Cover page

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Marine-cloud brightening: an airborne concept

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Abstract. Marine cloud brightening (MCB) is a proposed solar radiation modification (SRM) geoengineering technique to enhance marine boundary layer (MBL) cloud albedo. Extant proposals consider $10^4 - 10^5$ autonomous ships spraying seawater, generating and dispersing sea salt nanoparticles. Alternatively, this paper proposes industrially manufacturing NaCl nanoparticles using ethanol anti-solvent brine precipitation. With desiccation, size optimization and narrowed size distribution, aerosol mass flux reduces by $\sim 500\times$ ($17\times$ for the dry mass flux). This facilitates Unmanned Aerial Vehicle delivery (e.g. MQ-9 Reaper UAV). Increased speed, altitude and wake turbulence improves areal coverage per vehicle vs. ships — reducing fleet size. Utilizing extant airframe designs improves vehicle technology readiness level (TRL) — potentially improving system operational cost (est. $\$40B \cdot yr^{-1}$) and lead time. This approach further reduces energy requirements ($5\times$ less), technical risk and system complexity. Increased readiness amplifies proliferation risk — particularly for inexpensive regional heatwave and hurricane suppression — making governance more urgent.

Plain Language Summary

Marine Cloud Brightening (MCB) is a potential technique for reducing climate change. Fine seawater sprays from ships would dry in the open air, creating tiny salt particles. These can act as cloud condensation nuclei (CCN) — making clouds whiter and less likely to rain out. Current MCB designs propose thousands of robot ships — a design based on two limiting factors. Firstly, uneven salt particle size wastes 94% of the material on inefficient large aerosols. Secondly, seawater needs $\sim 30\times$ more volume than pure salt. Together, these effects give $\sim 500\times$ aerosol mass increase beyond the minimum required.

This paper considers making very small salt grains of precise size, by mixing salt water droplets into pure ethanol. By reducing total aerosol mass, medium sized drones (MQ-9 Reaper type) can replace ships. Drones are faster, so each covers a larger area, cutting fleet size ($5\times - 50\times$) and energy requirements ($5\times$). Their turbulent wake and altitude assists lofting and dispersion — which is challenging for ships. This technology makes it easier to start MCB and may enable other geoengineering types. This makes it more likely that people will try geoengineering soon — so society needs to make appropriate rules more quickly.

1. Introduction

MCB proposes injecting sea salt (mostly NaCl) nanoparticles in the marine boundary layer (MBL, 0-1 km altitude). Airborne micro- and nanoparticles of salt exist naturally in very high concentrations, up to $1000 cm^{-3}$ in some regions [25]. MCB aims to increase local number concentrations approximately two to four times [25]. These aerosols act as CCN, raising the concentration of cloud droplets — thus brightening MBL clouds, due to the Twomey effect [38].

MCB — together with the technically related Cirrus Cloud Thinning (CCT) — is one of two major proposed solar geoengineering techniques. The alternative is Stratospheric Aerosol Injection (SAI) [37] — which generally requires higher altitude (20-25km — albeit with altitudes comparable to tropical CCT for seasonal polar SAI). MCB offers finer spatial and temporal control of climate. Fine control potentially increases governance challenges; increasing degrees of freedom adds points of contention. Tropospheric salt particles remain local and last ≤ 10 days — vs. ~ 2 years for hemispherically mobile SAI particles.

MCB requires development and implementation of a scalable deployment system, before use at scale is possible. This system should have the capacity to achieve negative radiative forcing sufficient to offset greenhouse warming from anthropogenic CO_2; however regional MCB has also been proposed (e.g. Great Barrier Reef). Various researchers [25], [13], [11] propose $10^4 - 10^5$ ships spraying seawater aerosols in the MBL. This paper instead proposes centralized industrial manufacturing of monodisperse salt nanoparticles — with UAV dispersal suggested, facilitated by aerosol mass reductions. The overall concept is illustrated in Figs. 1 and 2.

2. Salt nanoparticle production

2.1. Design parameters

Wood et al. [41] evaluated MCB salt injection for offsetting a doubling of CO_2 (w.r.t. pre-industrial):

- Total particle injection rate of $\dot{N} = 6 \cdot 10^{20}\,\mathrm{s}^{-1}$
- Optimal particle diameter of $30 - 40\,\mathrm{nm}$

implying a minimum dry salt mass flux $\sim 10^2 kg\,\mathrm{s}^{-1}$; seawater mass is $\sim 30\times$ higher. Any upwards deviation from optimal diameter disproportionately affects mass efficiency, due to the cubic mass/diameter relationship.

2.2. Salt nanoparticle production using anti-solvent precipitation

Chen et al. [10] considered salt nanoparticles of configurable dimensions (20-80 nm diameter). The authors used anti-solvent precipitation from concentrated brine droplets ($2 mol.L^{-1}$ NaCl (aq.)) — using anhydrous ethanol through one capillary with flow rates of $37\,\mathrm{mL\,h^{-1}}$ ethanol and $0.9\,\mathrm{mL\,h^{-1}}$ brine. With average diameter $39 \pm 3.6\,\mathrm{nm}$, this apparatus generates particles averaging $1.3 \cdot 10^{-19}\,\mathrm{kg}$, at $1.05 \cdot 10^{-4}\,\mathrm{kg\,h^{-1}}$ — *i.e.* $2.2 \cdot 10^{11}\,\mathrm{s}^{-1}$. Anti-solvent precipitation methods offer a narrow normal size distribution ($\sigma = 3nm$), versus sprayers' wide lognormal distribution ($\sigma = 65nm$) [11]; this reduces total salt mass $17\times$ and eliminates harmful giant nuclei [19].

Scaling to generate $\dot{N} = 6 \cdot 10^{20}\,\mathrm{s}^{-1}$ requires $\dot{m} = 78\,\mathrm{kg\,s^{-1}}$; energy and resource requirements are detailed below.

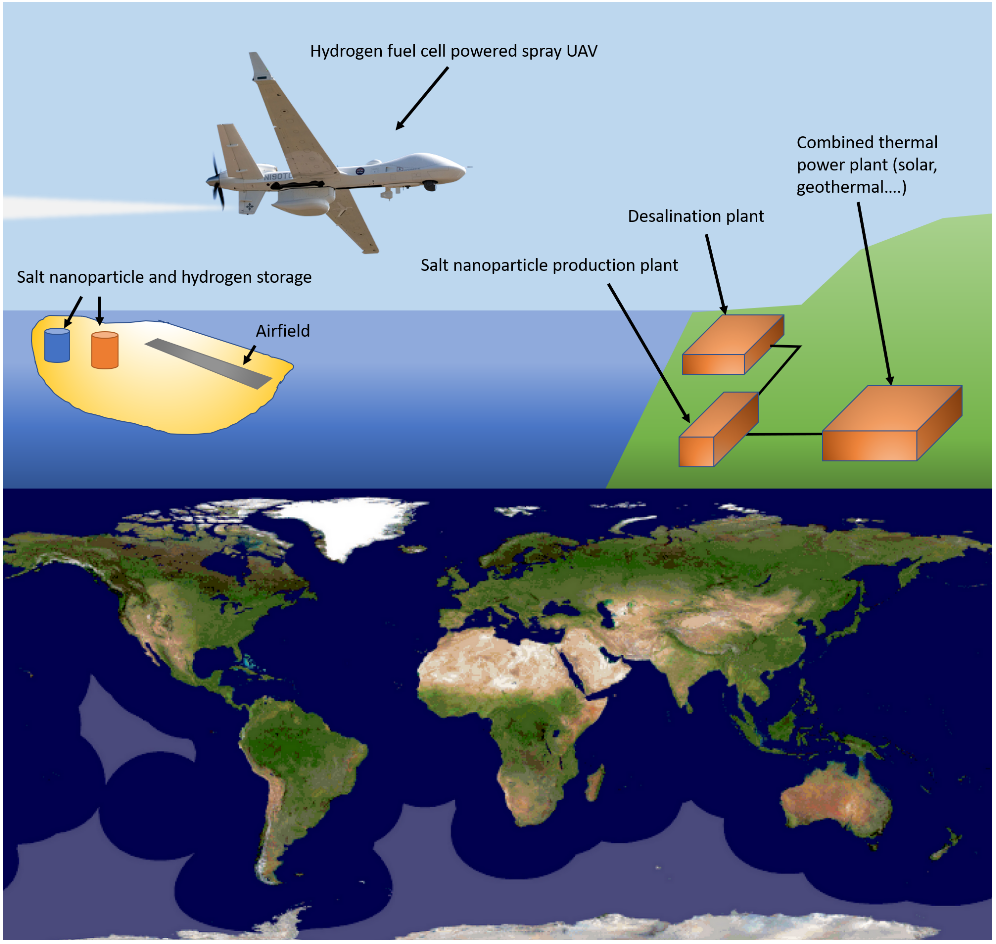

Figure 1. **Top:** proposed MCB system. Salt nanoparticles are generated industrially, using waste desalination brine.

Bottom: accessible area (navy blue), assuming a 2,200 km UAV range, from present Extended-range Twin engine Operations Performance Standards (ETOPS) airfields — diversion airfields for commercial twin-engine airliners, with significant maintenance facilities extant.

2.3. Particle generation inputs

The process outlined below is based on [10], and is experimentally validated with the parameters outlined below. This process could be made considerably more efficient by reusing the output 97.5% pure ethanol solution before reconcentration, though this possibility requires further lab testing. The lower limit of purity has not been experimentally established, and multiple reuse cycles cannot be ruled out. Hence, the energy requirements outlined below are "worst-case", and can therefore possibly be considerably reduced to perhaps below half with modest process changes.

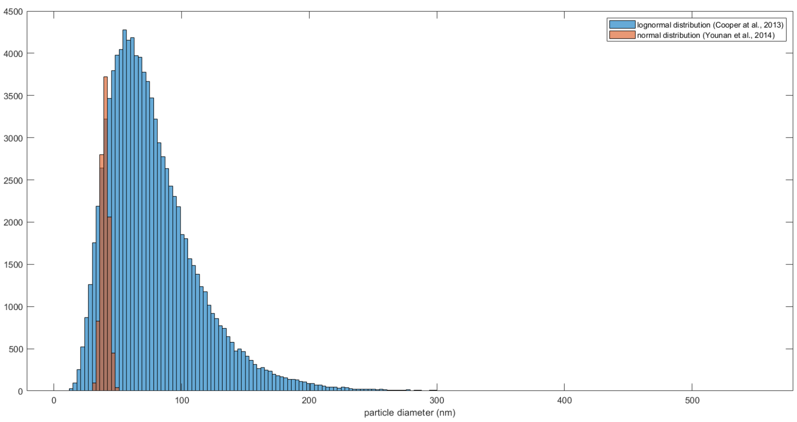

Figure 2. Comparison of particle size distributions for sprayers (blue) and anti-solvent precipitation (orange; normal). The spray system is a lognormal distribution with mean 70 nm and geometric standard deviation 1.57 [13], while the anti-solvent precipitation offers a normal distribution with mean 40 nm and standard deviation 3 nm [10].

Particle generation requires $2.7 \cdot 10^9$ capillaries, running 2M NaCl at $2.4 \cdot 10^3\,\mathrm{m}^3\,\mathrm{h}^{-1}$ into 99.6% purity (anhydrous) ethanol at $9.6 \cdot 10^4\,\mathrm{m}^3\,\mathrm{h}^{-1}$, with potential ethanol purity reductions discussed above.

Desiccation of post-precipitation waste ethanol-water mixture dominates system energy requirements ($> 90\%$).

Ethanol flux is $9.6 \cdot 10^4\,\mathrm{m}^3\,\mathrm{h}^{-1}$. Given a 40:1 volumetric ethanol-brine ratio [10], final volumetric ethanol concentration is $\sim 97.5\%$. The energy cost [23] of desiccating azeotropic ethanol (*i.e.* which cannot be distilled— 96% ethanol by vol.) is $1.25\,\mathrm{MJ\,kg}^{-1}$ ($1.134\,\mathrm{MJ\,kg}^{-1}$ for the pervaporation system [23]. Pervaporation is similar to distillation, but uses a selectively permeable membrane to reduce contamination of the vapor phase with the unwanted volatile. At the required flow rate, total power is 18.1 GW — mostly low temperature industrial heat ($> 95\%, 70\,°\mathrm{C}$). This is available from cogeneration, solar thermal, geothermal or heat pump inputs.

Generating the requisite 2M NaCl flux ($2.4 \cdot 10^3\,\mathrm{m}^3\,\mathrm{h}^{-1}$) requires less energy than desiccation. Reverse osmosis desalination generates brines $\leq 75\,\mathrm{kg\,m}^{-3}$ — *i.e.* 60% of the required 2M concentration ($117\,\mathrm{kg\,m}^{-3}$). Weak brine can be concentrated in open air evaporation ponds; a $7km^2$ pond can provide the required evaporation rate (in typical south western US humidity conditions: NV or AZ) to vaporize $1.6 \cdot 10^3 m^3 \cdot h^{-1}$ [15]. Brine flow rate is 40% of the outfall capacity of individual large plants; Ashkelon (Israel) generates $10^4 m^3 \cdot h^{-1}$ [34].

Separation of nanoparticles from ethanol can be achieved using cross-flow filtration [31]. Centrifugal drying cannot be used, due to the small particles low density differential (resulting in very low terminal velocity). In cross-flow filtration, the feed flow is tangential, across the filter surface. The liquid phase exits through the filter tube walls, normal to the mixture flow through the pipes. This enables continuous filtration in industrial processes — e.g. using ceramic filters with pore dimensions ≤ 5 nm [40, 9]. $27MW$ average mechanical power is required, at pressure $10^6 Pa$. Filtration requires $80,000m^2$ surface area — assuming a specific flux of $120l \cdot h^{-1}m^{-2}bar^{-1}$ [9],

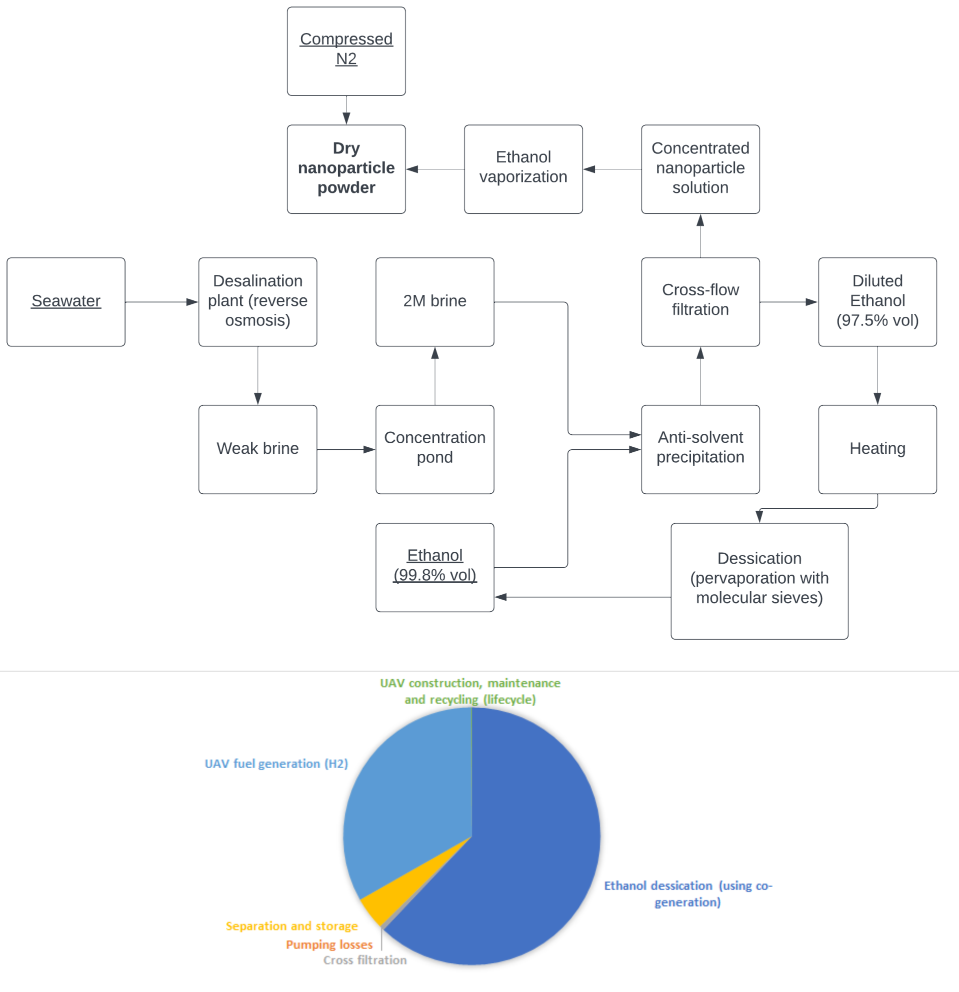

Figure 3. **Top:** process used to generate the salt nanoparticles. **Bottom:** overall system power usage (5 GW).

e.g. 1200 tubes of length $100m$ and radius $10cm$. Additional steps are needed to store nanoparticles as a powder within a pressurized inert gas. Vaporization of the concentrated ethanol solution, and the addition of nitrogen requires $\leq 200MW$ (e.g. with an airtight pond of surface area less than $0.5km^2$ and $1MW$ to generate the required N_2). This assumes 1:1 ethanol(l):NaCl(s) by volume, after filtration.

Pumping losses are negligible: capillary pressure drop is only $140Pa$ [2] requiring $1MW$. The power budget is summarized in Figure 3 below.

3. Nanoparticles MBL injection

UAVs are proposed to deliver MBL nanoparticles, facilitated by the $\sim 30\times$ mass reduction from desiccation and $\sim 17\times$ from size & homogeneity improvement [41]

($3.6 \cdot 10^4 \mathrm{kg\,h^{-1}}$ UAV vs $6 \cdot 10^6 \mathrm{kg\,h^{-1}}$ ships), giving $\sim 500\times$ total.

Particles per meter travelled is maintained $10^{16} m^{-1}$ as per ships [41]. This number concentration constraint is to prevent coagulation and agglomeration of the salt particles after emission. It is possible that the emission rate could be substantially higher with dry powder aerosols (as proposed), since the local ambient humidity would be much lower than in a seawater spray. Aircraft range limits (several thousand km) suggest a platform with several tonnes payload. Fixed wing UAVs are ideal; rotorcraft UAVs have poor endurance, range and payload; wide body tanker airplanes have excess payload, wasting energy and capital; crop dusters and small fire-fighting aircraft have littoral applications, briefly discussed later.

Fixed-wing UAVs are designed for endurance, with high lift to drag ratios. Their cruising speed (100 m/s) and operating altitude (0-10 km) are appropriate for efficient spraying. UAV speeds allow a higher particle emission rate per vehicle than ships, reducing fleet size. Effective discharge airspeed is enhanced by general wake turbulence and specifically by propeller wash. Potentially, distribution of particles suspended in heterogeneously sized droplets of a volatile carrier fluid could avoid excess drift, whilst broadening the distribution track [16]. Deployment must be near clouds; small aerosols do not reliably settle [14].

Wood et al. [41] consider 10^4 - 10^5 boats; particle injection rates are limited by local winds (average $7\,\mathrm{m\,s^{-1}}$), precluding a smaller fleet. UAVs travel $14\times$ faster than ships ($100\,\mathrm{m\,s^{-1}}$) [6]. With injection in the propeller wash, effective wind speed is further increased by 40% (propeller propulsive efficiency [8] of 0.8); performance does not increase by the same factor — due to travel time from airfields to spray zones, reducing spraying duration. Later design work can optimize for wake turbulence and wingtip vorticity at the expense of range — creating long and short range UAV variants. However, a radial distribution pattern around dispersed airfields risks proximal saturation coverage — arguably negating any short range variant advantages, absent additional runways. An alternative system design can include mid-air resupply (e.g. Global Hawk UAV); this involves various complexities not further considered. Finally, one-way flights between airfields may prove optimal given a sufficiently dense airfield network.

3.1. UAV platform

A particle injection rate of $6 \cdot 10^{17} s^{-1}$ (or $280 kg \cdot h^{-1}$) per UAV is considered, scaled up from [41] by 1-2 orders since:

(i) particles are stored as powder in pressurized inert gas or supercritical fluid (lowering coagulation risk)

(ii) Effective wind velocity is more than 1 order of magnitude higher than average sea level wind speed.

With assumptions as above, 500 on-station UAVs are required — 1-2 orders of magnitude fewer than ships. This number includes payload constraints, in particular the weight of empty aerosol tanks (10% of the payload). However, total active fleet size is $\sim 3\times$ higher than this number, considering maintenance and commuting time . This paper assumes a 4:1 ratio of total airframes to on-station airframes, to account for other factors: training, crashes, upgrades, unplanned outages, environmental monitoring, experimentation, and aborted missions.

Endurance, payload and speed requirements match existing UAVs — e.g. MQ-9 Reaper (20 h; 1700 kg; $100\,\mathrm{m\,s^{-1}}$) [6, 32]. For MQ-9 aeral coverage see Fig. 1b.

Comparable and less expensive alternatives are available from other nations — Chengdu Wing Loong III (China); TAI Anka (Turkey), $ 25M.

Alternative platforms are possible. Unmanned seaplanes provide superior high seas coverage, even using short range aircraft — but require support ships for refueling, resupply, storm shelter, and maintenance. Additionally they have more stringent maintenance requirements [17] with associated costs implications. Conceivably, UAVs could also be launched from existing or dedicated cargo ships, using catapults and recovery nets. Alternatively, manned crop-dusters and firefighters (e.g. Air Tractor AT 802-F) are immediately and inexpensively available ($\$4500h^{-1}$); these are likely useful for littoral use (e.g. reef protection), but are less suited to remote high seas operations. With appropriate support and configuration, aircraft based on these types could be used as high seas seaplanes, or could fly from marine runways — carriers or fixed platforms. Blue water operations using single engine aircraft would add substantial support costs and crew risks, necessitating the provision of costly infrastructure: search-and-rescue, crew accommodation, medical facilities, and storm-proof aircraft storage. Even with such marine infrastructure, any high seas piloted work would likely remain dangerous, lonely, and tedious — giving a locus for industrial action or political protest. Further, the alternative approaches above introduce substantial system and regulatory complexities unnecessary for this preliminary analysis.

MQ-9 UAVs can readily use sustainable aviation fuel (Fisher-Tropsch synthesized or biofuel). An alternative is green hydrogen, requiring a major redesign — *i.e.* a hydrogen powerplant, with compressed or cryogenic hydrogen storage. A brief discussion of hydrogen power options is merited, not least because this simplifies airside energy use calculations. Several options, including fuel cells [7] or hydrogen gas turbines [29] are currently available, all with very high TRL. For the proposed application, fuel cells are most suitable: they have a very high efficiency ($50-60\,\%$), and a very high time between overhaul (TBO) of between $5000-25000\,\mathrm{h}$ [7] — a particular advantage at remote airfields or for marine UAVs. Fuel cells have been demonstrated in flight in 2023 by Universal Hydrogen, using a fuel cell of dimensions, mass, and power compatible with the MQ-9 [1].

UAV fleet requirement ($2,000$) is six times the total production of MQ-9s to date (319); this may result in costs savings. For clarity, discussion of specific aircraft types does not mandate use of these actual designs — merely airframes with comparable capabilities. Accordingly, this allows practical production scaling — even if existing manufacturers fail to increase production, or to offer civilian versions. Absolute scaling requirement is modest, compared to all reasonable historic metrics: global aircraft tonnage, global aircraft count, single-model aircraft production volume, single-model aircraft production rate [20].

A military MCB program is not proposed. In common with other joint civil/military airframes (e.g. A-330 and A-330 MRTT [21]), civilian versions are already made for the MQ-9 [24]; this eliminates national security or misidentification concerns. Significant civilian savings are expected from the $\$30M$ military CapEx unit price — omitting military grade secure communications, stealth capabilities, electronic counter measures, threat detection systems, targeting optics, crew vetting, etc. OpEx costs are less flexible, but will still benefit from omission of costly spares and the maintenance of specialist components. HR & management costs are also likely to be substantially lower, given the routine, lower-risk nature of the work and the reduced vetting requirements. General maintenance could be done at operational airfields; centralized major maintenance would primarily involve powerplant replacement or refurbishment. With near 50% uptime, powerplants would have to be changed annually, assuming a conservative TBO of 8000 h [7]. This requires the production or refurbishment of 10^3 powerplants annually.

Total civilian cost per flight hour (including maintenance, fuel and amortization; excluding pilots and ground installations) is around $800 for civilian agencies [3]. Military cost per flight hour (all inclusive) is around $3500. Taking approximately 60% of flight hours as commuting, transfer, monitoring, training, and abortive gives military on-station cost of $8750 per hour. Civilian costings are likely to be no more than 75% of military — particularly given the large volume of orders, international market of airframes, simpler piloting work (4 flying airframes per on-shift pilot is assumed), and the lack of expensive military equipment (positioning in GPS denied environments, targeting optics, secure satellite communications, radio links with surrounding jets, missile pylons and interfaces). Hence, hourly on station cost is around $\$6,500$. This gives annual airside costs of $\$29B$ to reverse a doubling of CO_2 [41].

3.2. Cirrus Cloud Thinning

UAVs are also capable of Cirrus Cloud Thinning (CCT) operations; the MQ-9 has a $15km$ ceiling. CCT may require a change in particle size, by modifying the anti-solvent flow ratio [10]. Optimal performance may mandate alternative materials — e.g. BiI_3 [30], or some acids or proteins. CCT is less studied than MCB; consensus on materials, flow rates, seeding conditions, etc. is not established. Accordingly, affordable, safe and effective solvent/anti-solvent pairings may not exist for CCT, so further discussion is curtailed.

3.3. Stratospheric Aerosol Injection

Due to altitude limitations, the aircraft discussed are unsuitable for SAI, beyond very limited polar deployments [39]. However, the proposed approach may impact SAI development and deployment.

Firstly, antisolvent precipitation may conceivably be used for SAI —- as an alternative to environmental condensation from SO_2 or H_2S. Cost, material efficiency, and particularly size control advantages are equally applicable to SAI. Solids considered for SAI include titania, alumina, and diamonds [33]; candidate materials might feasibly be made via antisolvent precipitation, achieving optimal particle size distribution.

Secondly, there is no specific altitude limit preventing appropriately designed successor UAVs from performing SAI [36]. UAV programs for MCB will necessarily create technical and organizational capacity, partially applicable to SAI. As such, any UAV MCB program poses general SRM proliferation risks.

4. Discussion

4.1. Implementation

The proposed approach reduces lead time and implementation risks. Centralized production facilities can manufacture nanoparticles — leveraging existing power, desalination, and ethanol facilities. Similarly, international shipping and existing UAV platforms facilitate delivery. Therefore, the proposed system could be assembled using high TRL equipment. Hypothetical program pacing overlooks entirely the financial, environmental and governance development requirement — and therefore does not identify a critical path.

4.2. Cost, electricity and fuel usage

Most power required for recycling the ethanol solution and generating the 2M NaCl solution is low-temperature industrial heat (defined as $\leq$ 165 °C). This $20\,GW_{th}$ (thermal power) can be co-generated using existing thermal power plants (combined heat & power; CHP), geothermal heating plants, solar concentration heating plants (mirror arrays), or heat pumps with geothermal low temperature sources. In particular, under-utilized, geothermal-rich areas could be used. Ideal locations include the Pacific Rift Valley or Iceland — mirroring the approach taken by Climeworks for direct air capture [18].

With co-generation from existing thermal power, demand can be expressed as effective electrical power — i.e. electricity production loss due to co-generation. This is $3.3GW_e$ — since typically for each unit of electrical power lost, approximately six units of thermal power ($< 90°C$) are created [28]. The exact figure depends on the hot source T_h and cold source temperatures T_c, and is bounded by the Carnot limit $\frac{T_h}{T_h - T_c}$.

Given average worldwide electricity cost of $ 190 MWh^{-1} [5] (business users), this amounts to a yearly program cost (for process energy, not UAVs) of USD 5.4 B. However, realistic programs locate for optimal input prices; such optimization significantly lowers costs, but requires location-specific analysis beyond present scope. The cost of this system can be estimated from [23], which mentions the operating cost of the pervaporation system as EUR $0.0112 \cdot kg^{-1}$; with the required amount of ethanol to reprocess, a yearly cost of $\$8.9B$ is expected (with a $1.1 for 1 EUR conversion rate (August 2023).

Yearly electrical equivalent energy requirement $28.6\,TWh_e$ is $\sim$ 0.13 % of world [4] electricity generation ($2.2 \cdot 10^4\,TWh_e$; 2022). Again, opportunities to reuse waste ethanol one or more times before desiccating would reduce this figure very substantially.

Ships, require approximately 24.6 GW_e for the same numerical emission rate ($\dot{N} = 6 \cdot 10^{20}\,\mathrm{s}^{-1}$), based on 41 kW for $10^{15}\,\mathrm{s}^{-1}$ [12] — neglecting navigation, control, and other subsystems loads. The energy required by ships thus amounts to 210 TW h yr^{-1}, $\sim$ 0.9 % of the yearly world electricity production (2022) — approximately 5× less efficient than UAVs (even when considering UAV propulsion requirements). The electricity cost is $\$41B \cdot yr^{-1}$, which does not include ship, spray system and other ship systems (control and propulsion) amortization and maintenance. Capital equipment and energy requirements of the ship system are not analyzed, though decentralized electricity production (*i.e.* the ship system) is usually more expensive than centralized electricity production (*i.e.* the UAV system).

While conventional jet fuel is likely to be used — at least in the near term — analysis of hydrogen fuel requirements helps scale system energy requirements. Total annual UAV H_2 demand — conservatively assuming constant full throttle, and a typical fuel cell efficiency of 55 % — is $3.2 \cdot 10^8$ kg; 0.4 % of current worldwide hydrogen production of $7.5 \cdot 10^{10}\,\mathrm{kg} \cdot \mathrm{yr}^{-1}$ [26]. The total average power required to generate this hydrogen is 1.6 GW, assuming an electrolysis efficiency of 0.75 [35]. Hydrogen production rates will also likely increase in the near future.

4.3. Advantages and disadvantages

UAVs advantages:

- Centralized particle generation enables economies of scale and simpler plant maintenance (vs marine electricity generation), reducing CapEx and OpEx.
- Reduced total electrical equivalent power ($5\,\mathrm{GW}_e$ vs. $\geq 24.6\,\mathrm{GW}_e$ for marine). Power generation is simplified (centralized) and more economical (capital & maintenance costs). Ships required onboard power generation, which is potentially difficult to achieve continuously using renewables. By contrast, centralized powerplants are less expensive to build and maintain, and do not need to store energy during nights or adverse weather — but stranded renewables may require storage. For the UAV system, aerosol and fuel production facilities could be installed near stranded geothermal or solar energy resources.
- The proposed system is more weather-robust, particularly to hurricanes or typhoons. UAVs can evade extreme weather events, or shelter in hardened hangars — ships need more time to move.
- Dry particle ejection and higher UAV speed & altitude alleviates dynamical problems associated with ships — e.g. negative plume buoyancy from evaporative cooling.
- Injection altitude and location can be dynamically optimized by adjusting the UAV location in 3D — leveraging local wind, atmospheric and cloud conditions.
- UAVs can be operated from carriers (e.g. TCG Anadolu, commissioned April 2023), marine platforms, tethered barges, icebergs, and seaplane support vessels – albeit with diverse regulations, logistics requirements, and additional costs.
- Greatly simplified UAV maintenance. Ships would require design robustness and frequent maintenance, due to the harsh marine environment: corrosion, biofouling, guano, high winds & waves, cetacean strikes, vertebrate colonization, etc. Furthermore power generation systems, pumps, motors, sensors and actuators require periodic maintenance. This maintenance is more costly in ships than UAVs, due to fleet size ($5-50\times$) and accessibility issues. Ships would either have to travel thousands of miles to ports, or be maintained by long-distance repair ships. By comparison with established UAV programs, the operational robustness of complex autonomous remote ships is somewhat speculative.
- Accessibility of marine platforms makes them vulnerable to piracy, theft, scavenging and sabotage.

UAVs disadvantages:

- Lower systemic robustness, due to centralization and concentrated points of failure; however the system has redundancy. Nevertheless some large scale events could also defeat the high redundancy of a (distributed) marine system; a major hurricane or cyber attack could be particularly disruptive.
- Lower uptime: UAVs must avoid harsh weather, while unmanned ships are comparatively robust in severe weather.
- The MQ-9 has approximately 1.8 crashes per 10^5 flight hours [27]. With $4.38 \cdot 10^6$ flight hours annually, 80 crashes per year would be expected — representing substantial fleet attrition, comparable to airframe retirements (45 retirements per year). However most MQ-9 flights are military; these are inherently more risky than routine civilian operations and less able to sustain precautionary outages in challenging conditions. In civilian use, the crash rate should be greatly reduced — through better preparation, use of more robust systems, and avoidance of severe weather areas.
- Airbags and parachutes could be used to recover ditched airframes, though they would increase aircraft weight and complexity, meriting a cost-benefit analysis vs. payload.
- Requirement for specific geographically dispersed airfields gives significant political leverage to an unlikely collection of states. This imposes political risk and enables rent-seeking behavior [22].
- Accessing the entire oceanic surface requires the creation of remote airstrips or the use of local airports in some locations (e.g. Galapagos Islands, Antarctica, Kerguelen Island). Alternatively, mid-air resupply (per Global Hawk UAV) is possible. Currently accessible locations are shown in Fig. 1b.
- Requirement to ship nanoparticles and fuel from production facilities to airfields will add small energy and resource costs — outweighed by manufacturing centralization savings.
- Centralized supply chain increases military vulnerability

The key differences between ships and UAVs are summarized in table 1

5. Conclusions

Ethanol anti-solvent precipitation of brine leads 500× aerosol mass reduction for MCB, enabling UAV distribution. This is due to desiccation, size optimization and homogeneity.

The proposed approach relies on extant aircraft platforms and a terrestrial supply chain that is either extant or high TRL. This approach conserves energy (5×), compared to marine operations — with potential further savings available due to antisolvent reuse. This systemic approach is potentially adaptable to CCT (cirrus) operations, and may later influence SAI geoengineering.

This high TRL and cross applicable technology approach poses proliferation risks, and invites a governance response. The ready applicability of MCB to regional scale cooling using limited fleets further increases nearer-term proliferation risks.

Approach	Autonomous ships	UAVs with centralized production
Centralized aerosol production	No	Yes
Vehicles count	10^4 to 10^5	$2 \cdot 10^3$
Cost	$> \$41B \cdot yr^{-1}$ (electricity only)	$\$40B \cdot yr^{-1}$ (total cost excluding plant CapEx)
Average power requirement (electric equivalent)	24 GW	5 GW
Aerosol mass rate	$1300 kg \cdot s^{-1} = 40 Tg \cdot yr^{-1}$	$78 kg \cdot s^{-1}$
Vehicle location	Distributed	Centralized in airfields
Main risks	Energy requirements Maintenance requirements Production rate Lack of fine control Unproven ship design Atmospheric dynamics issues	Lower systemic robustness Infrastructure requirements Supply chain requirements Political risk and rent-seeking

Table 1. Summary of differences between autonomous ships and UAVs

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7. Open Research

No new data was used for this work.

8. Conflict of interest statement

The authors have no conflicts of interest to report.

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