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A subpolar-focused stratospheric aerosol injection deployment scenario

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Abstract

Stratospheric aerosol injection (SAI) is a prospective climate intervention technology that would seek to abate climate change by deflecting back into space a small fraction of the incoming solar radiation. While most consideration given to SAI assumes a global intervention, this paper considers an alternative scenario whereby SAI might be deployed only in the subpolar regions. Subpolar deployment would quickly envelope the poles as well and could arrest or reverse ice and permafrost melt at high latitudes. This would yield global benefit by retarding sea level rise. Given that effective SAI deployment could be achieved at much lower altitudes in these regions than would be required in the tropics, it is commonly assumed that subpolar deployment would present fewer aeronautical challenges. An SAI deployment intended to reduce average surface temperatures in both the Arctic and Antarctic regions by 2 °C is deemed here to be feasible at relatively low cost with conventional technologies. However, we do not find that such a deployment could be undertaken with a small fleet of pre-existing aircraft, nor that relegating such a program to these sparsely populated regions would obviate the myriad governance challenges that would confront any such deployment. Nevertheless, given its feasibility and potential global benefit, the prospect of subpolar-focused SAI warrants greater attention.

Abbreviation:

°C	degree Celsius
AMAP	Arctic Monitoring and Assessment Programme
GeoMIP	Geoengineering Model Intercomparison Project
GLENS	Geoengineering Large Ensemble
H_2SO_4	Sulfuric Acid
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
km	kilometer

MRTT	Multi Role Tanker Transport
SAI	Stratospheric Aerosol Injection
SAIL	Stratospheric Aerosol Injection Lofter
SO_2	Sulfur Dioxide
Tg	Teragram
TOW	Takeoff weight

1. Introduction

The three Working Group reports issued by the Intergovernmental Panel on Climate Change (IPCC) as a part of the Sixth Assessment Report present a sobering picture of the status of the changing climate and humanity's response to date. The average global surface temperature in 2011–2020 was 1.09 °C higher than that in 1850–1900 whereas by 2018, the global mean sea level had already risen by 0.20 m above the 1901 average (IPCC 2021). Under all shared socioeconomic pathways that serve as a basis for climate projections assessed by the IPCC, global surface temperatures continue to rise until at least mid-century (IPCC 2021). Perhaps most concerning, many changes caused by past and future greenhouse gas emissions are irreversible for centuries to millennia (IPCC 2021, 2022). The Arctic faces a particularly dire threat from climate change, warming at roughly twice the global average (IPCC 2021). This enhanced warming of the Arctic results from a combination of processes including: reduction in snow- and sea ice-albedo; increased downward longwave heating due to increased Arctic cloud cover and water vapor content; increased transport of energy from lower latitudes to the Arctic from changes in oceanic and atmospheric heat flux convergence; and enhanced heat absorption by the increase in soot and black carbon aerosols (Hansen and Nazarenko 2004, Gillett *et al* 2008, Graversen and Wang 2009, Shindell and Faluvegi 2009, Screen and Simmonds 2010, Serreze and Barry 2011). In fact, due to this 'Arctic amplification', the Arctic annual mean surface temperature had already increased by over 3 °C between 1971 and 2019 (AMAP 2021). In addition, the average September sea ice extent in 2010–2019 was 40 percent lower than that in 1979–1988 (IPCC 2021). By mid-century, if not earlier, summer Arctic sea ice will likely have effectively disappeared, with potentially catastrophic climate consequences for both the Arctic and the planet as a whole (AMAP 2017). Though polar amplification in the Antarctic is less pronounced, it too is warming faster than the planetary average and there remain concerns about Antarctic ice sheet melt as a climate change tipping point (Clem *et al* 2020, DeConto *et al* 2021, IPCC 2021).

Stratospheric aerosol injection (SAI) is a prospective climate intervention that would seek to abate global warming by slightly increasing the reflectiveness of the Earth's upper atmosphere. SAI is a potential supplement to (but not a replacement for) other climate strategies including mitigation, adaptation, and carbon dioxide removal. However, it remains controversial, and research on SAI technology and its governance are still at very early stages. The vast majority of SAI simulations involve deploying aerosols (or their precursors) globally in order to lower temperatures worldwide. For example, the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) project and the Geoengineering Model Intercomparison Project's (GeoMIP) G6Sulfur experiment both involve injecting SO_2 at low latitudes (30°S-30°N for GLENS, above the equator for GeoMIP G6) to offset climate change-driven increases in global mean temperature (Kravitz *et al* 2015, Tilmes *et al* 2018).

In contrast to global solar geoengineering, subpolar geoengineering would involve geographically limited deployments at latitudes of roughly 60°N/S. Because the tropopause is considerably lower at high latitudes, aerosols or their precursors would not need to be lofted as high, reducing the engineering challenges relative to a global deployment. Only a few existing studies consider Arctic and/or polar SAI deployment. In one of the earliest simulations, (Robock *et al* 2008) modelled both tropical and Arctic SAI deployments, finding that Arctic injection was more effective per unit of SO_2 at preserving sea ice than equatorial injection. (Jackson *et al* 2015) also modelled the sea ice impacts of Arctic injection of SO_2, finding that injection masses in excess of 10 Tg-SO_2/yr would be required indefinitely to recover sea ice. A recent study by (Lee *et al* 2021) finds that, per teragram of SO_2 injected, spring-only injection at 60°N restores approximately twice as much summer sea ice and achieves approximately 50% more Arctic and global mean temperature reductions than year-round injection at that latitude. While Arctic-only SAI deployment has been found to be highly effective, there are also potential concerns. (MacCracken *et al* 2013) and (Nalam *et al* 2018) find that deployment of SAI at higher latitudes in the Northern Hemisphere moves the Inter-Tropical Convergence Zone (ITCZ) southward, affecting global precipitation patterns. However, both papers also find that if counterbalancing SAI is deployed in the Southern Hemisphere, the position of the ITCZ can remain relatively unchanged (MacCracken *et al* 2013, Nalam *et al* 2018). These early findings motivate our focus on not only Arctic SAI deployment, but also on Antarctic SAI deployment.

There is a growing body of literature that considers the cost and logistics of SAI deployment (The Royal Society 2009, McClellan *et al* 2012, Moriyama *et al* 2017, Smith and Wagner 2018, Smith 2020, Smith *et al* 2022). All of these contemplate deployments intended to have global impact and which would therefore take place in the tropics or sub-tropics at altitudes of 20 km or higher. Existing studies of high latitude deployment limit their scope simply to climate impacts. No existing study builds a complete bi-hemispheric polar or subpolar SAI deployment scenario including logistical and cost considerations, nor do existing studies clarify whether existing aircraft would be suitable for this mission. In section 2 of this paper, we establish a subpolar SAI deployment scenario. In section 3, we lay out the logistics and costs of the scenario. In section 4, we consider the scenario's climate impacts both regionally and globally.

2. SAI subpolar deployment scenario

To clarify the feasibility of subpolar SAI, we seek here to articulate a plausible deployment scenario for which we can thereafter assemble a logistical plan. The key parameters of our deployment scenario are as follows:

- Temperature anomaly target: As mentioned earlier, the polar amplification has caused a substantially greater warming in the high latitudes compared to the global average warming over the last several decades. With global greenhouse gas emissions still rising, this additional warming means that the conditions at the poles are likely to be substantially warmer on the threshold of a prospective deployment than they are today. If the objective of such a deployment were to arrest ice and permafrost melt and therefore constrain global sea level rise, a substantial temperature anomaly would seem warranted rather than a barely detectable one. With these considerations in mind, we propose that a plausible temperature anomaly target for a Polar SAI program might be a 2 °C cooling in the Arctic (calculated as the area-weighted average of surface temperatures between 60°N and the pole); this allows us to estimate costs independently of the emissions scenario. We do not argue that this is an optimal or likely target, but as the impacts of deployments in the mass range discussed herein are reasonably linear, readers seeking to estimate the logistics and costs of a smaller or larger deployment may reasonably interpolate or extrapolate from our figures below.
- North/south symmetry: In order to minimize disturbances to distant weather and circulation patterns, any deployment in the Northern Hemisphere must take account of its impact on the Southern Hemisphere. Previous studies have done so by countervailing Northern deployments with roughly similar southern deployments, thereby reducing any shift in the Intertropical Convergence Zone (Ban-Weiss and Caldeira 2010, Kravitz *et al* 2016). To simplify the calculations and optimize aircraft usage, we define 'symmetry' here as calling for an equivalent aerosol mass deployment in the Antarctic rather than an equivalent temperature anomaly.
- Injection seasonality: Building on the conclusions reached in (Lee *et al* 2021), we propose to inject only in the spring and early summer months, which is to say March—June in the Northern Hemisphere and September —December in the Southern. Since the intended effect of deployment is to deflect incoming sunlight, deployment in the local winter would have limited impact, as there is little sunlight in the region (Peixoto and Oort 1992). Spring deployment takes advantage of the waxing days and resulting solar intensity, remaining aloft through the polar summer. Aerosols deployed in the very high latitudes have considerably reduced stratospheric endurance relative to that deployed at low latitudes, but since the effective season for deflecting sunlight is merely six months long, the earlier sedimentation of this material at the poles is of limited impact on its efficacy.
- Deployed material: (Lee *et al* 2021) assumes injections of SO_2, which will oxidize into H_2SO_4 (the sulfur species that is effective for radiative forcing) and coagulate into liquid super cooled aerosols after a month in the stratosphere. While recent studies have explored the direct injection of accumulation mode-H_2SO_4 as an alternative to SO_2 (Vattioni *et al* 2019, Weisenstein *et al* 2021), neither the aeronautical tradeoffs associated with carrying this heavier substance nor the mechanics of venting it at the optimal particle size have been convincingly explored. Therefore, despite the prospective advantages of deploying other species of sulfur, we have retained the selection of SO_2 as made in (Lee *et al* 2021).
- Injection locations: We propose target injection latitudes of 60°N and 60°S, which delimit zones that include the entirety of both Greenland and Antarctica. In the Northern Hemisphere, this is roughly the latitude of Oslo, Helsinki, Homer Alaska, and Magadan in eastern Siberia. In the Southern Hemisphere, the 60th parallel lies entirely in the Southern Ocean well south of the tip of Patagonia. It should be noted that these latitudinal bands delimit an area roughly twice as large as either the Arctic or the Antarctic, each of which are properly defined as the areas poleward of 66.30°. Our descriptions of deployment in the 'Arctic' and 'Antarctic' should

be understood in all cases herein to refer to these greater subpolar regions rather than merely to the areas poleward of 66.30°. Given the efficient East/West mixing, particularly at these high latitudes, we assume that injection longitudes are irrelevant to the design of the injection program and should instead be determined by the location of capable air bases proximate to the intended injection latitudes.

- Deployed masses: (Lee *et al* 2021) estimates that a 12 Tg-SO_2/yr spring deployment at 60°N would force a −3.7 °C annualized average surface temperature anomaly in the region north of 60°N. This estimate was made with a background RCP 8.5 °C scenario but should not be strongly dependent upon the specific scenario. Assuming for simplicity a linear radiative forcing in these mass ranges, this would suggest that each Tg of SO_2 begets approximately −0.3 °C of temperature response in the target zone. Given Arctic temperature forcing targets of −2.0 °C and the assumption of an equivalent mass deployment in the Antarctic, this calls for 6.7 Tg-SO_2/yr in each hemisphere or a total annual deployed mass of 13.4 Tg.
- Injection altitude: (Lee *et al* 2021) assumed an injection altitude of 14.8 km. Seeking to balance radiative forcing efficacy of deployed aerosols with operational efficiency, we reduce the assumed injection altitude herein to 13 km. Average tropopause altitudes in June (the final month of the northern deployment season) exceed 10 km, and to allow for longitudinal and diurnal tropopause height variability among other factors, 13 km is considered here to be a feasible and prudent deployment altitude, but we do not plan for higher deployments. While we acknowledge that there may be a small difference in the radiative forcing that may result from this lower deployment, we have assumed that the results would be broadly similar and have therefore applied no decrement to the radiative forcing efficacy assumed in (Lee *et al* 2021).

3. Logistical discussion

With the deployment scenario described in section 2 as the objective, we pivot to the matter of how it might be fulfilled. We will assume for this exercise that deployment is undertaken in what would, from an operational standpoint, be idealized conditions, wherein a single global monopolist deployer is able to operate continuously and consistently across multiple national airspace regimes without local interference. We do not seek here to address how such a legitimate global mandate might be secured other than to note that it would be very difficult. Alternatively, deployment plans that instead assume multiple uncoordinated actors, funding challenges, airspace sovereignty disputes, and other routine complications could only be less efficient than what is described below.

3.1. Platforms

For the sort of globally effective SAI deployment in the tropics and sub-tropics envisioned in (Smith and Wagner 2018) and (Smith 2020), a deployment altitude of 20 km is commonly assumed in order to remain well above the tropopause, which can often appear as high as 17 km in the tropics. Injection of large masses of aerosols at 20 km is not judged to be feasible with existing aircraft, requiring the development of new lofting platforms designed for this mission as envisioned in (Bingaman *et al* 2020). Alternative lofting technologies such as guns, rockets, and balloons were considered in prior studies (McClellan *et al* 2012, Smith and Wagner 2018) but were determined to be more expensive than aircraft on a cost-per-lofted-tonne basis. And while fixed hoses lofted by tethered balloons could have lower unit costs than aircraft (Davidson *et al* 2012), their technological immaturity renders them unreliable as lofting options for SAI (McClellan *et al* 2012, Kuo and Hunt 2015, Lockley *et al* 2020).

A threshold question arising in respect of the lower 13 km deployment altitude sufficient for a polar program is whether existing aircraft platforms can serve in this instance. After consideration, the simple but surprising answer is—only poorly, and therefore, likely not at all. Experimental sub-scale initial deployments could potentially reuse existing tanker designs, but to implement a program of the scale considered here, a much larger fleet would be required than could be assembled from used aircraft, and the reduced capabilities of existing designs would clearly justify a new, purpose-built platform.

In surveying existing platforms that would seem most likely to serve, the obvious starting point is the large air-to-air refueling tankers used to extend the operational range of military aircraft. In common with our prospective polar SAI deployment platform, these tankers are designed to haul a dense, heavy load of liquid (in their case, jet fuel) into the heavens and transfer it to other aircraft at altitude. By far the most numerous large tanker is the aged but still capable KC-135, which is still aiding US military efforts more than 60 years after its entry into service (U.S. Air Force). These are projected to remain operational at low utilization levels (U.S. Government Accountability Office 2020) through 2040 (U.S. Defense Science Board 2004), but will remain in service until each encounters its firm structural fatigue limits. This means there is not and likely will not be a substantial fleet of retired but operable KC-135s that can be drafted into service for SAI. Their replacements are

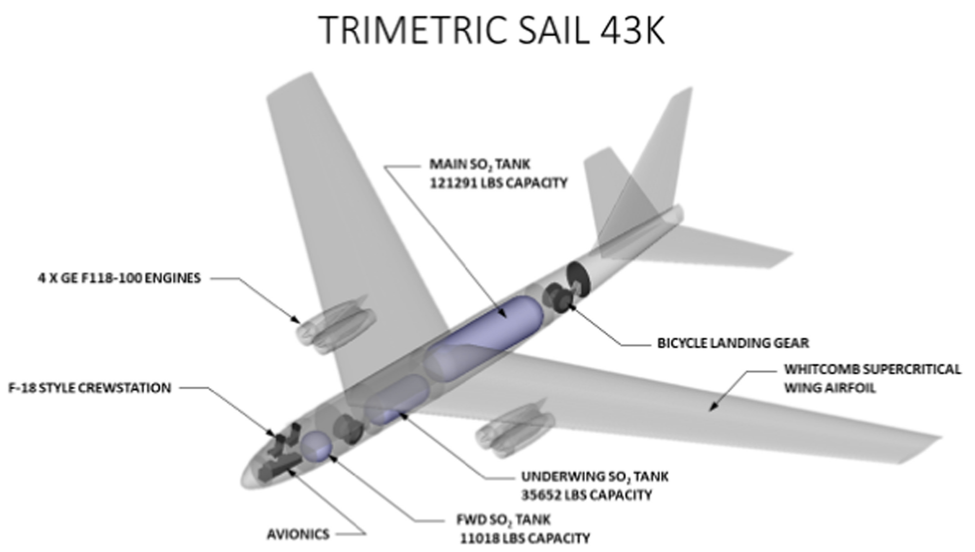

Figure 1. SAIL-43K Diagram.

two current-production tankers: the Boeing KC-46 and the Airbus A330 MRTT (Tegler 2022). An earlier but discontinued replacement tanker is the KC-10. For completeness, we have also considered a theoretical replacement tanker modified from the A340, whose four engines give it an advantage over its twin-engine challengers (KC-46, A330) in this competition. All five of these aircraft are capable of hauling fuel loads of at least 200,000 pounds to altitudes of at least 30,000 feet (roughly 9 km) and would therefore seem ideally suited to the SAI deployment mission.

However, none of these aircraft is capable of ascending with that full payload the additional 4 km necessary to get to our minimum target altitude of 13 km. To sustain a substantial rate-of-climb above their optimal cruise altitude in the 9–10 km range, each of these aircraft would need to get lighter by leaving payload on the ground. Flying reduced loads would enable these aircraft to reach as high as 12 km, but only the KC-135 has a service ceiling enabling it to get comfortably to 13 km. Nonetheless, to facilitate cost comparisons between all of these platforms, we will assume (perhaps unreasonably) that all can be stretched incrementally above their current service ceilings to attain 13 km, albeit with reduced payloads, which in turn increases fleet requirements and costs.

Since each of these pre-existing platforms achieves a dismal payload fraction (net payload/ maximum take-off weight) at 13 km (roughly 43,000 feet), we have added to the platform set a version of the SAIL-01 (Bingaman *et al* 2020) reconfigured specifically for the subpolar deployment mission. The 'SAIL-43K' could loft a payload nearly five times as great as its predecessor given that the air density at 13 km is so much greater than that for which the SAIL-01 was designed. Even with this huge payload increase, the SAIL-01's six engines are overkill for the 13 km mission, so SAIL-43K has merely four (see figure 1 below for a diagram of the SAIL-43K).

The much greater payload on the SAIL-43K required more robust structure and landing gears than SAIL-01, leading to a roughly 18% increase in operating empty weight despite the two fewer engines. Structural augmentation was also required to bring the ultimate load factor up to 4.5 g (from 3.0 g previously), such that it presents an apples-to-apples comparison with the former airliners being alternatively considered. Given these changes, the SAIL-43K could achieve a payload fraction of 56%, making it vastly more efficient for the subpolar mission than the alternatives (see table 1 below).

Another platform category often casually considered for high altitude flight is top-of-the-line business jets such as the Bombardier Global Express 6000 and the Gulfstream G650, both of which have service ceilings above 15 km. However, these aircraft can achieve such high altitudes in part because they are designed to carry essentially nothing—a handful of well-tailored passengers and their suitcases. Were these same aircraft to be freighted down with their full fuel capacity and maximum structural payloads, they too would be forced to remain at much lower altitudes, with payloads substantially smaller than those of the medium widebody tanker platforms noted above. For a tanker or freighter, the operative question is not how high the plane can get empty and out of fuel, but rather how high it can climb with a full payload at the commencement of cruise, which is a very different matter.

Despite the dramatically lower target altitude required in the polar deployment scheme relative to the global scheme, a purpose-built aircraft would still be warranted for this mission.

Table 1. Candidate aircraft (The methodology behind the calculation of the TOW for 43,000 ft has been explained in appendix I).

Aircraft	Service ceiling (ft)	Maximum takeoff weight (lb)	Takeoff weight for 43K ft (lb)	Net payload AT 43K ft (lb)	Net payload AS % OF PAYLOAD	Derivation
KC-135R	50,000	322,500	219,400	105,200	33%	Converted B707
A330 MRTT	42,700	514,000	357,105	88,300	17%	Converted A330
KC-46A PEGASUS	40,100	415,000	256,500	74,870	18%	Converted 767
KC-10	42,000	590,000	376,000	128,801	22%	Converted DC-10
A340F	40,100	840,000	492,000	102,761	12%	Converted A340
SAIL-43K	47,000	299,397	299,397	167,971	56%	Purpose built

Table 2. Activity and fleet requirements (Aircraft are scheduled for 240 deployment days per year, with a dispatch rate of 97%).

Aircraft	Deployment flight Hours	Ferry flight hours	Total annual flight hours	Sorties required for target masses	Sorties per deployment day	Aircraft required
KC-135R	288,652	9,599	298,252	279,347	2,328	200
A330 MRTT	343,898	11,437	355,335	332,811	2,773	238
KC-46A	405,586	13,488	419,074	405,991	3,271	281
KC-10	235,761	7,840	243,601	228,162	1,901	163
A340F	295,503	9,827	305,331	285,977	2,383	205
SAIL-43K	180,783	6,012	186,795	174,957	1,458	125

3.2. Fleet and activity

Another factor that would favor the development of a purpose-built deployment platform for subpolar SAI is that the fleet size required for a −2 °C temperature anomaly target would number in the hundreds, such that the development cost for such a novel aircraft would not overwhelm the program economics. Shown in table 2 below are fleet counts and annual sorties required to deploy 13.4 Tg-SO2/yr at an altitude of 13 km in just eight operating months—four in each hemisphere. The same fleet is assumed to be utilized in both hemispheres, such that after four operational months in the Northern Hemisphere, the entire fleet would be ferried south for maintenance in July and August, and then positioned at the southern bases by September 1 for the four-month southern operational season. They would fly north into maintenance bases in January, and back to the northern flight line by March 1.

Even with the more capable and efficient SAIL-43K, an SAI program intended to cool the polar regions by 2 °C would be a massive undertaking, requiring over 125 planes and nearly 175,000 sorties per year. This is more than two days of global commercial air traffic in 2021 (IATA 2022) or about two thirds of the annual flights departing New York's Kennedy Airport (JFK Airport 2022). This assumes that sortie length is kept to an absolute minimum: a 30-minute climb, a 2-minute cruise during which the tanks are quickly vented, and a 30-minute descent, for a 62-minute total flight time. Planes are planned to operate six cycles per day at a 97% dispatch rate. With taxiing time added and 60 min of ground assumed between cycles, this defines a roughly 13 h operational day, which is within reasonable parameters for freighter operations. Pole to pole fleet migrations are assumed to be accomplished in three eight-hour legs in each direction.

3.3. Bases

In the Northern Hemisphere, there is no shortage of existing major commercial airfields that could serve as operational bases for a polar SAI operation, without the need to additionally consider military bases. Oslo, Stockholm, Helsinki, and St. Petersburg (Russia) are all located less than half a degree from the 60th north parallel. Anchorage, with three runways longer than 10,600 feet (Alaska Department of Transportation and Public Facilitie), is located at 61.2°N latitude—close enough for our purpose. Moreover, the vast majority of the 60th north parallel falls on land—principally in Russia and Canada—on which additional bases could theoretically be built should they be required.

Not so at its southern counterpart. The 60th south parallel touches land nowhere in its circumference, and the islands to which it is closest are uninhabited. The Antarctic bases in the South Shetland Islands off the northern tip of the Antarctic Peninsula are south of 62 degrees and none have airfields with runways long and robust enough to support large tanker aircraft. The closest major airfields to the 60th south parallel are in Chile and Argentina at the southern tip of Patagonia. Puerto Williams in southern Chile is at 54.9°S, but its sole runway is less than 5,000 feet long (Great Circle Mapper). Ushuaia in neighboring Argentina at 54.5°S has a single paved runway exceeding 9,000 feet (Aeropuerto Ushuaia). A yet larger airfield at Punta Arenas Chile (53.0° S) has three runways including one over 9,000 feet (SkyVector Aeronautical Chart). Sub-optimal though these may be relative to our 60°S target, these Patagonian bases at approximately 54°S will have to serve. Rather than cruise the additional 6 degrees and approximately 420 nautical miles south to deploy exactly at 60°S, it is assumed herein that the impacts from deployment at 54°S and 13 km will be sufficiently similar to what would have obtained at 60°S to require no decrement despite the slightly higher tropopause altitude that should be expected at that latitude.

While Anchorage and Punta Arenas could fulfill the need for airfields in roughly the right geographies for the purpose of a subpolar SAI program, neither these nor any of the airfields discussed herein have even a small fraction of the capacity required to handle the volume of flights required for this program. In 2019 (and therefore before the impact of COVID), Anchorage Airport (among the world's busier cargo airports) handled 166,000 take-offs and landings (Alaska Department of Transportation and Public Facilitie)– an average over the full year on a 24-hour clock of nearly 20 per hour . Atlanta's Hartsfield-Jackson Airport (the world's busiest by passenger volume, with five long runways) handled over 900,000 operations the same year—slightly over 100 per hour (Airports Council International 2020). The subpolar SAI program envisioned herein if carried out with the SAIL-43K would require over 110 operations per hour during a 13-hour operational day—roughly six times the hourly pace of operations at Anchorage and more than the pace that is observed at the world's busiest airport. Not only would such an operational tempo require more and longer runways at each of these airfields, but a similar expansion of ground infrastructure of every sort would be required—hangars, fuel tanks, SO_2 storage facilities, crew accommodations, ground support vehicles, skilled maintenance personnel, airport ground staff, food preparation and service, staff housing—everything. And while this infrastructure build-out could be spread over many airfields (at least in the Northern Hemisphere), the same expansion of capacity would be required irrespective of how it is distributed geographically. To bolster operational robustness and resilience, it must also be built redundantly, in both hemispheres.

3.4. Speed to launch and governance

The development and build-out of the fleet of deployment aircraft, the ground infrastructure, and the cadre of personnel needed to implement this program are decadal time-scale projects. A reasonable developmental timeframe for a new aircraft program is in the range of five to seven years. The build rate for the KC-46 tanker program is currently 15 per year (Insinna 2020), which is close to the rate (18 per year) at which the KC-135s are scheduled to be retired (NDAA Subcommittee on Seapower and Projection Forces FY2). A deployment fleet of perhaps 125 aircraft procured on such a schedule could take 15 or more years to develop and manufacture. It seems unlikely that the required ground infrastructure (ideally at multiple redundant airfields) in both hemispheres could be assembled much more quickly assuming normal peacetime procurement processes.

Therefore, it should not be assumed that a -2 °C polar SAI program of the sort contemplated herein could be hastily assembled with a few spare KC-135s as a climate quick fix. Limiting oneself to current production tankers such as the A330 MRTT or KC-46 would obviate the five to seven-year developmental cycle, but would roughly double the required fleet size, meaning that the time necessary to ramp into a -2 °C subpolar SAI program is unlikely to be materially reduced.

Nor is it plausible to assume that an intervention in these remote regions of the world could bypass the global deliberations and governance challenges that would likely be necessary to establish its legitimacy. A tiny field experiment intended merely to test high altitude flight equipment without releasing any aerosols was scheduled in northern Sweden in 2021. Far from escaping notice, it was aborted after public objections by the Saami Council on behalf of local indigenous peoples (Saami Council 2021, SCoPEx Advisory Committee 2021). Residents of the far north who have already expressed concerns about SAI would remain disproportionately affected, though whether those effects would be positive or negative remains unclear.

Though the Arctic Council and the Antarctic Treaty System would appear to be the logical fora in which to commence discussions of subpolar SAI governance, neither is endowed by their existing members/signatories with the legislative and executive powers that would be needed to make tactical decisions about such a program. Nor does it seem likely that uninvolved nations would consent to granting either of these organizations exclusive governance dominion over a climate intervention that would have global repercussions. In fact, setting aside the particular nuances of political circumstances at the poles, it should be assumed that prospective SAI deployment anywhere in the world would likely draw in the global community. One should expect that every nation on earth and a long list of non-state actors and constituencies would demand a voice in the process and perhaps a seat at the table as decisions are made affecting polar thermostats. The roll out of any such program therefore should be assumed to be a long and deliberate affair rather than a potentially rapid response to a climate emergency.

3.5. Costs

In estimating the costs of a subpolar SAI program, we employ here a model similar to that developed for (Smith and Wagner 2018) and employed again in (Smith 2020) and (Smith *et al* 2022). It starts by estimating the developmental costs required to design and certify a novel aircraft type—either a modified version of a preexisting aircraft or a novel platform such as the SAIL-43K. It then establishes a production run based on the size of the fleet required for a -2 °C program and amortizes the aggregate development cost equally over the production run. A manufacturing cost for each ship is also estimated. The manufacturing cost per ship, the amortized portion of the development costs, and an allocation for an initial package of spare parts are all combined to form the capital cost of each aircraft. These capital costs are multiplied by a lease rate factor that assumes the assets are purchased by an external leasing company and leased in to the 'airline' that operates them. A market-standard lease rate factor is assumed here, although the unique nature of these aircraft and the lack of alternative uses for them would require extraordinary (likely governmental) lease guarantees were this financial structure actually utilized. The above mechanics establish the monthly capital cost for the aircraft and initial spares.

Operating costs are built up on a per-aircraft basis and account for airframe heavy maintenance, line maintenance, engine overhauls, landing gear overhauls, crew costs, insurance, and maintenance of the specialized equipment particular to the aerosol carriage and dispersal. Ground handling charges, navigational charges, and landing fees are also factored in. Fuel is modeled at a level price of $2.50 per gallon (all cost figures discussed herein are denominated in current US dollars), which assumes a base price of $2.00 plus a 50-cent surcharge that approximates a $50 per tonne future carbon price. We have used the price of SO_2 as suggested by (de Vries *et al* 2020). However, the amount of SO_2 required yearly for meaningful impact on radiative forcing would be a substantial fraction of current global demand, meaning that such a program could strain the current supply chain for sulfur and increase future prices beyond what is assumed here. Operational costs are variously driven by block hours, aircraft/engine cycles, aircraft-months, gallons, or pounds as may be appropriate to each item. An overhead charge per aircraft-month is added to account for the management of the operation. Details on cost build up methodology may be found in the appendix.

Predicting costs for a hypothetical global aeronautical endeavor operating a large fleet of conjectural aircraft in politically speculative circumstances decades into the future is a necessarily theoretical exercise, and we mean here to articulate merely order-of-magnitude cost estimates rather than to imply precision. With those caveats, our model estimates the cost of implementing the subpolar SAI program described herein to be ~$11 billion annually in 2022 dollars assuming the use of the SAIL-43K. This is a less than 1/3 the ~$36 billion annual cost estimated in (Smith 2020) to cool surface temperatures of the entire globe by 2 °C, with the differential being due primarily to the fact that cooling a much smaller proportion of the Earth's surface requires vastly smaller lofted masses. On a cost-per-deployed-tonne basis, the ~$800 subpolar costs are a similar proportion of the ~$2,400 cost required for a global deployment at 20 km. The differential here is due primarily to the fact that while the SAIL-43k has a similar take-off gross-weight similar to that of the SAIL-01, it can carry roughly five times the payload of its predecessor given the substantially lower deployment altitude. Subpolar deployment with any of the other platforms considered here would be substantially more expensive, as shown in table 3 below. These results will further reinforce the recurring theme that relative to other possible strategies by which to combat either the impacts or causes of climate change, SAI remains extraordinarily inexpensive.

4. Expected climate impacts

The subpolar SAI intervention described herein is calibrated to reduce the average surface temperatures north of 60°N by a year-round average of 2 °C. For simplicity, we have assumed an identical amount of deployed aerosols in the Southern Hemisphere. While the Antarctic is not heating as fast as the Arctic and may have a similarly muted response to SAI, we assume that such an intervention might offset a similar proportion of local warming. Despite the general poleward flow of the Brewer-Dobson Circulation into which the SO_2 would be injected, some of the aerosols would actually flow towards the equator rather than towards the poles. Both because of this, and because of changes in atmospheric and oceanic heat transport, the resulting cooling would not be confined northward of 60°N and would instead be detectable throughout most of the Northern Hemisphere (Lee *et al* 2021). Similar results north of the deployment zone can be expected with injections in the high latitudes of the Southern Hemisphere (Nalam *et al* 2018).

Several studies have shown that SAI at low- to mid-latitudes could be effective in reducing and reversing the losses of sea ice and permafrost brought on by global warming, since the injected aerosols would eventually flow poleward, enveloping the entire earth (Moore *et al* 2019, Chen *et al* 2020, Lee *et al* 2020). Furthermore, due to increased Arctic cooling per unit of aerosol optical depth, strategic injections at higher latitudes are more effective at reversing sea ice loss than global or mid- to low-latitude injections (Caldeira and Wood 2008, MacCracken *et al* 2013, Kravitz *et al* 2016). (Lee *et al* 2021) show that spring injection of 12 Tg of SO_2 annually restores the September sea ice extent in a climate model simulation by 5.0 million km^2. Annual Northern Hemisphere sea ice extent also increases considerably in the Arctic injection scenario.

Arctic SAI has been expected to shift the ITCZ southward, with potentially serious implications for the distribution of tropical precipitation (Robock *et al* 2008, MacCracken *et al* 2013, Nalam *et al* 2018, Lee *et al* 2020). Balancing the Arctic injection with an Antarctic injection is expected to nearly nullify such a shift (Nalam *et al* 2018).

Similar to the results from global or tropical injections, subpolar SAI will also result in heating of the lower stratosphere (Niemeier *et al* 2013, Ferraro *et al* 2015) , although because the aerosols would be focused at higher latitudes, there would be less heating per unit injection. In addition, the introduction of aerosols into the stratosphere enhances the aerosol-induced surface area density which leads to an increase in heterogeneous reactions required for halogen activations (Solomon 1999, Tilmes *et al* 2021), though as the aerosols would primarily be present during the summer this may be less of an effect than for global SAI. Consequently, subpolar SAI may impact stratospheric ozone concentrations through a combination of dynamical and chemical effects,

Table 3. Costs (A breakdown of individual cost components has been included in appendix II).

	Upfront cost			Annual cost					Cost per lofted tonne
Aircraft	Program development cost *Million USD*	Mfg cost per aircraft *Million USD*	Fleet acquisition cost *Million USD*	Fleet acquisition cost *Million USD*	Fuel cost *Million USD*	Payload cost *Million USD*	All other operating costs *Million USD*	Total cost *Million USD*	*USD*
KC-135R	2,500	72	16,899	2,188	1,857	4,667	4,077	12,788	959
A330 MRTT	500	135	32,665	4,301	3,740	4,667	5,975	18,683	1,401
KC-46A	500	158	44,758	5,821	3,014	4,667	6,456	19,957	1,497
KC-10	2,000	113	20,376	2,706	2,702	4,667	4,675	14,750	1,106
A340F	2,500	157.5	34,745	4,661	3,023	4,667	6,448	18,799	1,410
SAIL-43K	5,000	72	14,018	1,782	2,004	4,667	2,534	10,988	824

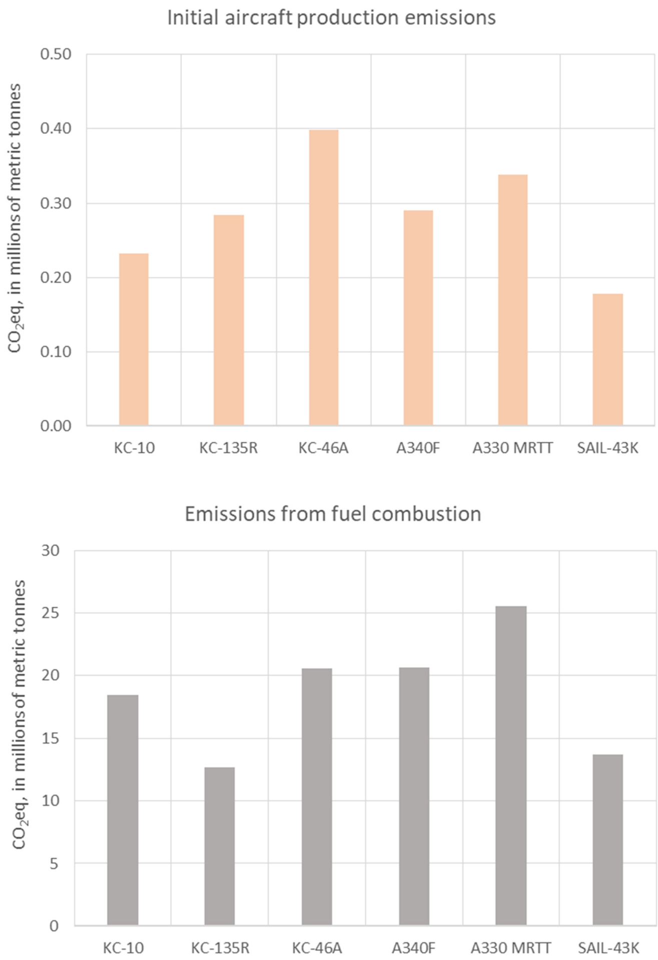

Figure 2. CO_2eq emissions from aircraft production and fuel combustion.

possibly slowing the recovery of the Antarctic ozone hole, or at higher deployed masses, reversing it (Pitari *et al* 2014, Lee *et al* 2021, Tilmes *et al* 2021). Further, both wet and dry depositions of the added sulfates pose a risk to humankind and ecosystem. Previous studies have shown that, under global injection, only a small fraction of the sulfate deposition takes place at high latitudes (Visioni *et al* 2020). Even under injections at 60°N, a significantly larger fraction of the injected aerosols can be expected to deposit southward of the injection latitude (Lee *et al* 2021). All of these effects would need more research to evaluate.

In addition to the direct climatic impacts resulting from the interaction of injected aerosols with the stratosphere, the carbon footprint associated with the deployment program also carries environmental risks. The pre-deployment emissions stem from the development and production of the deployment fleet as well as the retrofitting of the target airports with the infrastructure to enable SAI. We use the scope 1 and scope 2 carbon dioxide emission figures reported by Airbus for their commercial airliners as a proxy to calculate the total emissions associated developing the fleet for SAI (Airbus 2022). This category of emissions is directly dependent on the fleet size as shown in figure 2. A recent study (de Vries *et al* 2020) estimates that the CO_2eq associated with airport modifications are ~2.5 million metric tonnes per airport.

On top of these one-time preliminary emissions, the program also entails recurring operating emissions. These derive from: the combustion of jet A fuel by the planes; the manufacture, transport, and handling of the sulfur dioxide; and the ground handling operations at airports. Jet A fuel upon combustion releases carbon dioxide at a constant rate of 3.16 kg for every kg of fuel (Penner *et al* 1999).

In addition to the CO_2, aircraft engine combustion also results in non-CO_2 climatic impacts, primarily via the formation of contrails and the release of nitrogen oxides (Azar and Johansson 2012). To account for these in the overall impacts of fuel combustion, (Azar and Johansson 2012) have calculated an emission weighting factor of 1.7 (ranging from 1.3 to 2.9)—a multiplier that allows for computation of CO_2 equivalency based on a hundred-year global warming potential. Figure 2 shows the CO_2eq effects associated with direct combustion of fuel in aircraft engines.

While the calculation of life cycle emissions associated with the manufacture, handling, and transportation of sulfur dioxide is beyond the scope of this study, existing studies looking at the cradle-to-grave carbon dioxide emissions resulting from the manufacture of sulfur dioxide and sulfuric acid show that the emissions can vary by an order of magnitude (Veolia 2011, Adeniran *et al* 2017, Edwards *et al* 2017). This depends on the carbon intensity of the electricity, the means of sourcing the elemental sulfur, and transport distance required to ship the elemental sulfur to the destination of its use. Barring any significant deviation, over the lifetime of the program, the CO_2eq emissions from the combustion of fuel will likely be significantly larger than the emissions from preparing sulfur dioxide. Similarly, (de Vries *et al* 2020) found the emissions associated with operating and maintaining the airport to be negligible compared to that from fuel combustion.

5. Conclusion

Based on the foregoing, several conclusions emerge. While it has yet to be established that the physical or societal impacts of any SAI program would prove to be net positive, it seems clear that a program focused on substantially cooling the world's polar and subpolar regions would be logistically feasible. This could arrest and likely reverse the melting of sea ice, land ice, and permafrost in the most vulnerable regions of the Earth's cryosphere. This in turn would substantially slow sea level rise globally. Spring-only seasonal deployment would achieve substantially higher radiative efficacy per unit of mass deployed and would therefore minimize other negative environmental impacts relative to a year-round program. Despite the fact that Arctic warming is outpacing Antarctic warming, any deployment in one hemisphere should be countervailed by a roughly equivalent injection in the opposite hemisphere.

On the other hand, effective subpolar SAI could not be achieved with a small fleet of hand-me-down tankers or other pre-existing aircraft. Despite the roughly one-third reduction in deployment altitudes compared to a globally-focused program, operational economics would still call for a purpose-built platform, and the required fleet size would be large enough to justify such a new developmental effort if it were backstopped by government guarantees. If pre-existing tanker designs were employed instead, this would roughly double the required fleet size without shortening the time required to stand up such a program.

It is not merely the flight assets but the ground infrastructure that would need to be greatly enhanced in order to accommodate such a program. Appropriately located bases exist in multiple locations in the Northern Hemisphere, whereas in the Southern Hemisphere, the tip of Patagonia is the only plausible option and even it is not ideally proximate to the proposed deployment latitude. A single fleet of aircraft could be feasibly deployed to serve in both hemispheres. The design and build-out of both the flight and ground infrastructure would require more than a decade, such that a large subpolar SAI program is not a feasible emergency response to acute climate stress.

Nonetheless, as with alternative SAI applications, this would be extraordinarily cheap compared to other climate responses such as mitigation, adaptation, or carbon capture and sequestration. However, these are apple/orange comparisons since SAI would merely ameliorate a key symptom of climate change without curing the underlying disease. A subpolar SAI program would also be much cheaper than a program intended to cool the entire globe by the same -2 °C target.

While the cooling would be most pronounced poleward of the deployment latitudes, it would also be expressed in temperate latitudes. Hemispherically symmetrical deployments could likely minimize substantial shifts in the ITCZ, but other artifacts of SAI such as increased sulfur deposition, retarded ozone layer recovery, and increased stratospheric heating would remain. The deployment effort itself would add marginally to the CO_2 and non-CO_2 radiative forcings resulting from aviation via fuel combustion, supply chain-related emissions, and increased contrails.

Though deployment at or near 60°N/S would take place over the airspace of no more than a dozen countries and require bases in even fewer, it is unclear that this would substantially ease the governance and legitimacy challenges that would confront such a program. Therefore, a subpolar deployment seems unlikely to bypass the awesome governance challenges that would confront any SAI program, though this would seem to be a crucial avenue for subsequent social science research.

Nonetheless, an SAI program with global benefits that would entail deployment directly overhead of far less than 1% of the world's population and nearly none of its agriculture may prove an easier sell to a skeptical world than a full-on global deployment. Given its apparent feasibility and low cost, this scenario deserves further attention.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Competing interests

The authors declare no competing interests.

Author contributions

WS and DGM designed and conceptualized the study. Material preparation, data collection, and analysis were performed by CVR, WS and UB. DV, WRL, and BK provided inputs on aerosol efficacy in subpolar regions. A substantial portion of the first draft of the manuscript was written by WS, with contributions from UB and all authors commented on previous versions of the manuscript. CVR prepared appendix I. All authors read and approved the final manuscript.

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References

Aeropuerto 2022 Aeropuerto Ushuaia Ushuaia International Airport | The Airport (http://aeropuertoushuaia.com/en/airport.php)
Alaska department of transportation and public facilities ted stevens anchorage international airport - airport facts (https://dot.alaska.gov/anc/about/facts.shtml)Accessed 3 May 2022

Adeniran J A, Yusuf R O and Adetoro M A 2017 Life cycle engineering case study: Sulphuric acid production *J Eng Technol* **8** 1–25 (https://jet.utem.edu.my/jet/article/view/1142)

Airbus 2022 *Airbus Annual Report: Overview 2021* 1–22 (https://www.airbus.com/sites/g/files/jlcbta136/files/2022-04/Airbus%20Annual%20Report%20Overview%202021.pdf)

Airports Council International 2020 ACI reveals top 20 airports for passenger traffic, cargo, and aircraft movements - ACI World (https://aci.aero/2020/05/19/aci-reveals-top-20-airports-for-passenger-traffic-cargo-and-aircraft-movements/) Accessed 3 May 2022

AMAP 2017 *Snow, water, ice and permafrost in the arctic (SWIPA) 2017. arctic monitoring and assessment programme (AMAP)* Oslo, Norway (https://amap.no/documents/download/2987/inline)

AMAP 2021 *Arctic Climate Change Update 2021: Key Trends and Impacts. Summary for Policy-makers. Arctic Monitoring and Assessment Porgramme (AMAP)* Tromsø, Norway (https://amap.no/documents/doc/arctic-climate-change-update-2021-key-trends-and-impacts.-summary-for-policy-makers/3508)

Azar C and Johansson D J A 2012 Valuing the non-CO_2 climate impacts of aviation *Clim. Change* **111** 559–79

Ban-Weiss G A and Caldeira K 2010 Geoengineering as an optimization problem *Environ. Res. Lett.* **5** 034009

Bingaman D C, Rice C V, Smith W and Vogel P 2020 A stratospheric aerosol injection lofter aircraft concept: brimstone angel *AIAA Scitech 2020 Forum.* (American Institute of Aeronautics and Astronautics) (https://doi.org/10.2514/6.2020-0618)

Caldeira K and Wood L 2008 Global and arctic climate engineering: numerical model studies *Philos Trans R Soc Math Phys Eng Sci* **366** 4039–56

Chen Y, Liu A and Moore J C 2020 Mitigation of Arctic permafrost carbon loss through stratospheric aerosol geoengineering *Nat. Commun.* **11** 2430

Clem K R *et al* 2020 Record warming at the South Pole during the past three decades *Nat. Clim. Change* **10** 762–70

Davidson P, Burgoyne C, Hunt H and Causier M 2012 Lifting options for stratospheric aerosol geoengineering: advantages of tethered balloon systems *Philos Trans R Soc Math Phys Eng Sci* **370** 4263–300

DeConto R M *et al* 2021 The paris climate agreement and future sea-level rise from antarctica *Nature* **593** 83–9

de Vries I E, Janssens M, Hulshoff S J and DSE 16-02 2020 A specialised delivery system for stratospheric sulphate aerosols (part 2): financial cost and equivalent CO_2 emission *Clim. Change* **162** 87–103

Edwards R, Padella M, Giuntoli J, Koeble R, O'Connell A, Bulgheroni C and Marelli L 2017 Definition of input data to assess GHG default emissions from biofuels in EU legislation *Definition of input data to assess GHG default emissions from biofuels in EU legislation, Version 1c* (https://ec.europa.eu/energy/sites/ener/files/documents/default_values_biofuels_main_reportl_online.pdf)

Ferraro A J, Charlton-Perez A J and Highwood E J 2015 Stratospheric dynamics and midlatitude jets under geoengineering with space mirrors and sulfate and titania aerosols *J Geophys Res Atmospheres* **120** 414–29

Gillett N P *et al* 2008 Attribution of polar warming to human influence *Nat. Geosci.* **1** 750–4

Graversen R G and Wang M 2009 Polar amplification in a coupled climate model with locked albedo *Clim. Dyn.* **33** 629–43

Great circle mapper WPU - puerto williams [guardiamarina zañartu airport], MA, CL - Airport - great circle mapper (http://gcmap.com/airport/WPU)Accessed 3 May 2022

Hansen J and Nazarenko L 2004 Soot climate forcing via snow and ice albedos *Proc. Natl Acad. Sci.* **101** 423–8

IATA 2022 *Annual Review 2022* International Air Transport Association (https://iata.org/contentassets/c81222d96c9a4e0bb4ff6ced0126f0bb/annual-review-2022.pdf)

Insinna V 2020 US Air Force delays full-rate production decision for KC-46 aircraft *Def. News.* (https://defensenews.com/air/2020/06/09/the-air-force-delays-a-full-rate-production-decision-for-the-kc-46/)Accessed 16 May 2022

IPCC 2021 IPCC, 2021: Summary for Policymakers *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* (Cambridge: Cambridge University Press)

IPCC 2022 IPCC, 2022: summary for policymakers *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* (Cambridge: Cambridge University Press)

Jackson L S *et al* 2015 Assessing the controllability of arctic sea ice extent by sulfate aerosol geoengineering *Geophys. Res. Lett.* **42** 1223–31

JFK Airport 2022 JFK airport facts & figures *JFK Airpt.* (https://jfkairport.net/statistics/)Accessed 28 Jul 2022

Kravitz B *et al* 2015 The geoengineering model intercomparison project phase 6 (GeoMIP6): simulation design and preliminary results *Geosci Model Dev* **8** 3379–92

Kravitz B, MacMartin D G, Wang H and Rasch P J 2016 Geoengineering as a design problem *Earth Syst Dyn* **7** 469–97

Kuo K A and Hunt H E M Isothermal pumping analysis for high-altitude tethered balloons *R Soc Open Sci* **2** 140468

Lee W, MacMartin D, Visioni D and Kravitz B 2020 Expanding the design space of stratospheric aerosol geoengineering to include precipitation-based objectives and explore trade-offs *Earth Syst Dyn* **11** 1051–72

Lee W R, MacMartin D G, Visioni D and Kravitz B 2021 High-latitude stratospheric aerosol geoengineering can be more effective if injection is limited to spring *Geophys. Res. Lett.* **48** e2021GL092696

Lockley A, MacMartin D and Hunt H 2020 An update on engineering issues concerning stratospheric aerosol injection for geoengineering *Environ Res Commun* **2** 082001

MacCracken M C, Shin H-J, Caldeira K and Ban-Weiss G A 2013 Climate response to imposed solar radiation reductions in high latitudes *Earth Syst Dyn* **4** 301–15

McClellan J, Keith D W and Apt J 2012 Cost analysis of stratospheric albedo modification delivery systems *Environ. Res. Lett.* **7** 034019

Moore J C *et al* 2019 Greenland ice sheet response to stratospheric aerosol injection geoengineering *Earths Future* **7** 1451–63

Moriyama R *et al* 2017 The cost of stratospheric climate engineering revisited *Mitig Adapt Strateg Glob Change* **22** 1207–28

Nalam A, Bala G and Modak A 2018 Effects of Arctic geoengineering on precipitation in the tropical monsoon regions *Clim. Dyn.* **50** 3375–95

NDAA Subcommittee on Seapower and Projection Forces FY22 2022 *H.R. 4350 - FY22 National Defense Authorization Bill* (https://armedservices.house.gov/_cache/files/7/0/70fad5e5-f1c6-4507-976a-ea29a5ef0836/FDED2F7FA923421184232B8EC4CDA3D4.fy22-ndaa-seapower-and-projection-forces-subcommittee-mark.pdf)

Niemeier U, Schmidt H, Alterskjær K and Kristjánsson J E 2013 Solar irradiance reduction via climate engineering: Impact of different techniques on the energy balance and the hydrological cycle *J Geophys Res Atmospheres* **118** 905–11

Peixoto J P and Oort A H 1992 Physics of climate 1st Edition (American Institute of Physics)

Penner J E *et al* 1999 *IPCC special report: aviation and the global atmosphere.* (Cambridge: Cambridge University Press)

Pitari G *et al* 2014 Stratospheric ozone response to sulfate geoengineering: Results from the Geoengineering Model Intercomparison Project (GeoMIP) *J Geophys Res Atmospheres* **119** 2629–53

Robock A, Oman L and Stenchikov G L 2008 Regional climate responses to geoengineering with tropical and Arctic SO2 injections J Geophys Res Atmospheres 113 (D16101)

Saami Council 2021 Letter to SCoPEx Advisory Committee (https://static1.squarespace.com/static/5dfb35a66f00d54ab0729b75/t/603e2167a9c0b96ffb027c8d/1614684519754/Letter+to+Scopex+Advisory+Committee+24+February.pdf)

SCoPEx Advisory Committee 2021 SCoPEx advisory committee letter. Comm. (Accessed 28 Jul 2022)https://scopexac.com/march-31-2021/)

Screen J A and Simmonds I 2010 The central role of diminishing sea ice in recent Arctic temperature amplification *Nature* **464** 1334–7

Serreze M C and Barry R G 2011 Processes and impacts of arctic amplification: a research synthesis *Glob Planet Change* **77** 85–96

Shindell D and Faluvegi G 2009 Climate response to regional radiative forcing during the twentieth century *Nat. Geosci.* **2** 294–300

SkyVector aeronautical charts SCCI - pdte. carlos ibanez del campo airport | skyvector (https://skyvector.com/airport/SCCI/Pdte-Carlos-Ibanez-Del-Campo-Airport)Accessed 3 May 2022

Smith W 2020 The cost of stratospheric aerosol injection through 2100 *Environ. Res. Lett.* **15** 114004

Smith W, Bhattarai U, Bingaman D C, Mace J L and Rice C V 2022 Review of possible very high-altitude platforms for stratospheric aerosol injection *Environ Res Commun* **4** 031002

Smith W and Wagner G 2018 Stratospheric aerosol injection tactics and costs in the first 15 years of deployment *Environ. Res. Lett.* **13** 124001

Solomon S 1999 Stratospheric ozone depletion: A review of concepts and history *Rev. Geophys.* **37** 275–316

Tegler J 2022 *Air Force Seeks to Bridge Aerial Refueling Gap*. (https://nationaldefensemagazine.org/articles/2022/3/14/air-force-seeks-to-bridge-aerial-refueling-gap)Accessed 3 May 2022

The Royal Society 2009 *Geoengineering The Climate: Science, Governance And Uncertainty*. (London: The Royal Society) (https://royalsociety.org/-/media/Royal_Society_Content/policy/publications/2009/8693.pdf)

Tilmes S *et al* 2018 CESM1(WACCM) stratospheric aerosol geoengineering large ensemble project *Bull. Am. Meteorol. Soc.* **99** 2361–71

Tilmes S, Visioni D, Jones A, Haywood J, Seferian R, Nabat P, Boucher O, Bednarz E M and Niemeier U 2021 Stratospheric ozone response to sulfate aerosol and solar dimming climate interventions based on the G6 geoengineering model intercomparison project (GeoMIP) simulations *Atmos. Chem. Phys.* **22** 4557–4579Atmospheric Chem Phys Discuss1–31

U.S. Air Force KC-135 Stratotanker *Air force*. (https://af.mil/About-Us/Fact-Sheets/Display/Article/1529736/kc-135-stratotanker/) Accessed 3 May 2022

U.S. Defense Science Board 2004 Defense Science Board Task Force Report on AERIAL REFUELING REQUIREMENTShttps://irp.fas.org/agency/dod/dsb/aerial.pdf)

U.S. Government Accountability Office 2020 Weapon System Sustainment: Aircraft Mission Capable Rates Generally Did Not Meet Goals and Cost of Sustaining Selected Weapon Systems Varied Widely (https://gao.gov/assets/gao-21-101sp.pdf)

Vattioni S *et al* 2019 Exploring accumulation-mode H_2SO_4 versus SO_2 stratospheric sulfate geoengineering in a sectional aerosol–chemistry–climate model *Atmospheric Chem Phys* **19** 4877–97

Veolia 2011 Winnipeg sewage treatment program: south end plant (process selection report) (https://winnipeg.ca/finance/findata/matmgt/documents/2012/682-2012/682-2012_Appendix_H-WSTP_South_End_Plant_Process_Selection_Report/Appendix%207.pdf)

Visioni D *et al* 2020 What goes up must come down: impacts of deposition in a sulfate geoengineering scenario *Environ. Res. Lett.* **15** 094063

Weisenstein D K, Visioni D, Franke H, Niemeier U, Vattioni S, Chiodo G, Peter T, Keith D W *et al* 2021 A model intercomparison of stratospheric solar geoengineering by accumulation-mode sulfate aerosols *Atmos. Chem. Phys.* **22** 2955–73