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LETTER

Review of possible very high-altitude platforms for stratospheric aerosol injection

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Abstract

Economically efficient injection of aerosols into the stratosphere for the purpose of deflecting incoming sunlight and managing the Earth's energy budget would require high-altitude deployment platforms. Studies suggest that high-altitude injection at 25 km would substantially enhance the forcing efficacy of the aerosols compared to injections at 20 km. While platforms capable of lofting and releasing aerosols up to an altitude of 20 km have been explored in other studies, similar studies assessing the feasibility of deployment platforms at an altitude of 25 km seem to be lacking. No existing aircraft is suitable for this purpose. In this paper, we review five possible concepts for deployment at 25 km and conclude that all of them would multiply costs, complexity, and operational risk substantially relative to deployment at 20 km.

Introduction

Stratospheric aerosol injection (SAI) is a prospective climate intervention that would seek to reduce global average surface temperatures by deflecting away from the Earth a very small fraction of the incoming sunlight [1, 2]. SAI is a controversial [3–5] and untested climate intervention that could result in undesirable impacts [6–8] and is not proposed as a substitute for either emissions reductions or adaptation [2, 9]. However, similar aerosol injections from large volcanic eruptions have long been known to substantially reduce surface temperatures even at points far removed from their origin, an effect that was directly measured and attributed after the eruption of Mount Pinatubo in 1991 [10, 11]. There is also increasing confidence that SAI deployment would be both aeronautically feasible [12] and extraordinarily cheap [13] relative to other prospective measures by which to combat climate change or its impacts.

In order to achieve an atmospheric endurance on the order of 12–18 months rather than mere days or weeks, aerosols intended to cool the planet would need to be deployed above the vertically turbulent troposphere and instead in the relatively quiescent stratosphere [14]. If deployments occurred in the tropics and subtropics as is commonly assumed [6, 15, 16], this implies deployment altitudes above 16 km. To avoid having material immediately re-enter the troposphere as well as to allow for atmospheric and seasonal variation, a deployment altitude of 20 km is commonly assumed [17, 18]. Studies of alternative lofting concepts such as balloons, rockets, guns, or tethered hoses conclude that at 20 km, the most efficient and reliable lofting technology would be fixed-wing, self-propelled, air-breathing jets [19, 20]. Few jets can achieve such an altitude and those that do carry comparably tiny payloads [19]. However, conceptual design studies show that a fleet of jets appropriate to the deployment mission could be reliably created using existing engines, wing planforms, and sub-systems for a developmental budget of a few billion dollars [12, 19]. This would be a novel assemblage of well-established technologies.

However, modelling studies have suggested that higher deployment altitudes are positively correlated with atmospheric endurance, yielding a greater stratospheric aerosol mass and therefore radiative forcing efficacy per unit of aerosol deployed [6, 21, 22]. Moreover, compared to injections at lower altitude, injecting sulfur at higher altitude results in less heating of the tropopause which, in turn, reduces the amount of water vapor that is lofted into the stratosphere [23]. Water vapor enhances the longwave radiative forcing in the stratosphere and reduces the thickness of the total column ozone [24]. At latitudes in the tropics and subtropics considered viable for deployment, achieving a targeted level of cooling would require roughly 80% more material were it deployed at or near the tropopause relative to a deployment 5 km above the tropopause [6]. Nonetheless, these studies have given rise to a more general question of whether even higher deployment altitudes could lead to superior results. As both costs and prospective undesirable environmental impacts of SAI would be positively correlated to deployed aerosol mass, a more efficacious deployment altitude could substantially reduce the mass of aerosol that would need to be deployed to achieve a targeted temperature result. In this paper, we seek to determine the feasibility and cost implications of deployment at 25 km.

We do so by reviewing five aircraft concepts that could potentially achieve deployment at 25 km.

The 20 km baseline

The baseline lofting solution which we use for comparison is the first generation Stratospheric Aerosol Injection Lofter (SAIL-01) aircraft described in Bingaman *et al* (2020) [12] and used for costing purposes in Smith (2020) [13]. In the months between the publication of these two papers, fuel and payloads were recalculated such that the payload assumed in Bingaman *et al* (2020) was increased to 34,000 pounds in Smith (2020). It is assumed to be capable of lofting a 15.4 metric tonne payload to 20 km and venting it in level flight in an hour. To permit the aircraft to cruise in the very thin air at 20 km, the SAIL-01 has a large wing area similar to that of a Boeing 747 jumbo jet despite having a compact fuselage more comparable to a narrowbody B737. SAIL-01 is expected to undertake three or more sorties per day year-round (save for scheduled maintenance). It is assumed to enter service with pressure-suited pilots in the cockpit, but may thereafter evolve into a remotely piloted vehicle. SAIL-01's ability to achieve sustained level flight at altitude would enable it to carry any prospective aerosol type and release it sufficiently slowly to comply with the dispersion rate limits described in Pierce *et al* (2010) [18]. Observing the 'Pierce Limit' avoids the reduced aggregate surface area that would result from excessive coagulation and that would otherwise compromise Mie scattering efficiency and radiative forcing efficacy. However, the Pierce Limit is relevant only in respect of aerosols or aerosol precursors that are immediately condensable and does not constrain the venting rate of precursors such as sulfur dioxide that mix for weeks before oxidizing into sulfates [25]. To allow for apple-to-apple comparisons among varying deployment platforms, all the calculations noted herein assume that the deployed material is sulfur dioxide. Nonetheless, it should be noted that those platforms considered herein that do not accommodate level flight at altitude would therefore be limited only to payloads of non-condensable gaseous precursors. In this way, the choice of platform may constrain the choice of aerosol species, thereby inhibiting attempts to optimize particle size.

Despite its robust deployment capabilities at 20 km, the SAIL-01 would be unable to deploy as high as 25 km due to the reduction of dynamic pressures (and hence aerodynamic lift) at its Mach 0.9 speed limit. In addition, its six F118-GE-101 engines would likely flame out well below that altitude. To ascend to such heights, greater speed is required to produce enough dynamic lift, coupled with an engine capable of delivering sufficient thrust. This leads either to supersonic aircraft with afterburning turbojet, ramjet, or rocket engines, or to abandoning the objective of level flight at the deployment altitude.

Very high-altitude deployment concepts

To achieve the design objective of deploying substantial masses of aerosols or precursors at 25 km (roughly 82,000 feet), the authors considered five concepts. We do not claim that this is an exhaustive list. Rather, these are the salient ideas that arose as a group of experienced aeronautical engineers with more than a century-and-a-half of combined aircraft design experience brainstormed about how the deployment requirement could be reasonably fulfilled. These represent classes of aircraft that have been employed for other very high-altitude (VHA) aerial missions and should therefore represent a plausible first cut at possible solutions. Beyond the requirement to be able to haul a meaningful payload to the target altitude, other design considerations include: compatibility with existing runways and hangars; compatibility with standard communications equipment; and a minimum 4,000 nautical mile range in ferry mode, such that the aircraft can cross oceans and be deployable

Table 1. Aircraft weights (in pounds).

	Operating empty weight	Take-off gross weight	Fuel + oxidizer	Aerosol payload	Aerosol payload fraction
SAIL-01 at 20 kms	84,700	134,400	15,700	34,000	25%
25 km concepts					
Rocket Assisted Subsonic (SAIL + Rocket)	91,411	143,300	33,889	18,000	13%
Supersonic Ballistic Climber (F-15C)	28,200	46,200	15,000	3,000	6%
Mothership & RPD					
Mothership (WK2)	87,191	138,353	16,162		
Remotely Piloted Drone	14,261	35,000	12,739	8,000	6%
Supersonic Cruiser (SR-71)	60,000	118,000	35,000	23,000	19%
Mortar Platform (747–400)	404,600	848,440	200,000	30,694	4%

Table 2. Aircraft activity and fleet requirements.

	Maximum payload tonnes per sortie	Minutes block time per cycle	Sorties per day per active aircraft	Tonnes required per 1 °C cooling (Millions) per year	Sorties required per 1 °C cooling (Millions) per year	Fleet required per 1 °C cooling
SAIL @ 20 kms	15.4	90	3	18.6	1.2	1,215
25 km concepts						
SAIL + Rocket	8.2	40	4	10.3	1.3	1,052
Ballistic Climber	1.4	30	4	10.3	7.6	6,312
Mothership & RPD						
Mothership		60	3		2.8	3,156
RPD	3.6	60	3	10.3	2.8	3,156
Supersonic Cruiser	10.4	60	2	10.3	1.0	1,646
Mortar Platform	13.9	420	1	10.3	0.7	2,243

globally. All platforms considered here would be assumed to operate from a global array of bases in both the Northern and Southern Hemispheres and therefore from several countries.

The five very high-altitude lofting concepts considered here are:

1. A rocket-assisted subsonic version of SAIL-01
2. A supersonic ballistic climber derived from the F-15C fighter jet (Streak Eagle)
3. A two-stage mothership and rocket-powered drone modeled on the Virgin Galactic hardware
4. A supersonic cruiser updating the design of the SR-71 Blackbird
5. A modified 747–400 serving as a mortar platform

These vehicles are very different from each other in almost every dimension, but a comparative table of weights is presented in table 1 below.

Given the diverse payload capabilities and cycle times for these platforms, they require very different operational paces and fleet sizes, as is illustrated in table 2 below.

Rocket-assisted subsonic vehicle

Since the F118-GE-101 engines that power SAIL-01 would begin to flame out above 22 km, the first VHA concept is to equip a similar aircraft with a larger wing and a rocket engine that could be fired as the plane reached 22 km to power the craft on its final climb to 25 km. The aircraft utilizes a 10,000-pound thrust rocket motor burning hydrogen peroxide and Jet A fuel. The vehicle would remain at its apex for under two minutes, meaning the aerosol tanks would be rapidly evacuated in a manner inconsistent with the Pierce Limit.

This concept entails substantial operational risk since all the main F118 engines are expected to shut down as the vehicle climbs to 25 km altitude. Aircraft electrical and hydraulic power would be maintained with an onboard hydrazine powered Auxiliary Power Unit. Air restarts during descent are feasible and are assumed here, but with hundreds of thousands of flights per year, there is a significant likelihood of engines failing to restart in midair, resulting in an attempted dead stick landing or prospective crash. Having the vehicle designed to be remotely pilotable would remove the crew from danger but would not reduce vehicle or ground risks and would substantially complicate the certification path.

Supersonic ballistic climber (F-15C)

Another viable lofting concept would be an aircraft capable of climbing under its own power to an altitude in the range of 20 km and then undertaking a supersonic ballistic climb. In this case, a viable candidate already exists and remains in service today—the McDonnell Douglas F-15, a twin-engine high performance air superiority fighter jet. While F-15s generally operate at more conventional altitudes, a stripped down F-15C dubbed the 'Streak Eagle' set eight time-to-climb records in 1975 and topped out over 31 km [26]. The F-15 or a derivative could be de-weaponized and adapted to carry a small payload via a ballistic trajectory to 25 km, release the aerosol (or its precursor) at the apogee in the span of roughly a minute, and then descend. As the engine will have flamed out during the ascent, here too a mid-air engine restart would be required.

Rather than a full developmental budget, only a modification program budget is assumed for this platform so as to enable it to accommodate the payload, nozzles, and controls. Thereafter, new purpose-built F-15s would be manufactured consistent with the modified type certificate. However, a 'tankerized' F-15 would still carry a very modest payload, requiring a comparatively huge fleet.

Rocket powered drone launched from a mothership

An alternate method of lofting a substantial aerosol payload to 25 km would involve using a mothership paired with a second stage rocket powered drone (RPD). Our model for this is the White Knight 2/SpaceShipTwo combination by which Virgin Galactic intends to commercialize space tourism. The mothership launches from the ground base with the 'daughtership' tucked under its wing. At an altitude of roughly 15 km, the mothership would release the RPD. After a brief drop, the RPD would ignite its rocket motor and climb up to 25 km, where it would inject its aerosol payload. Virgin Galactic's space plane 'Unity' that hoisted Richard Branson to an altitude of 86 km in July 2021 uses RocketMotorTwo. This is an updated version of the first-generation engine designed by the Sierra Nevada Corporation that produces 72,000 pounds of thrust—substantially more than would be required to enable the RPD to reach the relative trifling altitude of 25 km. Using the mothership for the first stage of the operation reduces the fuel required to climb the remaining distance to altitude and increases the payload. After separation, the mothership would then return directly to base, while the RPD would undertake its climb, apogee, and descent. Since Virgin's SpaceShipTwo is intended to carry tourists, it is of course piloted *in situ*, but the RPD contemplated here would commence operations above commercial airspace while carrying a chemical load yet higher and is therefore a promising unmanned aerial vehicle candidate.

The RPD incorporates a scaled down 10,000-pound rocket engine similar to that considered in respect of the modified SAIL-01 above, with the same fuel and oxidizer. SpaceShipTwo is planned for final altitudes above 80 km, so with this two-stage concept, yet more altitude with reduced payload could be achieved were it desirable for deployment. Although similar rocket motors have been utilized in the past, a healthy modification budget is assumed herein rather than a full developmental budget.

Before we divert from rocketry, a logical question would seem to be whether the rapid recent advances in commercial rocket technology pioneered by such parties as SpaceX and Blue Origin would be directly applicable to the SAI deployment mission at 25 km. The simple answer is - not in the foreseeable future. Rockets are a vastly more expensive lofting technology than fixed wing aircraft, with a cost per tonne for SpaceX's Falcon Heavy rocket more than 500 times that of SAIL-01 [13, 27]. This is of course an apples-to-oranges comparison, as SpaceX is hauling satellites 300–500 km above the Earth's surface whereas the unmodified SAIL-01 tops out at roughly 5% of those altitudes. As the two-stage Virgin Galactic hardware demonstrates, rockets would be relevant only for the last few kilometers of altitude required for even VHA SAI deployment. A pure rocket solution is simply a very expensive mismatch for the SAI mission.

Supersonic cruiser (SR-71)

Though out of service for since 1998, the SR-71 aircraft is another high-altitude vehicle that demonstrates the feasibility of supersonic level flight at 25 km. Its service ceiling was roughly 26 km (85,000 ft) [28], but to continue to generate dynamic lift in such thin air it was required to operate at blazing speeds in excess of Mach 3. By comparison, the new Boom supersonic airliner cruises at a speed of Mach 1.7, whereas the long retired Concorde used to cruise roughly at a speed of Mach 2, both at an altitude of 18 km [29, 30].

The SR-71 was powered by two Pratt & Whitney J58 engines, each of which was capable of providing 32,500 pounds of static thrust [31]. To withstand the high temperatures encountered when operating at maximum speed, the aircraft was comprised mostly of titanium, making it vastly more expensive than aircraft composed of customary materials such as aluminum or composites.

Optimized for speed and altitude, the SR-71 had poor operational robustness, with a one-week maintenance interval required between flights. Moreover, 12 of the 32 aircraft ever built were lost to accidents [32]. Each of these defects would presumably be addressed in a modernized variant of such an aircraft, but the accident loss rate demonstrates that a Mach 3 + cruiser may never lend itself to the sort of routine high-frequency operational role required for aerosol deployment. On the other hand, it would accommodate level flight at altitude and therefore the sort of metered deployment consistent with the Pierce Limit. As the SR-71 is a 60s-era design that has been out of service for more than 20 years, a very substantial developmental budget is assumed herein for a new supersonic aircraft.

Mortar platform (747–400)
A final concept would be to install mortars in a pre-existing high payload aircraft and fire them from a normal airliner cruising altitude. The shells would be propelled from say 12 km to an altitude of 25 km where they would explode, deploying their aerosol (or precursor) payload. For example, a 747–400 could have two 155 mm guns installed each pointing up and slightly backward. A port covering the gun muzzles would be opened at altitude and firing would commence. Deployment would be over a restricted area likely at sea so as to minimize the hazard from falling debris and shrapnel. At three rounds per minute from each gun, a 747 could lob 2,160 shells over a six hour cruise leg, delivering over 30,000 pounds of aerosol to 25 km. This scenario assumes a modification budget for the 747–400 and a line restart to newly manufacture a modified design of this out-of-production aircraft.

Fleet and costs

In evaluating these diverse lofting solutions, we seek to make meaningful apples-to-apples comparisons. The figure of merit we target is the total cost to cool global average surface temperatures by 1 °C via different lofting solutions. To achieve the same cooling, roughly 80% more aerosol mass is required at 20 km than at 25 km. The mass burden efficacy was derived from the average of mass burdens required under high and low altitude injections at 30°N/30°S/15°N/15°S in Tilmes *et al* 2017 [6]. We therefore first determine the total annual mass of aerosol required for 1 °C at 25 km and then augment that to determine the mass required the same temperature impact at 20 km. Surface temperature reduction factor of 0.097 K per TgSO2 injected at 25 km per year was adopted from Kravitz *et al* 2017 [15].

There is an order of magnitude differential between the payload of the smallest hauler versus the largest. There are also substantially different cycle times, meaning that some vehicles can fly more sorties per day than others. These factors combine to mean that the required fleet counts to achieve the same aerosol mass lofting differ substantially among these platforms, as is illustrated in table 2.

Pivoting from fleet size to dollars, costs can be conceived in three separate buckets in ascending size order. The first bucket is developmental cost, representing the total cost to design, engineer, test, and certify the first articles in the deployment fleet. These range from \$1 billion in cases where mere modification programs are required up to \$10 billion for the new and novel supersonic cruiser. Developmental budgets were devised via a combination of authors' experience and knowledge along with the well-established, though aged, aircraft cost estimation tool developed in the 1970s by the RAND Corporation [33]. While predicted developmental budgets for such programs are notoriously unreliable, they are not of great consequence in the cost model, representing less than 1% of total program costs in all cases.

The second and substantially larger cost bucket is the funding required to actually build the deployment fleet. This is compiled by deriving a cost-per-plane (exclusive of developmental costs) for each vehicle type and multiplying that times the required fleet size. This is, in turn, translated into monthly costs via the utilization of a lease rate factor, as if the aircraft were owned by an external leasing company and leased in to the operator. Developmental costs are amortized over the expected economic useful life of the aircraft and allocated to the entire fleet, such that each aircraft is making an equal contribution to the recapture of those costs.

The third, and by far the largest, bucket is ongoing operating costs, which in the case of the SAIL-01 program comprised more than 70% of overall program costs. Using the operating cost template worked out in Smith & Wagner 2018, annual operating costs for each of the six lofting solutions (SAIL-01 plus five) were built up utilizing 21 different cost line items representing flight crews, ground crews, maintenance (airframe, engines, and components), fuel, oxidizer (where relevant), aerosol payload, insurance, overhead, navigation charges, and others. These line items are driven in various cases by month, cycle, block hour, kilogram, or gallon as the case

Table 3. Program Costs. For a breakdown of costs of each of the platforms, please see supplementary material (available online at stacks.iop.org/ERC/4/031002/mmedia).

	Program development cost *US ∃ in billion*	Manufacturing cost per aircraft *US ∃ in million*	Cost per lofted tonne *in US ∃*	Annual comprehensive cost for 1 °C cooling *US ∃ in billion*
SAIL @ 20 kms	5	100	2,296	42.6
25 km concepts				
SAIL + Rocket	7	115	6,850	70.6
Ballistic Climber	1	80	13,531	139.5
Mothership & RPD			16,167	166.7
Mothership	1	80		
RPD	3	25		
Supersonic Cruiser	10	250	10,335	106.5
Mortar Platform	1	160	79,727	821.9

Table 4. Very high-altitude platform summary.

	Accommodates metered flow	Annual cost per 1 °C cooling *US ∃ in billion*	Multiple of SAIL-01 cost	Technical readiness level	Operational risk level
SAIL @ 20 kms	Yes	42.6	1.0	4	Low
25 km concepts					
SAIL + Rocket	No	70.6	1.7	3	High
Ballistic Climber	No	139.5	3.3	7	High
Mothership & RPD					
Mothership				7	Low
RPD	No	166.7	3.9	3	Medium
Supersonic Cruiser	Yes	106.5	2.5	4	Medium
Mortar Platform	N/A	821.9	19.3	6	Medium

may be. Comprehensive annual costs including aircraft capital costs are then divided by the annual aerosol mass required to produce a cost-per-lofted-tonne of aerosol. The costs for each solution are displayed in table 3.

Conclusions

All of the 25 km concepts increase cost-per-lofted-tonne by more than a factor of three relative to SAIL-01 at 20 km. Even after adjusting for the considerable efficacy differential that the higher altitude affords, this still multiplies the cost per degree of cooling for most concepts by a factor of two to four (see table 4 below). The least expensive 25 km solution is the Rocket Assisted SAIL at 1.7 times the baseline. If level flight at altitude is required, the Supersonic Cruiser boosts costs to 2.5 times the baseline. The Supersonic Ballistic Climber and Mothership plus RPD push costs between 3 and 4 times the baseline, with the mortar platform inflating to nearly 20X.

While these calculations suggest that the Rocket Assisted SAIL delivers superior cost performance, the requirement to undertake air restarts of its six engines on over 1 million sorties per year would likely represent an unacceptable safety hazard. With seven times as many annual sorties given its small payload, the Supersonic Ballistic Climber is an even more remote prospect from a safety perspective.

The Supersonic Cruiser has the safety advantage that its engines would remain lit throughout the flight, but flying nearly 1 million sorties a year at speeds in excess of Mach 3 can hardly be considered a low-risk program, and the SR-71 itself had a very problematical hull loss record due to accidents. This concept would require by far the most costly and ambitious developmental program with all the attendant risks in terms of possible delays and cost overruns. Moreover, a newly developed blazingly fast high-altitude aircraft would be all but guaranteed to be highly restricted by export controls, making it a poor candidate for a cooperative global program including one's allies and adversaries alike.

Among these concepts, the Mothership plus RPD would seem to present the fewest safety hazards particularly if the 'daughtership' is a remotely piloted vehicle. There is the considerable advantage that working prototypes of both platform stages are already operational, reducing developmental risks. However, its costs are nearly four times the baseline. The mortar platform concept is mooted not only by its outsized costs but by the safety and pollution hazards associated with the hailstorm of the shrapnel and debris that would emanate from it.

If there is a winning concept here, it is marginally the Virgin two-stage approach, though we would characterize this as the least problematical solution rather than the best. Should reliable developmental funding for a 25 km SAI deployment fleet actually materialize, we have little doubt that other and perhaps more promising lofting concepts may emerge than those we have reviewed here. We therefore offer this appraisal more nearly as a window into the issues and difficulties that arise when considering deployment at this altitude rather than an optimized aeronautical concept to pursue. We do not expect that these shortcomings would be overcome by diverting to lofting concepts other than jets such as balloons, guns, or rockets. It is clear that relative to 20 km, deployment at 25 km will come at a substantial cost premium and may place both flight crews and flight assets at an elevated risk.

A more traditional deployment platform like SAIL-01 could likely eek out another kilometer or two above its 20 km design target if pushed to its limit. However, raising the deployment altitude from 20 to 25 km entails a step change in both costs and safety hazards that climate modelers should account for as they consider deployment altitudes. As SAI remains quite cheap relative to other prospective climate responses, cost may not be the determinative factor. Nonetheless, these last few kilometres are far from free.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Author contributions

W S designed research; W S, U B, D C B, J L M, and C V R performed research; W S and U B analyzed data; and W S wrote the paper.

Competing interest statement

The authors declare no competing interest.

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