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Marine-cloud brightening: an alternative system concept

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Key Points:

- Marine cloud brightening can be obtained using a system with lab-generated salt particles, dispersed using Unmanned Aerial Vehicles (UAVs).
- Salt nanoparticles generated by this system have a narrow size distribution, saving weight and making UAVs a viable solution for dispersion.
- Preliminary analysis shows that this system could be more readily developed, and would cost less than a ship-based system.

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Abstract

Marine Cloud Brightening (MCB) is a proposed solar radiation management climate engineering technique to enhance the albedo of marine clouds (Latham et al., 2012). In the current approach to MCB, a large number of ships spray seawater in the atmosphere to simultaneously generate and disperse sea salt nanoparticles. In this commentary, we describe an alternate approach for producing and delivering NaCl nanoparticles in the atmosphere, using anti-solvent precipitation techniques and hydrogen-powered UAVs as delivery vehicles. We show that this approach has lower energy costs than the current ship approach, with greatly simplified system development, power generation, and maintenance.

Plain Language Summary

Marine Cloud Brightening (MCB) is one of the most promising techniques for mitigating some effects of climate change. It involves spraying a large quantity of sea salt nanoparticles into the lower atmosphere to enhance the reflectance of clouds. The current vision of MCB is to use a fully decentralized system of spray ships that simultaneously generate salt nanoparticles and disperse them. In this paper, we propose and discuss an alternate, centralized system that costs less to implement and operate, uses less total energy, and leverages technologies that have higher Technology Readiness Level (TRL).

1 Background

The core idea of MCB is to inject large quantities of sea salt (mostly NaCl) nanoparticles in the marine boundary layer (MBL), an atmospheric layer extending from the ocean surface up to approximately 1000 meter altitude. Micro- and nanoparticles of salt naturally exist in the atmosphere in very high concentrations. The objective of MCB is to slightly increase the salt particle concentration, and hence the concentration of cloud droplets that grow from these salt particle, resulting in an increase in the brightness of low-level marine clouds (Twomey, 1977).

MCB is one of two major possible solar geoengineering intervention techniques currently considered. The alternative method is Stratospheric Aerosol Injection (SAI) (Smith & Wagner, 2018). MCB can be argued to be a much safer method than SAI, with the possibility of finer control of climate. This is due to the fact that the lifetime of salt particles in the troposphere is less than 10 days, versus 2 years for stratospheric particles. Hence, the effects of MCB can be quickly reversed, in a matter of days, by stopping further particle injection (Latham et al., 2012). One of the major problems associated with MCB is, however, the development and implementation of a scalable system that could achieve the levels of negative radiative forcing required to offset the greenhouse effect caused by anthropogenic CO_2. Latham et al. (2012), Cooper et al. (2013), Connolly et al. (2014), and others propose to use a distributed system of ships continuously spraying salt nanoparticles in the marine boundary layer, using specially designed spraying equipment. In this commentary, we propose an alternate system using land-based industrial facilities to generate salt nanoparticles, and hydrogen-powered Unmanned Aerial Vehicles (UAVs) to spray them where needed. The overall concept is illustrated in Fig. 1

2 Salt nanoparticle production

2.1 Design parameters

Wood (2021) recently evaluated the required amount of salt that should be injected in the marine boundary layer. The design parameters required to completely offset the greenhouse effect caused by anthropogenic CO_2 are the following: A total particle injection rate of $\dot{N} = 6 \cdot 10^{20}\,\mathrm{s}^{-1}$ and an optimal particle diameter of $30 - 40\,\mathrm{nm}$.

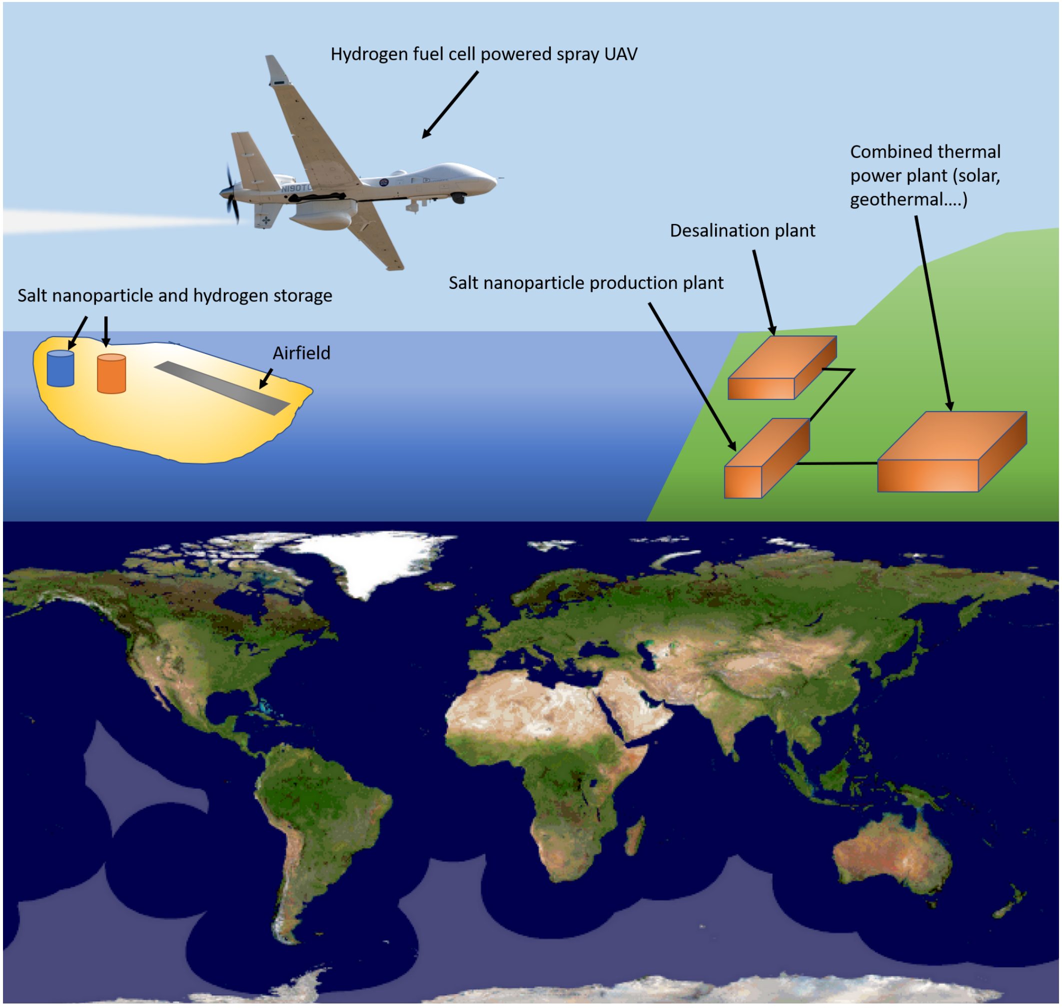

Figure 1. Top subfigure: proposed system for marine cloud brightening. In this system, the salt nanoparticles are generated in land-based industrial facilities, using power from combined heat and power (CHP) plants, and waste brine from desalination plants. The particles are then sprayed using hydrogen fuel cell powered UAVs, based on airfields located near the areas to spray. Bottom subfigure: reachable area (deep blue) of UAVs, assuming a range of 2,200 km, and operations from an ETOPS airfield.

2.2 Salt nanoparticle production using antisolvent precipitation

Recent work by Chen et al. (2019) has focused on generating salt nanoparticles of configurable dimensions, ranging from several nm to more than 50 nm in diameter. The particles are generated using anti-solvent precipitation from a concentrated 2M NaCl solution (2 mol NaCl dissolved per 1 L of water), using ethanol to precipitate the salt nanoparticles. In this experiment, the authors generated salt nanoparticles using one capillary with flow rates of $37\,\mathrm{mL\,h^{-1}}$ of ethanol and $0.9\,\mathrm{mL\,h^{-1}}$ of 2M NaCl solution. With an average edge size of $39 \pm 3.6\,\mathrm{nm}$, this apparatus generates particles of an average mass of $1.3 \cdot 10^{-19}\,\mathrm{kg}$, at a rate of $1.05 \cdot 10^{-4}\,\mathrm{kg\,h^{-1}}$ or equivalently $2.2 \cdot 10^{11}\,\mathrm{s^{-1}}$. Particles generated using antisolvent precipitation methods have a very narrow size distribution, in contrast with the wide lognormal distribution of the particles generated by sprays (Connolly et al., 2014). Such a narrow size distribution does not only reduce the mass of salt needed to produce the required number of particles, but also prevents the production of so-called giant nuclei that could initiate precipitation and hence unintended cloud darkening (Hoffmann & Feingold, 2021).

Scaling up to generate the required $\dot{N} = 6 \cdot 10^{20}\,\mathrm{s^{-1}}$ would require the generation of $\dot{m} = 78\,\mathrm{kg\,s^{-1}}$, or equivalently 280 tonnes of salt nanoparticles per hour. This production would require the following reactants and energy.

2.3 Resources and power needed to generate the salt nanoparticles

The generation of salt nanoparticles would require $p = 2.7 \cdot 10^9$ capillaries, running 2M NaCl solution and ethanol solution at flow rates of $9.6{\cdot}10^4\,\mathrm{m^3\,h^{-1}}$ for the ethanol and $2.4 \cdot 10^3\,\mathrm{m^3\,h^{-1}}$ for the 2M NaCl solution.

Most of the energy required in this process is related to the dessication process of the ethanol-water solution, and the preparation of the 2M NaCl solution.

Dessicating the ethanol-water solution generated by the antisolvent precipitation process carries by far the highest energy cost. The total flow of ethanol is $9.6{\cdot}10^4\,\mathrm{m^3\,h^{-1}}$. Given the chosen flow-rate ratio $R = 40$ by volume (Chen et al., 2019), the final concentration of ethanol in the ethanol-water mixture should be approximately 97.5% by volume, which is near azeotropic (96% by volume). Based on Kunnakorn et al. (2013), the energy cost of dessicating azeotropic ethanol is measured at $1.25\,\mathrm{MJ\,kg^{-1}}$ ($1.134\,\mathrm{MJ\,kg^{-1}}$ for the pervaporation system, and $0.1\,\mathrm{MJ\,kg^{-1}}$ to raise the ethanol temperature from $20\,^{\circ}\mathrm{C}$ to the pervaporation temperature of $70\,^{\circ}\mathrm{C}$). At the required flow rate, the total energy requirement thus on the order of $6.5 \cdot 10^{13}\,\mathrm{J\,h^{-1}}$ or 18.1 GW. Note however that most of this power is low temperature industrial heat, that can be efficiently generated through cogeneration, using geothermal sources, or using heat pumps.

Generating the 2M NaCl solution requires a comparatively lower energy cost. First, it can be noted that desalination plants generate brine (as a byproduct) with a concentration of $50 - 75\,\mathrm{kg\,m^{-3}}$, close to the required 2M concentration of $117\,\mathrm{kg\,m^{-3}}$. This reconcentration can be performed using solar heating in evaporation ponds, requiring an evaporation rate of $1620 m^3 \cdot h^{-1}$, which can be achieved with a pond surface area of $7 km^2$ (Friedrich et al., 2018). The required flow rate of brine ($4{\cdot}10^3\,\mathrm{m^3\,h^{-1}}$) is well within the capacity of existing large desalination plants, for example the Ashkelon desalination plant (Israel) generates more than $10^4 m^3 \cdot h^{-1}$ (Sauvet-Goichon, 2007).

The separation of the salt nanoparticles from the ethanol can be achieved using cross-flow filtration (Niu et al., 2018), using for example ceramics filters that can have pores of dimensions less than 5 nm (Werner et al., 2014; Buekenhoudt et al., 2013), suitable for our application. The average mechanical power required for this process, assuming a pressure of $P = 10^6 Pa$ is $27 MW$. This filtration system would require surface area of $80,000 m^2$, assuming a specific flux of $120 l h^{-1} m^{-2} bar^{-1}$ (Buekenhoudt et al., 2013).

This can be achieved for example using 1200 tubes of length $100m$ and radius $10cm$. Additional small energy costs are associated with the vaporization of the highly concentrated ethanol solution, and the addition of Nitrogen ($< 0.5kWh \cdot m^{-3}$). The power requirements are less than $200MW$ (which can be achieved through solar heating, requiring an airtight pond of surface area less than $0.5km^2$) and $1MW$ respectively. These estimates assume a concentrated solution of Ethanol with 50% nanoparticles by volume.

Pumping losses in the production process are negligible: the pressure loss in the capillaries is estimated to be $140Pa$ only (estimated with a microfluidics calculator), leading to a power requirement considerably less than $1MW$.

3 Salt nanoparticles injection in the boundary layer

The proposed approach involves the use of hydrogen-powered UAVs to deliver the salt nanoparticles in the marine boundary layer. Hydrogen fuel is preferred to hydrocarbon fuels, to minimize further CO_2 emissions associated with the project.

Fixed-wing UAVs are the best option, since they have very good efficiency (lift to drag ratio), and high endurance. Their high cruising speed and adjustable operating altitude increase the efficiency of spraying, and allow a faster particle emission rate per vehicle, reducing the required number of vehicles.

In Wood (2021), the required number of spraying boats ranges from 10^4 to 10^5. The salt nanoparticle injection rate is limited by the local wind conditions, with an estimated average wind speed of $7\,\mathrm{m\,s^{-1}}$. Using a UAV flying at high speed allows proportionally higher injection rates, since the highly turbulent area in the wake of the UAV would increase mixing rates and effective wind speeds (particularly in the wingtip vortices area). Some UAVs can reach speeds exceeding $100\,\mathrm{m\,s^{-1}}$ in the boundary layer (Agbeyangi et al., 2016).

3.1 UAV platform

We propose to use an injection rate of $6{\cdot}10^{17}s^{-1}$ (or $280kg{\cdot}h^{-1}$) per UAV, which is scaled up from the injection rates proposed in Wood (2021) by a factor of $10-100$. The higher injection rate is possible since the particles injected are in the form of a powder stored in an inert gas, the surface area of injection is very large (due to wake turbulence mixing), and the UAV velocity is high. Because of the high velocity of the UAV, the particles have a low risk of coagulation. With this injection rate, a total of 10^3 UAVs are required. Higher spray rates are technically possible.

The required speed, endurance and payload parameters are matched by several existing UAV platforms, in particular the MQ-9 Reaper platform has sufficient endurance (20 h), payload (1700 kg) and speed ($> 100\,\mathrm{m\,s^{-1}}$)) to satisfy the mission requirements (Agbeyangi et al., 2016). With a 2,200 km radius (Petrelli, 2020), it can cover most of the areas of interest, as illustrated in Fig. 1.

A major redesign would involve converting the existing powerplant (turboshaft) into an hydrogen powerplant. Several options are available: fuel cells or hydrogen gas turbines could be used to power the aircraft. For the proposed application, fuel cells are the most suitable solution: they have a very high efficiency ($50-60\,\%$), and a very high TBO (time between overhaul) between $5000 - 25000$ h (Ahluwalia et al., 2021).

The number of required UAVs (1000) is comparable to the total production of MQ-9s to date (319). Most maintenance could be done in the airfields where the UAVs are located, during the turn-around time between flights. The major maintenance operations would involve the replacement of the fuel cells: with continuous operation, the power-plants would have to be changed once every year, assuming a conservative TBO of 8000 h (Ahluwalia et al., 2021). This requires the production of about 1000 fuel cells per year.

4 Discussion

4.1 Implementation

One of the major benefits of the current approach is the ease of implementation: with a few centralized production facilities, and leveraging existing power production, hydrogen production, ethanol purification facilities, international shipping and existing UAV platforms, the proposed system could be readily implemented with a low development time, and a high technical readiness level technologies, reducing development and implementation costs.

4.2 Cost, electricity and fuel usage

Most of the power required to recycle the ethanol solution and generate the 2M NaCl solution is low-temperature industrial heat (less than 165 °C). This heat power of $20\,GW_{th}$ (thermal power) can be generated through co-generation with existing thermal power plants (combined heat and power), geothermal heating plants or solar concentration heating plants. With co-generation from existing thermal power plants, the effective power required (i.e., the net electrical power production loss due to co-generation) is about $3\,GW_e$ (electrical power), assuming efficiencies of 45 % without co-generation and 30 % with co-generation (Havelskỳ, 1999).

With an average worldwide electricity cost of USD $0.167\,\mathrm{kWh}^{-1}$, this amounts to a yearly cost of USD 4.4 B. It can also be noted that the yearly energy requirement of $25.9\,TWh_e$ corresponds to about 0.1 % of the world yearly energy generation ($2.2{\cdot}10^4$ TWh, as of 2022). This is in contrast with the current approach involving ships, which requires approximately $24.6\,\mathrm{GW}_e$ for the emission rate of $\dot{N} = 6{\cdot}10^{20}\,\mathrm{s}^{-1}$, based on the 41 kW for $10^{15}\,\mathrm{s}^{-1}$ estimated by Cooper et al. (2014), neglecting for on-board boat power. This energy amounts to about 210 TWh, or about 0.9 % of the yearly world electricity production (2022).

The yearly quantity of hydrogen required by the UAVs, assuming full power at all times (a conservative hypothesis), and a fuel cell efficiency of 55 %, is $3.2{\cdot}10^8$ kg, while the current worldwide hydrogen production is $7.5{\cdot}10^{10}$ kg per year (Li et al., 2023). Hence, the hydrogen required by the system would correspond to about 0.4 % of the hydrogen produced every year, as of now. The total cost of this hydrogen, assuming green hydrogen prices of USD $10\,\mathrm{kg}^{-1}$ is USD 3.5 B per year, and the total average power required to generate this hydrogen is 1.6 GW, assuming an electrolysis efficiency of 0.75. While this quantity of hydrogen is relatively high, more efficient UAVs that are specifically designed for this purpose could be designed in the future to reduce cost and consumption. It is also expected that hydrogen production rates will increase in the near future. Finally, this calculation is a "worst-case" analysis assuming maximum power usage at all times, which would not happen in real usage.

4.3 Advantages and disadvantages

The proposed system has several advantages over current approaches:

- Centralized generation of NaCl nanoparticles in a few locations enables economies of scale, and easier maintenance of the production system, with lower upfont expenses required to build the system.
- The proposed approach requires less total power ($20\,\mathrm{GW}_{Th}$ and $2\,\mathrm{GW}_e$ than the current approach of using a ship-based system ($< 24.6\,\mathrm{GW}_e$, not including the

ship propulsion system). Most importantly, the power generation is greatly simplified and more economical (centralized vs. distributed). Using co-generation for the thermal power needs, the net power requirements (including salt nanoparticle generation and hydrogen production through electrolysis for the UAVs) are less than 5 GW_e vs. 24 GW_e. Geothermal low-temperature heat sources could also be used to power a large fraction of the energy required by the system. Since energy costs associated with shipping are very low (given the low mass to transport), the production facilities could be installed where geothermal or solar energy are abundant, and leverage existing desalination plants and industrial plants (ethanol refineries).

- The proposed system is more robust to extreme weather events, including hurricanes or typhoons. UAVs could be flown away from bases ahead of extreme weather events to safeguard them, unlike ships that have limited power and speed.
- The proposed system alleviates some of the problems associated with the ship-based system, e.g., the coalescence of salt nanoparticles in the spray stream, negative buoyancy of the air mass caused by evaporating seawater droplets.
- Locally, the injection of salt nanoparticles can be optimized by adjusting the UAV altitude.
- On synoptic and seasonal scales, the UAV flight planning can be adapted to avoid areas without the potential for substantial cloud brightening (e.g., cloud-free regions, highly polluted clouds, very deep clouds). This might enable a much higher efficiency of the proposed approach, and might reduce the number of UAVs the the mass of salt to be injected.
- Greatly simplified maintenance of the UAVs. In the current approach, a large number of ships would be subjected to the harsh marine environment (high winds, corrosion, biofouling, system failures), and require periodic maintenance, which is more difficult and time-consuming than the maintenance of a lower number of UAVs in airfield maintenance facilities.

The proposed system also has some disadvantages:

- Lower robustness, due to to a higher centralization and potential points of failure
- More difficult to operate: UAVs can be difficult to operate in harsh weather conditions, while unmanned ships are comparatively easier to operate. The crash rate for the MQ-9 has been approximately 1.8 per 100,000 flight hours (Light et al., 2020). Given these statistics, and with $8.7{\cdot}10^6$ flight hours per year, an average of 140 crashes per year would be expected, which is very high. Note however that most of the flights of the MQ-9 are performed for military applications, which are inherently more risky than routine civilian use. In civilian use, we expect that the crash rate will be reduced by an order of magnitude or more, with only a few airframes lost every year in operations.
- Accessing the entire oceanic surface requires the creation of new airstrips in some remote locations (e.g. Galapagos Islands, the Antarctica, Kerguelen Island). Currently accessible locations are shown in Fig. 1.
- Need to ship nanoparticles and hydrogen from production facilities to airfields. This need for transport will cause additional small energy and resource costs.

5 Concluding remarks

Because global warming increasingly threatens human societies and ecosystems alike, actions are necessary. Since transitioning to a carbon-neutral economy might take too long to avoid some of the expected consequences of climate change in the following decades, climate engineering can be a valid intermediate option. While many different physical and technical approaches to climate engineering are currently discussed, it is important to investigate all possible options at the planning stage, taking into account all decision factors including technical feasibility, economics, technical readiness levels and robustness.

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