different manufacturers are already making pipes of 5–20 cm diameter for use as undersea fibre optic cable runs, umbilical systems for offshore oil and gas production or distributed district heating systems. Individual pipe runs can be many kilometres long. Based on manufacturers' quotations to the authors, and taking a conservative estimate that the facility costs are proportional to the volume of pipe produced, suggests a plant cost of about £40 million. The marginal material cost of the tethers would be around £10 million each; assuming seven tethers would be needed for development, with a development personnel cost of 20 staff for five years at an all-in cost of £200 000 per person year including equipment and facilities (£20 million) would make a total of £130 million. Allowing development and facility costs of the order of £130 million to £250 million would seem to be adequate.

The balloon has to withstand gusts and is envisaged to be a pressurized balloon with an operating differential pressure of around 800 Pa across the balloon envelope. Operating with pumpkin balloons might allow less fabric weight but such balloons have had launch issues, with large diameter balloons buckling at intermediate altitudes [45]. A $375 \mu\text{m}$ balloon fabric wall thickness gives a low wall stress of 170 N m^{-2} with a balloon weight of 160 tonnes and a payload of 10 tonnes (in addition to the weight of the tether).

One of the most contentious aspects of this proposition is the development and costing of the very large balloon. McClellan *et al.* [3] make a comparison with an airship and arrive at a costing of around \$400 million for a volume equivalent to that of a 300 m diameter balloon. For four units using these costs there would be a capital outlay of \$1.6 billion or £1 billion. However, an alternative strategy is to manufacture cheap balloons and not to re-use them after each deployment. That would obviate the need for expensive fan systems but could mean that descent would be uncontrolled. Simple high altitude balloons can be made in relatively cheap plant, essentially consisting of gore welding equipment, with the materials costs being simply those of the balloon fabric and the gondola.

Estimates of costs have been provided by a commercial balloon manufacturer. Fabric costs for material with a six month life at 20 km and design stresses of 1500 N mm^{-1} are around £20 m^{-2} . Manufacturing costs are comparable with fabric costs. Adding a 50 per cent margin gives conservative manufactured costs of £60 m^{-2} . For a 315 m diameter balloon with a surface area of around $300\,000 \text{ m}^2$, the manufactured cost on this basis would be around £18 million. A comparable cost needs to be added for the ballonet, which has a similar amount of fabric, giving a total balloon cost of around £40 million.

Alongside airships, this option has been classified as having a low environmental and social impact.

Table 2. Balloon system costs.

	capital per balloon (million £)	capital for four balloons (million £)	operating cost for four balloons (million £ p.a.)
tethers	20	80	80
lifting surfaces	10	40	20
balloons	40	160	160
pumps	50	200	30 maintenance + 200 electricity
ships/sites			100
total	120	480	590

(i) *Cost summary (excluding costs of aerosol and dispersal system)*

The estimated costs for the balloon system are shown in table 2. It is assumed that each balloon will operate for 7000 hours per year, giving an electrical power cost of about £50 million per year per balloon. It is assumed that the balloon and tether will be replaced each year and that annual pump maintenance will cost 15 per cent of the pump capital cost, and the cost of providing the ships and maintaining the launch sites will be £100 million per year. Together these give a total operating cost of about £600 million per year.

Development costs are likely to be less than four years' costs of a single station if infrastructure costs (ships) and SO₂ or particle generation facilities are excluded, leaving a total for capital + development costs of £600 million. Extended discussion on siting and legal/governance issues might increase these to £700 million but this may be a significant overestimate given the inherent simplicity of the design. Allowing between £700 million and £1000 million in development costs would seem to be adequate.

Such a sum would buy the plant to produce the tethers (£40 million), seven tethers (at £10 million each), seven assemblies of lifting devices (at £9 million each), seven large balloons (at £40 million each), a development, manufacturing, legal and management staff of 400 for 4 years (£320 million), and site facilities of £50 million.

If it were decided by a body, such as the Security Council of the UN, that SRM had to be introduced as a matter of extreme urgency, it is believed that this could be done within a period of 5 years and is the basis of the data point plotted in figure 8.

The facilities for manufacture of the tether already exist in the offshore industry, although some retooling would be necessary. Manufacturing facilities for balloons larger than any built so far would need to be established, and the balloons themselves tested, but this should just be a scale-up of existing technology. Parallel developments would need to be carried out for pumping and particle dispersal.

A more measured approach would however be highly desirable and might be spread over a generation. It would allow refinements of climate modelling, testing of the albedo effects and of the atmospheric chemistry impacts of the particles. It would allow testing of the actual delivery systems, first at low level, then at 20 km: in the first instance, nitrogen could be injected, followed later by injection

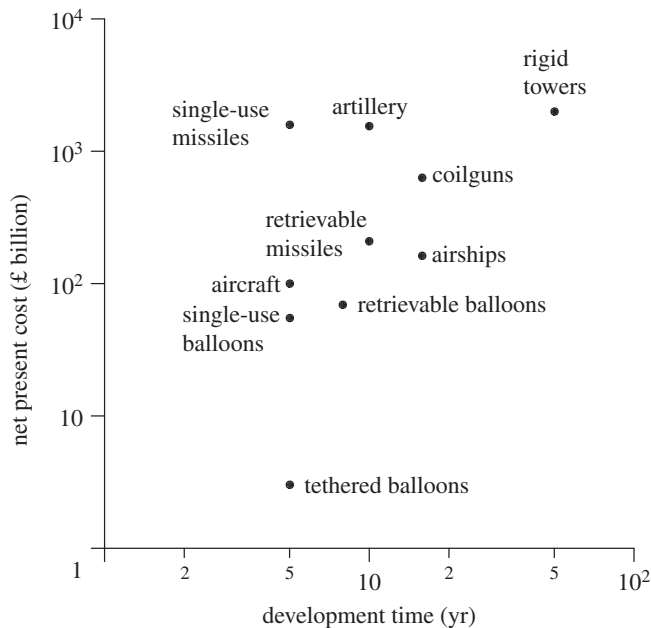


Figure 8. Costs and development times (both on logarithmic scales) for various options, excluding cost of material to be dispersed. Costs are net present costs taking a 5% discount rate and amortizing over 10 years for the injection of 10 million tonnes p.a. into the stratosphere, to mitigate the temperature effects of a doubling of CO₂ levels.

of very limited amounts of particulate matter whose effects could be monitored by ground-based, aerial or satellite observation. Only if these tests worked, and then only if a supranational body such as the UN mandated the work, would prototype and production versions of the system be implemented.

Were it found necessary to implement SRM climate remediation then the authors estimate that the research, development and governance process may take about 20 years with perhaps another 10–15 years for implementation in normal conditions. The basis for this estimate along with estimates of costs for each stage of the process are given in appendix A. These estimates are necessarily very approximate given the uncertainties of future global climate, economics and politics.

Appendix A shows an outline science and technology roadmap for developing not only the delivery technology but also the particle science and technology, the modelling of effect and some broad brush dialogue, communication, and governance issues. It should be noted that the cost estimates are dominated by the particle material costs if a manufactured particle (such as titanium dioxide) is used. These would be the same for all systems.

This delivery method has four main developmental issues:

- the size of the balloon (significantly larger than the world's largest balloon to date, which had a diameter of 120 m),
- the manufacture of a reliable high pressure tether,

- the need to ensure that no transient oscillations or dynamics compromise the integrity of the system, and
- the need to scale up pumping technology.

It is believed, however, that all of these factors, although challenging, are at the edge of existing technology in one or more fields and can be overcome with suitable development resource. Consideration is being given to the possibility of using an aerodynamically shaped tether. Allowing for imperfections of manufacture, the drag coefficient for an aerodynamic tether would typically be a third to a fifth of that for a circular tether. Since the design case for the balloon is that it must generate enough lift to prevent blow-over by the wind forces on the tether, an aerodynamic tether with intermittent lifting surfaces has the potential to significantly reduce the size of the balloon by a factor of 2–3 in diameter. However, each balloon would then only support a smaller pipe so more balloons (by a factor of 15–20 times) would be needed. Such a design would allow smaller scale tests to be carried out more readily. A stratospheric injection system with eighty 125 m diameter balloons rather than four 315 m balloons could be envisaged for a full-scale system. The total tether and balloon fabric weights for the two systems would be comparable.

4. Comparing aerosol delivery technologies

It is now possible to compare the various options for delivering aerosols to the stratosphere. Table 3 shows a comparison of the systems discussed above in purely financial terms; the costs are taken from the discussion made earlier and then a net present cost has been calculated for establishing each technology and operating it for 10 years, taking a discount rate of 5 per cent. Allowing for differences in the injection rate, the costs show good agreement with McClellan *et al.* [3] for the more limited number of technologies considered in that work, except for the tethered balloon. This difference can be explained by the much larger development costs suggested there, and the greater number of balloon systems.

Table 4 shows non-financial aspects, including the time needed to set up the facility.

Figure 8 shows the time and cost data together.

Rigid towers are extremely expensive mainly because of their very high initial cost, although their running costs would be low. And uniquely among the options they could allow manned access to a permanent dispersal facility at high altitude.

Single-use missiles, artillery and coilguns are all expensive, primarily because of the cost of the expendable delivery systems. It might well be possible, especially for coilguns where the accelerations during launch can be kept fairly modest, for the costs to be brought down if the delivery systems could be made to return autonomously to a landing facility.

Most of the other systems cluster around the middle of the figure, with the exception of the tethered balloon concept. It is worth reflecting on why this system is so cheap to ensure that no important factor is missing from the analysis.

Table 3. Summary of delivery technology costs. The initial procurement cost refers to the purchase price of capital necessary to begin delivery. In the case of technologies that involve fleets of delivery vehicles (e.g. planes, retrievable balloons, retrievable missiles) the cost of purchasing the initial fleet is taken. Single-use vehicles have procurement costs factored into operating cost. The net present cost is computed assuming a discount rate of 5% and covering a period of 10 years.

technology	initial procurement cost	annual operating cost (excluding particle costs)	net present cost (£billion)
single-use balloons	facilities + infrastructure	£7 billion	55
retrievable balloons	facilities + infrastructure + £1 billion	£9 billion	70
tethered balloons	ships + facilities + £0.7 billion development and initial setup costs	£600 million	5
rigid towers	£2000 billion for 4 towers	400 MW pumping power = £350 million	2003
50 : 50 fast jets/tankers	fleet of 500 fast jets + 65 tanker planes £17 billion	£11 billion	101
artillery	460 guns = £1 billion + facilities + infrastructure	£204 billion	1576
single-use missiles	low	£200 billion	1544
retrievable missiles	£20 billion	£25 billion	213
coilguns	£2 billion	£80 billion	619
airships	£80 billion	£11 billion	165

- The connection between the ground and the stratosphere, although permanent, is in tension and thus will tend to straighten, whereas the tower is in compression and tends to buckle. The lift for the supporting structure comes free, from the natural buoyancy of helium or hydrogen.
- Only the material to be dispensed at high altitude has to be lifted, and this is done by pumps at ground level. There are no casings to be manufactured, lifted, discarded or recovered.
- The accelerations during launch, pumping and recovery are all small, which means that the system can be made from lightweight materials.

All of these factors, taken together, mean that the system has the potential to have very much lower operating costs than the alternatives.

There is an additional advantage in that the system would remain in place more or less continuously. Unlike systems that have to dispense their payload in a very short time, the dispensing system can operate semi-continuously, and would not get thrown away after every shot. This opens the way to improving both the effectiveness of the dispersion techniques, and also the choice of particles to be dispensed.

5. Conclusion

There may be arguments against SRM of any kind, for instance that it does not directly retard ocean acidification, and there may be arguments against

Table 4. Estimates of non-financial criteria. It should be noted that this is a summary for comparison purposes only.

technology	time at altitude	minimum development time (years)	environmental impact	social impact
single-use balloons	hours	5	high	moderate
retrievable balloons	hours	8	moderate	moderate
tethered balloons	continuous	5	low	low
rigid towers	continuous	50	medium	moderate
aircraft	hours	5	high	moderate
naval artillery	seconds	10	moderate	moderate
single-use missiles	minutes	5	high	moderate
retrievable missiles	minutes	10	moderate	moderate
coilguns	seconds	15	moderate	low
airships	hours	15	low	low

geoengineering itself. But while it is desirable that we work on reducing carbon emissions now, it would be prudent to have emergency systems in reserve as an insurance policy. We should design the emergency mechanism before we need it, so that it can be tested to make sure that it is safe to use.

After considering the various options for SRM by stratospheric particle injection, we suggest that a tethered balloon supporting a pressurized pipe is likely to be efficient, practical, controllable and much cheaper than any probable alternative.

A tethered balloon system might be used to deliver SRM, not just as an emergency measure, but also as part of a well-moderated and thoughtful process of climate control.

Peter Davidson is employed by Davidson Technology Limited which has a patent application pending regarding SRM technologies. Hugh Hunt and Chris Burgoyne are employed by the University of Cambridge. They provided consultancy services for Davidson Technology Limited in 2009, in their personal capacities, and were named as inventors on the patent application. All ownership and rights in the patent application reside with Davidson Technology Limited. Hugh Hunt and Chris Burgoyne are currently working on the SPICE project at the University of Cambridge which is funded by EPSRC and NERC. Matt Causier is a research student at the University of Cambridge also working on the SPICE project.

The work described here was partly funded by the Engineering and Physical Sciences Research Council, the Natural Environment Research Council and Davidson Technology. The authors would like to thank Tony Cox and Francis Pope (University of Cambridge), who provided input on the chemistry of the stratosphere, Don Grainger and Dan Peters (Universities of Oxford and Bristol), and John Temperley (Huntsman Tioxide) who provided input on scattering. In addition, Peter Braesicke and Richard McMahon (University of Cambridge), Matt Watson (University of Bristol), Olivier Boucher and Jim Haywood (Met Office) and Lesley Gray (University of Oxford) provided wind data and helpful comments on early versions of this paper. Hilary Costello and Kirsty Kuo (University of Cambridge) have also provided background work on balloon and tether dynamics, and with Jonathan Cooper (University of Liverpool) measurements of aerodynamic tether drag. David Loew (University of Cambridge) carried out calculations on some of the comparative systems.

Appendix A. An outline science and technology roadmap for SRM climate remediation

1. Laboratory and concept development 3 years £2–3 million. Modelling of climate at approximately 50 km horizontal cell size.
 - (a) Explore the potential feasibility of managing ozone destruction processes in laboratory experiments, particularly by keeping N_2O_5 and chlorate surface reactions to a minimum.
 - (b) Demonstrate coating technologies in the laboratory that allow the potential to achieve coatings that are stable for 3 years, that are non-toxic and allow for 6000 bar slurring and dispersion.
 - (c) Demonstrate light scattering in the laboratory by suitably dispersed particles.
 - (d) Produce preliminary models of the impact on the flora and fauna of more diffuse light.
 - (e) Develop lower cost delivery technology: aerodynamic tether, vibration model, pumping concepts.
 - (f) Carry out public engagement at a modest level:
 - (i) communicate and discuss the scale of the problem,
 - (ii) discuss the concept of research to minimize the risk that we may have to carry out a ‘panic implementation’,
 - (iii) discuss the need to have a reversible intervention, and
 - (iv) discuss the strengths and weaknesses of the moral hazard argument.
 - (g) Examine the advantages and drawbacks of pre-made particulates in comparison with those created by slow hydrolysis of sulphates.
 - (h) Consider mechanisms that allow incremental testing of effect rather than a step change approach.
 - (i) Initiate a scientific, engineering and social debate on modelling needs and pace of implementation with a wide variety of stakeholders. Encourage dialogue with governments and non-governmental organizations including environmental groups.
 - (j) Develop scale-up and testing scenarios, and initiate discussion on what tests need international agreement, e.g. would tests not resulting in measureable ground illumination or precipitation changes over inhabited areas or areas of special scientific interest be routinely accepted?
2. Pre-trial development: injection of 100 tonne p.a. nitrogen at 20 km altitude: approximately 3 years £6–10 million.
 - (a) Test pumping concepts, stabilization of tether, aerostat, launch and recovery steps.
 - (b) Develop modelling scenarios: computing power, measurement and science fundamentals.

- (c) Continue laboratory work on phase 1 science + measurement techniques for operation off 20 km platforms and identify other monitoring technologies suitable for observing the microphysics of plumes.
 - (d) Begin dialogue with UN to establish mandate for micro- and small-scale tests, governance and legal structure.
 - (e) Obtain buy-in to research from some mainstream environmental organizations: consider options to protect biodiversity.
3. Micro trials at 20 km of 0.01 per cent full scale: 100 tonne p.a. or 2 tonne per week approximately 3 years £40–80 million, approximately £10–20 million p.a.
 - (a) Develop mandate for small-scale tests.
 - (b) Establish a climate remediation R&D centre on an ocean island with UN support, relatively near the equator.
 - (c) Test delivery technology, dispersion and pumping technology at a modest scale using a 150 000 m³ aerostat.
 - (d) Check atmospheric chemistry and opacity of plume, approximately 50 miles downstream, with balloons, satellites and aircraft; continue laboratory R&D and development work.
 - (e) Check coating stability, local weather effects.
 - (f) Demonstrate a variety of observation technologies from 20 km platforms.
 - (g) Computer model at approximately 10 times the resolution of 2011 capability with approximately 7 km horizontal cell size.
 - (h) Reaffirm environmental buy-in with preliminary field results. Further dialogue with disparate communities.
 4. Mini tests at 20 km. One per cent full scale (10 000 tonne p.a. or 200 tonne per week): approximately 6 years £80 million p.a.
 - (a) With UN support, test effect of plume to 500–2000 miles lengths over oceans: atmospheric chemistry, solar scattering, precipitation.
 - (b) Implement five 20 km altitude sampling points and three base stations.
 - (c) Monitor impact on a baseline series of ‘most sensitive areas’, e.g. South Asian monsoon, Sahel and Amazonian precipitation.
 - (d) Examine precipitation and vegetative impacts as well as microbiology under plume.
 5. Five per cent scale at 20 km. 50 000 tonne p.a. £200 million p.a. approximately 6 years.
 - (a) With UN support, increase to just-detectable effects over whole planet.
 - (b) Monitor ozone levels and regional precipitation.
 - (c) Modelling to 100 times the resolution of current capability (approx. 500 m resolution).

6. Implementation only if mandated by UN Security Council. Allow four years to build facilities and then ramp up full implementation in 10 years. Cost approximately £500 million p.a. at the start, rising to £3 billion p.a. at the end (2011 prices) for complete scaled-up system, including the cost of a manufactured particle such as 1 Mt p.a. titanium dioxide (approx. 15% of current world production rates). It is assumed that costs of TiO₂ are comparable to 2011 prices (around £2000 per tonne), but they could be lower because of the scale of the operation or higher because of an increased demand. At a rate of 2.5 Mt p.a., titanium dioxide costs would increase to £6–7 billion p.a. and would account for around 25 per cent of world titanium dioxide production but it is hoped that these rates would not be needed.

References

- 1 Shepherd, J. *et al.* 2009 *Geoengineering the climate: science, governance and uncertainty*. Royal Society Policy Document 10/09. London, UK: Royal Society.
- 2 Blackstock, J. J., Battisti, D. S., Caldeira, K., Eardley, D. M., Katz, J. I., Keith, D. W., Patrinos, A. A. N., Schrag, D. P., Socolow, R. H. & Koonin, S. E. 2009 Climate engineering responses to climate emergencies. (<http://arxiv.org/abs/0907.5140>)
- 3 McClellan, J., Sisco, J., Suarez, B. & Keogh, G. 2010 Aurora Flight Sciences Corporation geoengineering cost analysis final report, no. AR10-182, prepared under contract to the University of Calgary.
- 4 Robock, A., Marquardt, A. B., Kravitz, B. & Stenchikov, G. 2009 The benefits, risks, and costs of stratospheric geoengineering. *Geophys. Res. Lett.* **36**, L19703. (doi:10.1029/2009GL039209)
- 5 Committee on Science Engineering and Public Policy (COSEPUP). 1992 Geoengineering options, appendix Q. In *Policy implications of greenhouse warming: mitigation, adaptation, and the science base*, pp. 433–464. Washington, DC: National Academies Press.
- 6 Davidson, P., Hunt, H. E. M. & Burgoyne, C. J. 2011 *Atmospheric delivery system*. Patent application no. GB 2476518.
- 7 Archer, D. *et al.* 2009 Atmospheric lifetime of fossil fuel carbon dioxide. *Annu. Rev. Earth Planet. Sci.* **37**, 117–134. (doi:10.1146/annurev.earth.031208.100206)
- 8 Teller, E., Wood, L. & Hyde, R. 1997 Global warming and ice ages: prospects for physics based modulation of global change. UCRL-JC-128157, Livermore National Laboratory, Livermore, CA.
- 9 Keith, D. W. 2009 Photophoretic levitation of engineered aerosols for geoengineering. *Proc. Natl Acad. Sci. USA* **107**, 16 428–16 431. (doi:10.1073/pnas.1009519107)
- 10 Katz, J. I. 2010 Stratospheric albedo modification. *Energy Environ. Sci.* **3**, 1634–1644. (doi:10.1039/C00244ID).
- 11 Barksdale, J. 1966 *Titanium: its occurrence, chemistry and technology*, 2nd edn. New York, NY: The Ronald Press Company.
- 12 Pope, F. P., Braesicke, P., Grainger, R. G., Kalberer, M., Watson, I. M., Davidson, P. J. & Cox, R. A. In press. Properties and impact of stratospheric aerosol particles proposed for solar radiation management. *Nature*. (doi:10.1038/nclimate1528)
- 13 Haywood, J. M. *et al.* 2010 Observations of the eruption of the Sarychev volcano and simulations using the HadGEM2 climate model. *J. Geophys. Res.* **115**, D21212. (doi:10.1029/2010JD014447)
- 14 Deshler, T., Liley, G. B., Bodeker, G., Matthews, W. A. & Hofmann, D. J. 1997 Stratospheric aerosol following Pinatubo, comparison of the north and south mid latitudes using *in situ* measurements. *Adv. Space Res.* **20**, 2057–2061. (doi:10.1016/S0273-1177(97)00595-4)
- 15 Guo, S., Bluth, G., Rose, W., Watson, I. M. & Prata, A. 2004 Re-evaluation of SO₂ release of the 15 June 1991 Pinatubo eruption using ultraviolet and infrared satellite sensors. *Geochem. Geophys. Geosyst.* **5**, Q04001. (doi:10.1029/2003GC000654)

- 16 Lambert, A., Grainger, R. G., Remedios, J. J., Rodgers, C. D., Corney, M. & Taylor, F. W. 1993 Measurement of the evolution of the Mt. Pinatubo aerosol cloud by ISAMS. *Geophys. Res. Lett.* **20**, 1287–1290. (doi:10.1029/93GL00827)
- 17 Pierce, J. R., Weisenstein, D. K., Heckendorn, P., Peter, T. & Keith, D. W. 2010 Efficient formation of stratospheric aerosol for climate engineering by emission of condensable vapor from aircraft. *Geophys. Res. Lett.* **37**, L18805. (doi:10.1029/2010GL043975)
- 18 Rasch, P. P. 2008 Exploring the geoengineering of climate using stratospheric sulfate aerosols: the role of particle size. *Geophys. Res. Lett.* **35**, L02809. (doi:10.1029/2007GL032179)
- 19 Wigley, T. M. 2006 A combined mitigation/geoengineering approach to climate stabilization. *Science* **314**, 452–454. (doi:10.1126/science.1131728)
- 20 Bluth, G. J. S., Rose, W. I., Sprod, I. E. & Krueger, A. J. 1997 Stratospheric loading of sulfur from explosive volcanic eruptions. *J. Geol.* **105**, 671–684. (doi:10.1086/515972)
- 21 Berrisford, P., Dee, D., Fielding, K., Fuentes, M., Kallberg, P., Kobayashi, S. & Uppala, S. 2009 The ERA-interim archive. ERA Report Series Number 1, ECMWF.
- 22 Endlich, R. M., Solot, S. B. & Thur, H. B. 1955 The mean vertical structure of the jet stream. *Tellus* **7**, 308–313. (doi:10.1111/j.2153-3490.1955.tb01167.x)
- 23 Rose, K. & Steinbüchel, A. 2005 Biodegradation of natural rubber and related compounds: recent insights into a hardly understood catabolic capability of microorganisms. *Appl. Environ. Microbiol.* **71**, 2803–2812. (doi:10.1128/AEM.71.6.2803-2812.2005)
- 24 Joshi, M. M. & Jones, G. S. 2009 The climatic effects of the direct injection of water vapour into the stratosphere by large volcanic eruptions. *Atmos. Chem. Phys.* **9**, 6109–6118. (doi:10.5194/acp-9-6109-2009)
- 25 Smitherman Jr, D. V. 2000 Space elevators: an advanced Earth-space infrastructure for the new millennium. Report NASA/CP-2000-210429, NASA Marshall Space Flight Center, Huntsville, USA.
- 26 Tritton, D. J. 1988 *Physical fluid dynamics*, 2nd edn. Oxford, UK: Oxford University Press.
- 27 Timoshenko, S. P. & Gere, J. M. 1961 *Theory of elastic stability*. New York, NY: McGraw-Hill.
- 28 Bolonkin, A. A. 2007 Optimal rigid space tower. In *Proc. 45th Aerospace Science Meeting, Reno, Nevada, 8–11 January 2007*, AIAA-2007-367.
- 29 Krinker, M. 2010 Review of new concepts, ideas and innovations in space towers. (<http://arxiv.org/abs/1002.2405>)
- 30 Irvine, H. M. 1981 *Cable structures*. Cambridge, MA: MIT Press.
- 31 Kiureghian, A. & Sackman, J. L. 2005 Tangent geometric stiffness of inclined cables under self-weight. *J. Struct. Eng.* **131**, 941–945. (doi:10.1061/(ASCE)0733-9445(2005)131:6(941))
- 32 Gimsing, N. J. 1997 *Cable supported bridges*. New York, NY: Wiley.
- 33 Quaine, B. M., Seth, R. K. & Zhu, Z. H. 2009 A free-standing space elevator structure: a practical alternative to the space tether. *Acta Astronaut.* **65**, 365–375. (doi:10.1016/j.actaastro.2009.02.018)
- 34 Buxton, I. 2008 *Big gun monitors: the history of the design, construction and operation of the Royal Navy's monitors*. Barnsley, UK: Seaforth Publishing.
- 35 National Materials Advisory Board. 2010 Selling the nation's helium reserve. Committee on Understanding the Impact of Selling the Helium Reserve; National Materials Advisory Board; National Research Council.
- 36 Chan, A. K., Hyde, R. A., Myhrvold, N. P., Tegreene, C. T. & Wood, L. L. 2008 *High altitude atmospheric alteration system and method*. US Patent application no. 11/788383.
- 37 Badesha, S. S., Euler, A. J. & Schroeder, L. D. 1996 Very high altitude tethered balloon parametric sensitivity study. In *Proc. 34th AIAA Aerospace Science Meeting, Reno, NV, 15–18 January 1996*, AIAA-1996-0579.
- 38 Redi, S., Aglietti, G. S., Tatnall, A. R. L. & Markvart, T. 2011 Dynamic response to turbulence of tethered lighter than air platforms. *AIAA J. Aircraft* **48**, 540–552. (doi:10.2514/1.53522)
- 39 Aglietti, G. S. 2009 Dynamic response of a high-altitude tethered balloon system. *J. Aircraft* **46**, 2032–2040. (doi:10.2514/1.43332)
- 40 Badesha, S. S. & Bunn, J. C. 2002 Dynamic simulation of high altitude tethered balloon system subject to thunderstorm windfield. In *Proc. AIAA Atmospheric Flight Mechanics Conf., Monterey, CA, 5–8 August 2002*, AIAA-2002-4614.

- 41 Badesha, S. S., Euler, A. J. & Schroeder, L. D. 1996 Very high altitude tethered balloon trajectory simulation. In *Proc. AIAA Atmospheric Flight Mechanics Conf., San Diego, CA, 29–31 July 1996*, AIAA-1996-3440.
- 42 Giannopoulos, I. P. & Burgoyne, C. J. 2009 Stress limits for aramid fibres. *Proc. Inst. Civ. Eng. Struct. Build.* **162/SB4**, 221–232. (doi:10.1680/stbu.2009.162.4.221)
- 43 Kitagawa, T., Ishitobi, M. & Yabuki, K. 2000 An analysis of deformation process on poly-*p*-phenylenebenzobisoxazole fiber and a structural study of the new high-modulus type PBO HM+ fiber. *J. Polym. Sci. B: Polym. Phys.* **38**, 1605–1611. (doi:10.1002/(SICI)1099-0488(20000615)38:12<1605::AID-POLB50>3.0.CO;2-Z)
- 44 Al-Mayah, A., Soudki, K. & Plumtree, A. 2006 Development and assessment of a new CFRP rod–anchor system for prestressed concrete. *Appl. Compos. Mater.* **13**, 321–334. (doi:10.1007/s10443-006-9019-6)
- 45 Pagitz, M. & Pellegrino, S. 2007 Buckling pressure of ‘pumpkin’ balloons. *Int. J. Solids Struct.* **44**, 6963–6986. (doi:10.1016/j.ijsolstr.2007.03.021)