# MARINE CLOUD BRIGHTENING (MCB)

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## Introduction

Seeding clouds with nucleating particles to induce rainfall has been practised for many decades, with mixed success. Seeding marine clouds in order to brighten them and thence provide cooling by reflecting more sunlight than otherwise is a more recent strategy in response to the threat and actuality of excessive global warming. More recently, it has been proposed to use seawater droplets, or the salt crystals resulting from their evaporation, to nucleate clouds. Korhonen et al. 2010 indicate that MCB could have major net beneficial effects on global temperatures and precipitation.

Whilst some research has been done into cloud physics, modeling, optimising cloud condensation nuclei (CCN) size, composition and methods to generate and place the nuclei, this has rarely resulted in industrial-scale technology. This paper describes what is thought to be a superior method for achieving regional cooling and of favorably influencing precipitation downwind as near as tens of kilometres, to as far off as halfway round the world. In addition, the method may find use in avoiding coral bleaching, in mitigating extreme weather events, and, when misting a ferric chloride (FeCl3) solution into the troposphere, in catalyzing the conversion of atmospheric methane into the less dangerous carbon dioxide by the catalysts produced by photolysis (photodecomposition or disassociation using solar energy) from the nanodroplets of the solution. These same catalysts also convert other atmospheric pollutants, such as soot, smoke, NOx and ozone into more benign forms.

Identified by Gokturk (AGU meetings 2012, 2013 and 2016), a third beneficial effect may also be achieved if high-valence anions, such as phosphate or silicate, are added to the brine and/or ferric chloride solutions for atmospheric release. Nanodroplets of these salts reportedly attract and react with the CO2 dissolving in the droplets to (photo?)-oxidise it to carbonate, CO3--. This should have the effect of reducing the partial pressure of CO2 in the droplets, allowing them to take up still more CO2. When the nanodroplets eventually form raindrops, they will thus ‘rain-out’ considerably more CO2 from the atmosphere than otherwise, thereby reducing CO2’s average lifetime there that some climate experts estimate at being of the order of a hundred years. Such nucleation particles also attract other atmospheric pollutants, such as NO2 and SO2, thereby serving to cleanse the atmosphere of them.

## Method

The key technological breakthrough came from the invention by Sheffield University chemical engineers of a means to generate dense clouds of designer microbubbles by means of a fluidic oscillator effect from a no-moving-parts void that employs the Coanda Effect. The bubbles require close to the theoretical minimum of energy for their production, that is typically some three orders of magnitude below that of other, more traditional methods. In addition, the bubbles are of a controllable spacing and size, from milli- down to nano-metric diameters. The Sheffield researchers have already applied such bubbles to isothermal distillation whereby the bubbles are produced from warm gas pulses entering a thin film of water. It is this process that is to be applied to the generation of microbubbles on the trailing edges of a boomerang-shaped aerostat. Jet droplets produced when these microbubbles burst provide the required CCNs at optimal MCB altitude. Even better, the FO-produced nuclei could meet the ideal requirements of being monodisperse, of a narrow size distribution, and of optimal water droplet size. Connolly et al. 2014 found that salt particles within median dry diameter range 30-100nm are the most effective sizes for cloud brightening. These coincide with seawater droplet diameters of 120-400nm.

Typically, an aerostat will be towed by a vessel going about its normal business, though some vessels, possibly drones, may be specially contracted to deliver CCNs far from normal shipping lanes. Vessel operators might also be paid to divert to, or linger in, a vicinity should their MCB services be required there. It is even conceivable that water-carrying/bombing aircraft might be contracted to deliver CCNs where shipping cannot get to the dissemination zone in time – such as to aid fire-fighting or hurricane mitigation efforts. In particularly favorable locations, such as off continental west coasts or in remote oceans having moist air above them, it may also be possible to use lines of moored aerostats using renewable energy to generate wind-borne CCNs either continuously or on demand. Such mooring might be made to happen even in deep water. A single, floating offshore wind turbine could power the gas and water pumps for many, linked MCB aerostats. These lines or arrays of aerostats, centred on a floating wind turbine power source, could be located wherever conditions were favorable to MCB generation and where there was sufficient (possibly only seasonal or occasional) wind to power them. A ship-borne aerostat might be only of (folded) dimensions that the crew could reasonably handle and that could be stored on/in-ship, whereas those of moored aerostats might be much larger, perhaps having a total diffusing width of 70m or more. When not in use and there being no suitable storage space aboard ship, a folded but semi-inflated aerostat might be towed on the water behind a vessel. It might even be designed to act as a surrogate life raft.

Whilst the expensive, composite aerostat tow cable is to be conserved if possible, the aerostat assembly is to be designed as a cheap and replaceable sub-assembly. Spares for both are to be kept on board unless otherwise indicated.

Typical average marine wind speeds range from 3-12m/s, with a median around 7m/s. Wind turbines typically operate within a band of wind speeds from 4-25m/s. Excess power from the wind turbines might be used to generate hydrogen by the electrolysis of water. Vessels might care to use bottled hydrogen as replacement gas. This would be used in place of expensive and increasingly scarce helium to replenish lost aerostat gas. Due to the slow leakage of highly-mobile hydrogen from the aerostats, top-ups would need to be made periodically. The hollow, toroidal buoy supporting the floating wind turbine might be used for temporary hydrogen storage. Excess hydrogen might be sold. The aerostat envelope material will probably be a tough, thin, multilayer film that includes one or more Mylar-type, vapour-deposited metal barriers to restrict excessive hydrogen loss through diffusion. Closed cell polymer bubbles inside the aerostat, replenished with hydrogen gas released at the aerostat centerline may also serve to slow down hydrogen loss. Whilst employing the KISS principle early on, the design will preferably take cognizance of the possibility of providing for additional functions for the MCB assembly.

The ship-borne elements of the system are few and could typically be retrofitted to existing vessels. The ship’s engine exhaust, or else lightly-compressed air, is used to provide the modest-pressure, warm or cool gas necessary to power the fluidic oscillators (FO) on the aerostat. However, to avoid clogging the diffusers, the exhaust must first be passed through a cyclone to remove the black carbon particulates. Such exhaust treatment and use might avoid the necessity to install expensive exhaust scrubbers on the vessel. An electro-hydraulic, umbilical stab plate is used manually to make and break the connections to the cable. Standard electro-hydraulic relief valves control water and gas pressures to the aerostat and diffusers. The cleaned gas is fed into a flexible pipe on a powered reel and thence inside the hollow, probably PBO Zylon HM (or else carbon-fibre or nanocarbon-based) cased, towing cable. This casing also contains the flexible pipe that transports filtered seawater to the aerostat. A high-pressure pump inside the vessel pressurizes the filtered seawater to approximately 248bar (3,600psi), which is well within the 10,000psi rating for high pressure hydraulic lines that are routinely used for subsea applications. An outer casing of plaited, fine, aluminium-alloy wire may also be needed for lightning protection, unless this would only attract lightning strike. The aerostat might also be reeled in, folded and secured when dangerous lightning was expected. The plaited wire might also function as a communications aerial. Other power and communications cables could be encased within the hollow, strong tow cable. Only a portion of the ship’s exhaust might be required to generate the desired rate of nanodroplet production. A third tube in the towing assembly would carry the hydrogen to replenish any gas lost from the aerostat. An AI controller might be used to manage the control surfaces on the aerostat, including making changes to have the aerostat follow a helical path, in order to maximize the cloud volume nucleated.

The aerostat would achieve its lift via its contained buoyant hydrogen gas, though additional lift might be achieved by its aerofoil cross-section. Many small, fluidic oscillators, each feeding possibly an array of diffusers, would be embedded in the trailing edges of the aerostat. The embedding could be in a light, semi-rigid foam polymer for ease of handling. Diffusers might best be in the form of slot-based, backwards-pointing ones, in order to provide for their easy and effective suffusion with seawater under windy conditions, as well as to avoid the excessive loss of unbubbled water. It possibly would not matter much if some of the bubbled water were carried away by the wind, as this spume should still release CCNs, if possibly somewhat less effectively. Experimentation will tell whether any additional surfactant should be added to the seawater to improve performance. Most surface seawater already contains natural surfactants resulting from their release by dying phytoplankton.

The seawater would be directed by narrow, polymeric pipes to suffuse each diffusing groove. The warmth of the flowing, treated, ship exhaust should be sufficient to de-ice both the diffusers and towing cable in most icy conditions. Otherwise, electrical power from the ship or wind turbine might do so, as well being used to de-ice the leading edges of the aerostat when required. The SOx (sulphur oxides) content of the exhaust, when using heavy, sour bunker fuel well away from cities (sweeter fuel being used near cities), should increase the nanodroplets’ propensity to nucleate marine clouds efficiently. On its return to the sea, the now-dissolved SOx should also help nutriate the production of cloud-generating dimethyl sulphide (DMS) by phytoplankton.

For additional functionality, the aerostat could also mount directable cameras to aid in the detection of navigational hazards, approaching storms, for search & rescue, aerial/space shots above the cloud tops, for wildlife detection (whale-spotting), or even to take zoomed photos of things and people on the ship, or to provide live-stream aerial videos of approaching sights (coastlines, cities, icebergs, shipping, wildlife, etc.) – at least during daytime. The aerostat and towline could mount sensors to provide information on the changing conditions at different altitudes in the atmosphere. Inside the aerostat envelope could be mounted a low-power radar system that scanned the ocean surface below, out to a radius from the vessel of perhaps thirty kilometres. Combined with a computerized algorithm, this could predict the occurrence, location and movement of ship-killer waves (including the especially dangerous ones resulting from crossing seas) in time for them to be either avoided, or at least for the ship to be positioned and secured, the authorities notified, and the crew prepared best to ride them out. It should also be able to detect radar-reflecting objects in the sea at night, possibly even those lightly submerged.

The exhaust gas to the aerostat is to be re-directable to alternative sets of FOs, set to produce microbubbles of different sizes (and hence jet nano- and microdroplets of different standard mass each). This would allow a measure of control over the extent of cloud brightening and the distance down-wind at which precipitation was desired (the smaller the CCNs, the further away tends to be the resulting precipitation). The various FO sets might even be used in frequent alternation, so that precipitation occurred over a wide area, rather than delivering its payload harmfully in a concentrated area. Sets might thus be chosen to deliver most of the aqueous payload to specific water/snow catchment areas or else to meet the requirements (wet or dry) of specific regional crops.

Each bursting microbubble tends to release 4-7 jet nanodroplets of seawater (Lewis & Schwartz, pp187-193) vertically from the water surface (film droplets only result from larger bubbles), the actual number depending upon such variables as temperature, salinity and the concentration of surfactants in the filtered seawater. It is thought that generating microbubbles of approximately 8μm diameter may provide nanodroplets with optimal cloud nucleating effect. A book by Soloviev & Lukas (p412) suggests that such droplets will be roughly one tenth the diameter of the original microbubble, i.e. 0.8μm or 800nm (as opposed to Cooper’s suggested optimal average diameter of 150nm, Connolly’s of 120-400nm, and the author’s earlier estimate of 263nm, but the same as Kohler’s of 800nm). Note, that the optimal seawater droplet diameter may well vary, depending upon the degree of supersaturation of the air and whether the droplets are injected at sea level or at marine cloud formation altitude. Should the 800nm droplets evaporate and not coalesce, the resulting impure and cloud-nucleating salt crystals should have cubic dimensions of approximately a fourth this, or 200nm, each. Each such CCN would be capable of nucleating a water droplet of average volume 0.05ml. Hence, a litre of seawater, turned into CCNs at cloud nucleating height, would theoretically be capable of initiating rainfall, or its snowy or icy equivalent, of approximately 200 Gigalitres. In practice, there would be large losses. However, even a 5% success rate would deliver a ten billion-fold product in terms of induced precipitation, as well as measurable regional cooling. Whilst that atmospheric moisture would have condensed and fallen anyway, sometime and somewhere, the induced nucleation could be arranged to influence to net benefit the severity, spread and location of the precipitation. The negligible salt content that this method would add to precipitation means that there is no danger of its extensive use salting the land.

It is surmised that, with the extra levels of control and efficiency provided by this method, that a saltwater usage rate of 10-15 litres per second should suffice for most aerostats. Using droplets of a standard 800nm diameter, theoretically this should be sufficient to generate ~5x10\*\*16 CCNs/sec. At a 5% nucleation success rate, these would deliver ~2.5x10\*\*15 or 2.5 quadrillion raindrops/sec downwind.

As marine clouds typically have their bases at an altitude of around 1,000m and their tops at around 1,500m, it seems likely that the optimal altitude for cloud-nucleating aerostats will be just below 1,500m, though this will, of course, vary with different atmospheric conditions. Such an altitude means that the towing cable is likely to needs be in the vicinity of 2,000m long, allowing for a towing (or blowing) angle of >48° and its catenary shape. One of 2,500m length would allow nucleation at ~1,900m altitude above sea level. Now, the combined tensile strength of the towing assembly will need to be larger than the catenary tension caused in it by the assembly’s weight, its liquid contents, and a safety margin sufficient to cover wind gust stresses on aerostat and cable, helical movement, reeling-in tension, cable twisting, violent ship movement in bad weather, acceptable material and construction variations, weathering, temperature change, icing, lightning strike, and modest degradation in the assembly over its expected lifetime. Whilst the peak loadings of some of these individual stressors can be smoothed by spring-loading the cable or other means, most cannot. The calculation is yet to be made whether one of the strongest polymeric cable materials, such as Zylon HM, with a longitudinal tensile strength of 5,800MPa and a density of 1.56gm/cm3 will be strong and light enough for the task, or whether a material, such as graphene or a nanocarbon composite, could be formed into a cable to meet the requirements. Much will doubtless depend upon how narrow can be the pipe that delivers sufficient seawater volume rate to the aerostat for optimal operation. In the event of the chosen material being not strong enough, a second, streamlined aerostat to support the middle of the cable is an option to be considered, if hardly an ideal one.

## Regional Deployment

Favorable regions for MCB include: the Southeast and Central Pacific; off some western coastlines of continents; the Indian and Arabian Oceans; the Central and South Atlantic; areas having warm-water coral reefs; tropical, sub-tropical and temperate waters in that order; and the high seas generally. Except in the summer months (see Latham et al. “Marine Cloud Brightening” paper for its effect on reducing sea ice loss), polar regions may not be prospective ones because they are useful at other times for their ‘radiator effect’ of long-wave radiation into space. Inland, high and dry desert regions and downwind of high mountain ranges are unlikely to have the necessary atmospheric moisture from which clouds might be generated, though the CCNs themselves would result in some useful albedo increase. Highly polluted atmospheric regions offer poor MCB prospects because they are already over-supplied with CCNs. MCB will generally be more effective regionally in some seasons than in others and when done at certain times of the day. For instance, off the west coast of India, more nucleation is likely to occur around monsoon season; and off the coast of California, MCB is likely to produce more onshore precipitation when delivered from 2 to 10pm, when there are onshore winds brewing, resulting from the land heating and cooling faster diurnally than does the sea surface. Hurricanes may either be averted, or mitigated in intensity, by preventive MCB operations in marine areas where they form, intensify or move.

When used to convert atmospheric methane into the less-global-warming carbon dioxide, MCB of ferric chloride solution may be usefully deployed upwind of methane emissions, such as over oceanic regions where methane clathrates are melting to emit erupted or bubbled methane, or where offshore gasoil wells or natural sources emit methane, or over land where methane is being emitted through fracking operations, other fossil fuel extraction processes, leaky pipelines, forest fires, industrial processes, the digestive processes of ruminants and termites, melting permafrost, humus and soil carbon destruction by microorganisms, wetlands, rice paddies, landfills, and land clearing operations.

Nitrogen oxides, NOx, are also catalyzed by both ferric chloride (FeCl3) and sea salt (NaCl) to form more benign molecules, thereby reducing their strong global warming effect. Wittmer et al. (2014) report that the combination of the two salts is roughly a thousand times more effective than is just atmospheric NaCl on its own.

## Controllability

It is noteworthy that Prather et al. 2013 found that the aerosol size range most relevant for light scattering and the direct aerosol effect on climate was 300-1,000nm in diameter. Salter, in his paper “Measurement of a World-wide Transfer Function for Marine Cloud Brightening” shows how spray (or presumably MCB) in one region can substantially affect precipitation (+/-) downwind (up to and) more than half a world away. Increasing the CCN count can be used to suppress, delay or shift precipitation to further downwind. Salter also notes that “A key feature of marine cloud brightening is that it allows control of the magnitude, place and time of the spraying”, to which can now be added the control factors of the precise sizing (or selected sizes) and concentration of the nuclei, and the altitude of their release.

## Governance

Sophisticated Earth Systems modeling would be required for proper MCB targeting, together with the establishment of a single world authority to co-ordinate the planning, delivery and monitoring, whilst necessarily being freed from legal liability in a manner similar to that given to some emergency services, international agencies and first responders. The same authority should probably also be given authority over other climate and ocean intervention initiatives, these being intimately related.

## Experimentation

Pilot MCB experiments might use a delivery vehicle as simple as a light aircraft fitted with: gas bottles, a tiny in-line combustion unit, a gas-pressurised seawater container, fluidic oscillators, piping, and wing-located diffusers. MCB success could be measured photographically. It would be different from many rain-making field trials that have been made over the past two hundred years, mainly in that it used typically even more benign nucleation materials, cost less and was more controllable.

Similar experimentation should be conducted on the effects of catalyzing atmospheric methane, NOx and other pollutants by means of releasing nanodroplets of a mixture of ferric and sodium chloride solutions at cloud-nucleating altitude.

## Conclusion

Many Earth Systems Modelling (ESM) runs have already been made by other cloud-seeing researchers. Typically, these have shown that considerable climatic and ocean remediation is possible using MCB. Some of the most interesting runs indicate that downwind cooling and precipitation can be strongly influenced, if not absolutely controlled, by MCB activity. Moreover, because of its relatively low cost, its designed-in fine level of control over seawater droplet concentration, release altitude, and size; and most particularly because of the superb energy efficiency of the fluidic oscillator method, it is thought that this technological concept demands immediate investigation and development by scientists & engineers, together with supportive action from those other key parties involved in crafting acceptable climate and ocean solutions.

As this may also be the best way of seeking to remedy the adverse effects of large-scale methane emissions, the urgency of the demand is only increased by its equal applicability to reducing atmospheric methane concentrations by means of the catalysis of GHGs by the mid-level tropospheric release of a mixture of ferric and sodium chloride solutions, in long-enduring nanodroplet form, over both sea and land, by similar means.

Because there is MCB complementarity and synergy with two other prospective methods of climate intervention by the author, namely that of Buoyant Flakes and Ice Shields, it is recommended that model runs that combine their effects in optimal ways be investigated.