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EDITED BY
Romaric C. Odoulami,
University of Cape Town, South Africa

REVIEWED BY
Haruki Hirasawa,
University of Washington, United States
Michael Diamond,
Florida State University, United States

*CORRESPONDENCE
Diana C. Hernandez-Jaramillo
diana.hernandez@scu.edu.au

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A review of plume dispersion and measurement techniques applicable to marine cloud brightening

Diana C. Hernandez-Jaramillo*, Brendan Kelaher and Daniel P. Harrison

National Marine Science Centre, Southern Cross University, Coffs Harbour, NSW, Australia

Rising sea surface temperatures are causing more frequent and intense coral bleaching events, threatening the long-term survival of coral reefs globally. Marine Cloud Brightening (MCB) is a proposed intervention that could be applied globally or regionally to cool sea surface temperatures and reduce the risk and severity of coral bleaching. The effectiveness and logistical feasibility of this technique depends on what fraction of the sea salt aerosols are incorporated into clouds after being emitted from a seawater spraying operation at the ocean surface. Here, we review the literature on the dispersion of MCB sea salt aerosols from a point source within the marine boundary layer. We focus our consideration on the processes, mechanisms, and current ability to predict the horizontal and vertical evolution of the plume from its generation at surface level to its downwind dispersion and mixing to cloud height. Overall, we found that in the more than three decades since the MCB concept was first proposed there have been eight studies investigating this aspect of MCB, which is crucial to informing engineering systems design, marine logistics, and assessing the overall potential effectiveness of MCB. To date, only one study has validated the modeling of the aerosol dispersion using empirical experiments and only a few studies have considered non-passive processes such as the negative buoyancy associated with the evaporative cooling of the water droplets, as well as particle scavenging due to coagulation and deposition. Priority areas for future research are identified as far-field dispersion of the MCB plume and estimations of the portion of MCB aerosol reaching cloud base.

KEYWORDS

marine cloud brightening, plume dispersion, coral bleaching, cloud albedo, sea spray aerosols, marine boundary layer

1 Introduction

The rapid rise in sea surface temperatures due to climate change is driving significant ecological disruptions in marine ecosystems. One of the most immediate consequences is the increasing frequency and severity of marine heatwaves, which lead to widespread coral bleaching around the world. During such events, thermal stress causes corals to expel their symbiotic algae, leaving them pale or "bleached." While corals can recover from mild bleaching, prolonged or repeated heat stress often results in mass mortality, fundamentally altering reef ecosystems (Brown, 1997; Hoegh-Guldberg, 1999; Hughes et al., 2018; Jones et al., 1997; Sully et al., 2019).

Coral reefs, known as biodiversity hotspots, are particularly vulnerable to warming oceans (Bureau of Meteorology & CSIRO, 2020). They provide critical services, such as coastal protection and fisheries, that support livelihoods for millions of people globally (Oxford-Economics, 2009; Rolfe and Valck, 2021; Stoeckl et al., 2011). However, without intervention, the increasing intensity and frequency of marine heatwaves are expected to escalate coral bleaching events, threatening coral reef survival (Baker et al., 2008; Bohensky et al., 2011; Hoegh-Guldberg, 1999; Hoegh-Guldberg and Hoegh-Guldberg, 2004).

Marine Cloud Brightening (MCB) has been proposed as an intervention to mitigate the thermal stress on coral reefs by cooling sea surface temperatures (Latham et al., 2012a, 2014, 2013). This technique involves the release of sea salt aerosols into the atmosphere, where they act as cloud condensation nuclei, increasing cloud droplet concentrations and enhancing cloud albedo. By reflecting more sunlight, MCB could reduce heat stress on marine ecosystems, including the Great Barrier Reef (Condie et al., 2021; Harrison, 2018, 2024; Harrison et al., 2020). The effectiveness of MCB depends on complex aerosol-cloud interactions, including the size distribution of the generated sea salt aerosols, the fraction of sea salt aerosols reaching clouds, and their activation as cloud condensation nuclei. While previous studies have investigated the climatic impacts of MCB (Ahlm et al., 2017; Alterskjær and Kristjánsson, 2013; Bower et al., 2006; Jones and Haywood, 2012; Korhonen et al., 2010; Latham et al., 2012a; Partanen et al., 2012; Wang et al., 2011), there is much less research on the processes affecting aerosol transport and dispersion (Figure 1), such as vertical and horizontal mixing (Hernandez-Jaramillo et al., 2023a), negative buoyancy associated with the evaporative cooling of the water droplets (Jenkins and Forster, 2013), and particle scavenging due to coagulation and deposition (Maalick et al., 2014; Stuart et al., 2013).

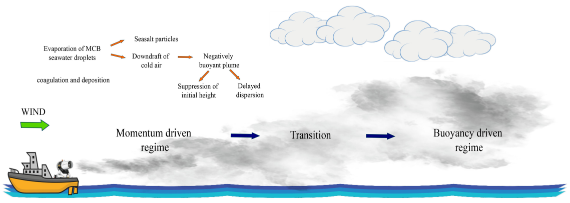

FIGURE 1
Schematic diagram summarising the key processes that influence the dispersion of the marine cloud brightening sea salt aerosol plume.

Plumes of aerosol from industrial sources (Baggio et al., 2022; García et al., 2008; Srivastava et al., 2001; Toja-Silva et al., 2017) and ship tracks (Chosson et al., 2008; Durkee et al., 2000b; Frick and Hoppel, 2000; Hobbs et al., 2000; Petzold et al., 2008), exhibit similar characteristics to MCB in terms of dispersion dynamics in the atmosphere. However, it is essential to note that these phenomena cannot be taken as direct analogues for Marine Cloud Brightening due to distinct differences in the nature and behaviour of the aerosols involved and characteristics of any associated gases. Industrial plumes and ship tracks primarily release pollutants and particles with varying compositions and sizes, whereas MCB aerosols are specifically designed to be in a range of particle sizes that can most effectively influence their albedo. Modelling studies suggest that particles with a mean diameter of 30–60 nm are most efficient at enhancing cloud albedo (Wood, 2021). Additionally, the composition of the aerosols plays a crucial role, as the high hygroscopicity of sea salt makes it particularly effective as a cloud condensation nuclei (CCN). For combustion-related aerosol pollution, the heat released from industrial and ship exhausts has an effect on the buoyancy fluxes close to the source impacting the plume dispersion and plume rise height. In contrast, the MCB aerosols are produced from the evaporation of seawater droplets near the source, potentially suppressing plume heights due to cold pools and negative buoyancy (Jenkins and Forster, 2013; Maalick et al., 2014) (Figure 1). The unique properties and intended function of MCB aerosols set them apart from other aerosol sources, highlighting the need for tailored studies and models specific to MCB.

This review summarises the published information on the dispersion of MCB sea salt aerosols from a point source. First, an overall description of studies found addressing marine cloud brightening is presented. The MCB concept is then described as well as the key parameters arising from the proposed seawater spraying techniques and the relevant studies addressing plume characterization and dispersion in the near-field. It concludes with a summary of airborne measurement techniques of aerosol emission sources to provide a technological basis that could be used to conduct empirical measurements of the sea salt aerosol plume in future field studies of MCB.

2 Overall description of studies

A literature search using combinations of the keywords "marine cloud brightening", "plume dispersion", "cloud seeding", "marine cloud albedo", "marine sky brightening", "aerosol indirect effect", and "evaporative cooling" in search engines; Science Direct, Scopus, ResearchGate, Google Scholar and Web of Science, resulted in 114 publications directly addressing marine cloud brightening. These results temporally spanned the first publication in 1990 until March 2024. Although the first mention of cloud brightening was in 1990 (Latham, 1990), it was around 2006 when interest in this topic started to increase with a first peak in the number of publications between 2012 and 2014. There was a low number of publications between 2015 and 2017. However, in recent years, MCB has attracted significant attention within the scientific community, evidenced by a surge in the number of publications especially during 2023. Studies were assigned to one of four categorical topics (Figure 2): aerosol emission technology and engineering challenges (technical feasibility), dispersion of MCB aerosols through the atmosphere (plume dispersion), aerosol-cloud interaction and its effect on climate (effectiveness) and socio-economic impacts, legislation and risks (governance). The great majority (81) of publications addressed MCB effectiveness by modeling cloud response to prescribed aerosol perturbations and the effects of injected sea salt particles on cloud properties and climate. Fourteen of the 114 studies discussed the development of aerosol technology to produce sea salt particles in the size range expected to effectively modify cloud properties, as well as technical and engineering challenges involving the scaled application of MCB. Seven publications modelled the transport of the MCB sea salt aerosols within the marine boundary layer and only one presented measurements of experimental data (Table 1).

3 Marine cloud brightening

Marine Cloud Brightening (MCB) is a proposed solar radiation management tool aimed at mitigating global warming, by increasing the albedo (Latham, 1990) and longevity (Latham, 2002) of low-level maritime clouds. The technique proposes to seed marine stratocumulus clouds by dispersing sub-micrometre seawater droplets, into the marine boundary layer. As these droplets evaporate, they generate nano-sized salt crystals that act as cloud condensation nuclei (CCN) (Salter et al., 2008). These CCN increase the cloud droplet number concentration from typical natural levels of 50-300 cm^{-3} to enhanced concentrations of 400-1000 cm^{-3} in seeded regions (Baughman et al., 2012; Jones et al., 2009; Latham et al., 2008; Rasch et al., 2009). Furthermore, as the droplet concentrations increases, the mean droplet size decreases, changing the optical and physical properties of the clouds and, eventually decreasing the amount of solar radiation reaching the ocean surface (Latham et al., 2012a).

Changes in cloud properties resulting from aerosol-cloud interactions occur through multiple mechanisms, encompassing both direct and indirect effects, as well as cloud adjustments (Figure 3). The primary mechanism is the Twomey effect, which fundamentally explains how, at a constant liquid water path, increasing aerosol concentrations lead to a higher number of smaller droplets, thereby enhancing cloud optical thickness and reflectance (cloud albedo) (Twomey, 1974, 1977), thus causing more solar radiation to be reflected back into space. This is a key process in marine cloud brightening (MCB), where the goal is to increase cloud albedo. However, cloud adjustments can significantly modify this initial effect. Suppressed precipitation as described by Albrecht (1989), occurs when increased aerosol concentrations lead to smaller droplets that are less likely to coalesce and fall as rain, potentially prolonging cloud duration and increasing cloud cover (Ahlm et al., 2017; Forster et al., 2021; Hoffmann and Feingold, 2021).

Entrainment effects, as highlighted by Ackerman et al. (2004) and Bretherton et al. (2007), are another important cloud adjustment. Increased aerosol concentrations produce smaller cloud droplets, reducing sedimentation rates. This can enhance the entrainment of dry air from above the cloud layer, leading to cloud thinning and a reduction in liquid water path (LWP), potentially counteracting the initial increase in albedo from the Twomey effect. Additionally, non-precipitating cloud adjustment mechanisms, as explored by Igel (2024), highlight how aerosol-induced changes in cloud microphysics can influence cloud

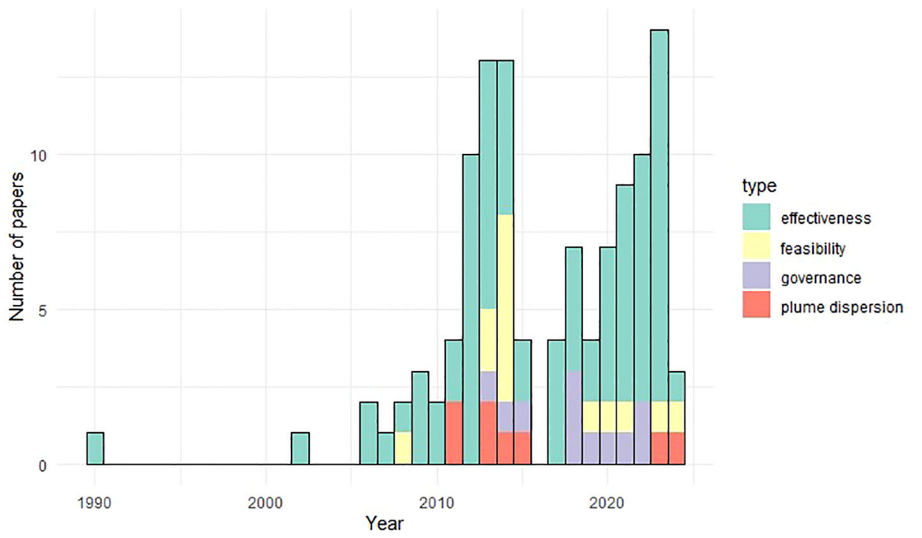

FIGURE 2
Database of papers collated through search engines with search terms "marine cloud brightening", "plume dispersion", "cloud seeding", "marine cloud albedo", "marine sky brightening", "aerosol indirect effect", "evaporative cooling" and sorted according to their relevance in marine cloud brightening. The coloured bars represent the proportion of total papers that concern marine cloud brightening topics.

TABLE 1 Previous relevant publications in plume dispersion of marine cloud brightening emissions.

Publication	Key findings
Wang et al. (2011)	Cloud brightening effectiveness has a strong dependence on meteorological and background aerosol conditions
Anand and Mayya (2011)	Coagulation, condensation/evaporation and atmospheric dispersion are key processes on the evolution of aerosol size distribution and number concentration
Stuart et al. (2013)	In-plume aerosol coagulation could reduce the efficacy of marine cloud brightening by reducing the number flux of injected particles
Jenkins and Forster (2013)	Droplet evaporation could suppress initial plume height by up to 30%
Maalick et al. (2014)	Cooling due to droplet evaporation can cause a delay in particle dispersion enhancing particle scavenging
Anand and Mayya (2015)	Parametrised models considering aerosols coagulation can be incorporated into global/regional models for cloud brightening applications
Hernandez-Jaramillo et al. (2023a)	Evaporative Cooling does not prevent vertical dispersion of the MCB plume generated with effervescent technology
Prabhakaran et al. (2024)	Aerosol disperse faster under pristine background conditions as a result of a transverse circulation
McMichael et al. (2024)	Physics-based, simplified model that can predict the spreading of aerosol plumes from ship emissions
Hoffmann and Feingold (2021)	Size distribution of the seeded aerosol particles significantly affects the efficiency of cloud brightening

dynamics without directly affecting precipitation. These adjustments, such as changes to droplet evaporation rates and cloud edge dynamics, further contribute to uncertainties in understanding cloud-aerosol interactions.

Additionally, Ahlm et al. (2017) describe a direct effect where accumulation and coarse mode sea salt aerosols scatter incoming solar radiation before they are incorporated into clouds. This aerosol direct effect can also contribute to cooling, particularly in regions with limited cloud cover. It's important to note that this direct effect is different from the cloud brightening effect achieved by using smaller, Aitken-sized particles as suggested by Wood (2021), which are more efficient at increasing cloud albedo but would not effectively scatter light. Microphysical properties, such as the size distribution of seeded particles and the role of interstitial particles also influence cloud optical thickness, as well as the impact of aerosols on cloud evaporation and entrainment (Hoffmann and Feingold, 2021). Aerosol particles are generally classified into three major size modes: Aitken mode (less than 100 nm in diameter), accumulation mode (100 nm to 1 μm), and coarse mode (greater than 1 μm). The size of the aerosol particles strongly affects cloud response, clear-sky radiation impact, and energy requirements for a spraying system. Smaller particles (Aitken mode) are more efficient at increasing cloud albedo through the Twomey effect, while larger particles (accumulation and coarse modes) contribute more to direct radiative effects and have different sedimentation properties.

Although marine cloud brightening was originally considered on a global scale, it could be implemented sub globally in regions of particular interest. Latham et al. (2012b) explored the idea of a regional application of this technique to cool ocean surface waters in regions where hurricanes develop, therefore, potentially reducing hurricane intensity. Latham et al. (2013) also evaluated computationally the potential of sub-global MCB to relieve stress on coral reef areas (Caribbean, French Polynesia, and the Great Barrier Reef) by cooling ocean surface waters. The results from those simulations indicated that cloud brightening could ameliorate coral bleaching processes under doubled CO_2 conditions. Furthermore, Harrison et al. (2020) proposed the localized implementation of this technique over coral reefs, during periods of increased thermal stress. This strategy might mitigate bleaching severity, and potentially coral mortality, due to the aerosol direct and indirect effects on the incoming solar radiation (shading).

Cloud brightening has been identified as one of the cooling and shading interventions that could be scalable to operate regionally to reduce stress on corals at the Great Barrier Reef (Harrison et al., 2020). Harrison et al. (2020) simulated the impact of this intervention over the 2015/2016 and 2016/2017 bleaching events, showing an average reduction of bleaching stress of approximately

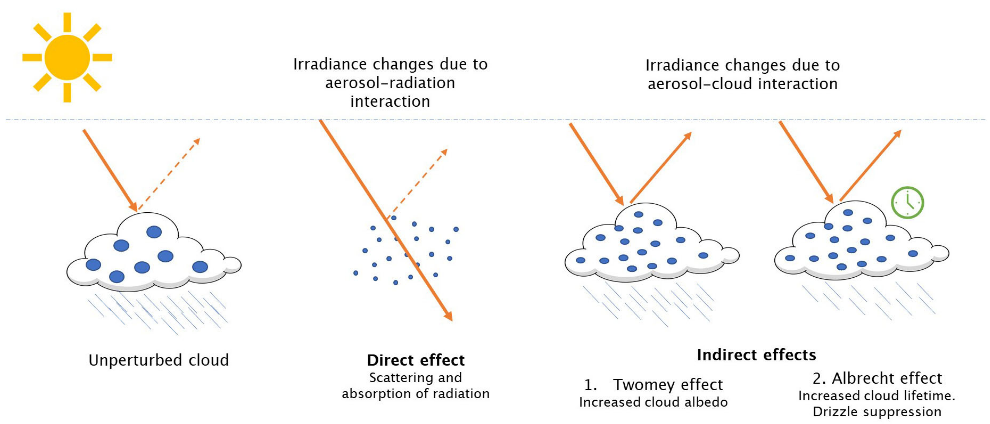

FIGURE 3
Diagram of direct and indirect effects due to interactions between radiation, aerosol and clouds.

50% for the former event and around 65% for the latter, resulting from an average 6.8% decrease in short wave solar radiation. The term "bleaching stress" describes the physiological stress that corals endure as a result of high sea surface temperatures, intense light, and other climatic conditions that affects their symbiotic relationship with algae, causing the algae to be expelled or degraded and resulting in coral bleaching. Subsequently, Condie et al. (2021) modelled the impact of different large-scale interventions, including cloud brightening, to protect and restore coral communities at the Great Barrier Reef. Their results suggest that shading (MCB) interventions could be particularly effective to help maintain coral cover over the next two decades. However, it's noteworthy that MCB benefits were significantly enhanced when used in conjunction with other interventions, such as crown-of-thorns starfish (CoTS) control.

4 Spraying techniques

To determine the technical feasibility of cloud brightening, it is important to answer the question of how to produce sea salt particles in the size range appropriate to effectively modify cloud properties. Various methods have been studied to answer this question starting with the theoretical design of a wind-driven spray vessel that was first described by Salter et al. (2008), aiming to produce a monodisperse spray with 0.8 μm diameter and the option to vary the diameter. This method was intended to spray 30 L/s of seawater producing 10^{17} Cloud Condensation Nuclei (CCN) per second. Various spraying techniques have been studied by Cooper et al. (2013), for instance, the formation of electrically driven Taylor cone jets from salt water, which could result in an expensive spraying structure due to the amount of emitters required, among other technical considerations. Another technique described by Neukermans et al. (2014) involved spraying saltwater under supercritical conditions. This method leverages the unique properties of water near its critical point to produce sub-micrometer salt particles. This method has a high energy demand, and its implementation could have potential corrosion problems for the spraying nozzles and equipment.

Connolly et al. (2014) compared the efficiency of four potential spraying methods: Rayleigh jet-instability, Taylor cone jet, supercritical fluid, and effervescent spray. Their analysis addressed the question of what is the appropriate size distribution to obtain the desired modification in cloud albedo. Their results suggested that salt particles within 30–100 nm median dry diameter are the most effective considering the assumed amount of energy used to spray the aerosols. Among the methods evaluated, the Rayleigh jet method emerged as the most energy-efficient, followed by the effervescent spray method. However, other factors should also be considered to determine the most efficient spray distribution, especially the technical feasibility of the proposed technology. These factors not only include technical considerations such as maintenance, and energy availability but also issues that may affect the dispersion of the salt aerosol such as the effect evaporative cooling could have on the buoyancy of the plume (Connolly et al., 2014).

Cooper et al. (2014); Foster et al. (2020) and Harrison et al. (2020) explored the potential application of effervescent spray nozzles for cloud brightening. This technique uses converging nozzles to atomise seawater using a mixture of pressurized water and air. This method produces seawater droplets that are smaller than the 0.8 μm originally proposed by Latham et al. (2008). Instead, it produces mean dry modal diameters between 30 and 400 nm, which is more in line with the optimal dry size range of 30–

FIGURE 4
The prototype seawater atomizing sprayer was developed during the MCB proof of concept in 2020. Resembling a snow-making cannon, it consists of 100 effervescent nozzles distributed in 10 individual radial manifolds.

60 nm proposed by Wood (2021) for cloud albedo modification. These smaller particles are suitable for enhancing the cloud indirect effect and therefore the cloud albedo. The effervescent spray technique is presented as a promising approach for localized implementation of cloud brightening.

A version of effervescent spray technology was implemented in the design and development of a sprayer system tested over the Great Barrier Reef in the first cloud brightening outdoor experiments (Harrison et al., 2020). The purpose of the trial was to determine the *in-situ* characteristics of the emitted sea spray and the behaviour of the plume generated, which contained nano-sized saltwater droplets. The spraying atomisation system developed by Harrison et al. (2020) and tested during the 2020 MCB trial, integrates a spray generator assembly, an external self-priming low-pressure pump, a seawater intake, filtration, a high-pressure water pump, a high-pressure high-flow air compressor, and a diesel generator for power. The sea sprayer, which resembles a snow-making cannon, contains an original arrangement of 100 effervescent nozzles distributed in 10 individual radial manifolds (Figure 4). The nozzle assembly, which is similar to the one described by Cooper et al. (2014), produces an estimated of 2.7 x 10^{14} sea salt aerosols per second with a mode of around 40 nm from 20 mL per second of seawater, resulting in a plume of nano-sized saltwater droplets that disperse downwind in the marine boundary layer. The results from this trial demonstrated the engineering viability of producing a large number of sea salt aerosols from seawater and it constitutes the first step to demonstrate the feasibility of MCB for the reef.

A more recent work by Claudel et al. (2024) proposes to industrially manufacture salt nanoparticle using anti-solvent precipitation techniques. The particles within a narrowed size distribution would be dispersed in the atmosphere by a fleet of unmanned aerial vehicles (UAVs). The process of manufacturing the nanoparticles is based on the production method described by Chen et al. (2019), in which anhydrous ethanol is used around concentrated brine droplets. One of the main advantages discussed by Claudel et al. (2024) from this technique compared to spraying methods is the ability to produce a narrow normal size distribution reducing total salt mass.

These diverse spraying techniques illustrate the ongoing advancements in MCB technology. While each method presents unique strengths and challenges, continued research and development will be essential to refine these technologies, optimize their efficiency, and address the practical and environmental considerations critical for large-scale deployment.

5 Plume characterisation and dispersion

The effectiveness of marine cloud brightening (MCB) relies heavily on the behavior of injected aerosols within the marine boundary layer and their subsequent interaction with clouds. Early studies primarily utilized global climate models (GCMs) to assess MCB by assuming a direct increase in cloud droplet number concentration without explicitly accounting for the processes of aerosol production, transport, or activation. For instance, Bala et al. (2010); Jones et al. (2009); Latham et al. (2008); Rasch et al. (2009) all employed prescribed aerosol perturbations to evaluate the climatic effects of MCB. However, these models lacked the representation of aerosol dynamics and their interactions with clouds, which are critical to assessing the true potential of the technique. Korhonen et al. (2010) advanced this work by incorporating aerosol emissions into a global aerosol model to simulate particle transport. While this approach provided a more realistic representation of emissions, it was still unable to resolve essential aerosol-cloud interactions.

Subsequent research sought to bridge this gap by including meteorological dependencies and detailed cloud microphysics. Wang et al. (2011) implemented a cloud resolving model to evaluate how injected aerosol particles are transported by organised eddies within the marine boundary layer, and the impact of those particles on cloud microphysical processes. Their results showed a dependence of cloud brightening effectiveness on meteorological and background aerosol conditions, being more efficient in a weakly precipitating boundary layer where drizzle formation is suppressed by the injected aerosol interaction with clouds. They also showed that albedo enhancement is less effective in strongly precipitating or polluted clouds and ineffective in a relatively dry boundary layer with clouds of low liquid water path. Similarly, Chun et al. (2023) used large eddy simulation (LES) to investigate subtropical marine clouds' microphysical and radiative responses to aerosol injections, highlighting that the effectiveness of aerosol-cloud interactions varies with background aerosol concentrations and atmospheric moisture. They emphasized that cleaner conditions amplify cloud responses, while dry or polluted environments limit the effectiveness of aerosol injections.

A key advancement in MCB modeling was the incorporation of droplet evaporation and its impact on plume dynamics, particularly the generation of negative buoyancy. Jenkins and Forster (2013) incorporated those effects for the first time by including water in the sea salt aerosol emission to study the impact on the vertical transport of the aerosols. They used the Weather Research and Forecasting model coupled with chemistry (WRF/Chem) in a large-eddy simulation configuration to show how droplet evaporation generates cold pools resulting in a negatively buoyant plume, thereby suppressing initial aerosol mixing heights by up to 30% (40 m). They also showed how the plume mixing height achieved is impacted by the effects of relative humidity on the rate of evaporation, as well as by the changes in the turbulent structure of the boundary layer over the diurnal cycle. The inclusion of a representation of the cooling associated with droplet evaporation in global scale models or cloud resolving models would contribute to a more realistic estimation of MCB effectiveness (Jenkins and Forster, 2013).

Building on these findings, researchers began to explore high-resolution simulations and experimental models to further refine their understanding of aerosol dispersion. Stuart et al. (2013) explored the evolution of sea salt plumes with a multi-shelled Gaussian plume model to estimate the impact of aerosol coagulation on the effectiveness of MCB. This model showed that coagulation significantly reduces the number of particles reaching cloud heights, a limitation not addressed in earlier studies. The mathematical representation of this dispersion process follows:

$$C(x,y,z) = \frac{Q}{\sqrt{2\pi}\sigma_y\sigma_z} exp\left(\frac{y^2}{2\sigma_y^2}\right) exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right)$$

where $C(x,y,z)$ is the aerosol concentration, Q is the emission rate, σ_y and σ_z are the standard deviations of the plume spread, and H is the effective plume height. This approach provided a critical step forward in understanding near-source aerosol behavior. The proposed model by Stuart et al. (2013) follows the mean wind speed using a Lagrangian approach, and the Gaussian evolution of the plume is captured in ten shells expanding from the source. The results from this work suggested previous studies (Jenkins and Forster, 2013; Wang et al., 2011) have overestimated the number of particles that reach cloud heights because they were not able to resolve sub-grid aerosol coagulation due to coarse spatial resolution. Anand and Mayya (2015) compared the expanding plume model proposed by Stuart et al. (2013) with a diffusion-based approach to solve the diffusion-coagulation equation for a plume in steady-state conditions for cloud brightening applications. Each of these studies resulted in particle survival fraction expressions that might be suitable for implementation into global/regional scale aerosol-climate models.

Recent work by McMichael et al. (2024) used large eddy simulations (LES) and Lagrangian particle models to investigate the influence of shear on plume spreading in different aerosol conditions. Similarly, Maalick et al. (2014) studied the dispersion of sea salt particles from a moving source considering the condensation, evaporation, and the effect of aerosol water on ambient temperature. The explicit treatment of aerosol water allowed them to capture the negative buoyancy caused by water evaporation from aerosols. When the seawater plume is injected into the boundary layer, the difference in water vapour pressure between the water content of the plume and the ambient air, along with the latent heat uptake will cause the evaporation of water from the emitted particles until equilibrium with the relative humidity is reached. Mass and energy balance equations were then used to calculate the maximum cooling and the resulting relative humidity in ideal conditions. This evaporation process causes a temperature decrease close to the emission source resulting in a negative buoyancy and producing a downdraft of cold air, which delays the dispersion of the plume (Maalick et al., 2014). They used a higher resolution large eddy model UCLALES with the aerosol module SALSA to capture the loss of aerosol particles due to coagulation near the plume source and surface deposition. Together, these findings underscore the complexity of aerosol plume behaviour and provide critical insights for the design and optimization of emission systems for Marine Cloud Brightening (Maalick et al., 2014; McMichael et al., 2024).

In a recent work, Prabhakaran et al. (2024) explored the effects of MCB aerosol injections in the stratocumulus to cumulus transition. They used a LES model with a Lagrangian domain, coupled to a bin-emulating, two-moment bulk microphysics scheme. This means that while the model tracked the evolution of the cloud system as it moved across the ocean, it did not track individual aerosol or cloud particles (Lagrangian cloud microphysics). Instead, it used a bulk microphysics approach to represent the aerosol and cloud droplet size distributions. By varying the injection rates and timing, as well as the number of sprayers, they showed how the aerosol plume spread rate is faster under pristine conditions compared to a polluted case. This is due to a transverse circulation generated by the gradient in rain rate in the plume track (Prabhakaran et al., 2024).

Models of buoyant plume rise have been developed (Alessandrini et al., 2013; Anfossi et al., 1993; Briggs, 1975, 1984; Hurley and Physick, 1993) to include the temperature difference between the plume and the background air and predict plume heights and maximum ground concentration of pollutants. For instance the formula for neutral conditions given by (Briggs, 1975):

$$\Delta h(t) = \left(\frac{3}{0.6^2} F_M \frac{t}{u} + \frac{3}{2*0.6^2} F_B \frac{t^2}{u}\right)^{1/3}$$

where the final plume rise is defined in terms of the flux of momentum.F_M, the flux of buoyancy F_B, the horizontal wind velocity u, and the time from the plume release t. The early stage of ship plume dispersion and the effect of additional buoyancy due to the heat release from ships have been explored by Chosson et al. (2008) using a plume rise scheme integrated into a Lagrangian particle dispersion model. Their approach suggests that the initial buoyancy flux has an impact on the plume dispersion pattern. Despite the inclusion of buoyancy in plume rise models, those studies are limited to updrafts due to heat flux and the subsequent rising of the plume.

The buoyancy-sorting concept proposed by Raymond and Blyth (1986), suggests that the mixing between moist convective plumes and dry environmental air produces negatively buoyant parcels leading to plume detrainment. Although originally applied to convective cold plumes, this concept provides valuable insights into the dynamics of evaporative cooling plumes such as the one proposed for MCB. Several studies have adopted different approaches to parameterize the influence of environmental conditions such as the relative humidity on entrainment and detrainment rates (Bechtold et al., 2008; Böing et al., 2012; Dawe and Austin, 2013; de Rooy and Siebesma, 2008; Kain and Fritsch, 1990; Savre and Herzog, 2019; Stirling and Stratton, 2012). Savre and Herzog (2019) suggest that negatively buoyant parcels might detrain if the original parcel's momentum is not strong enough to maintain the vertical updraft, exposing the complex dependency of the entrainment rate on updraft velocity, buoyancy, and relative humidity. Similar to convective plumes, the MCB plume entrainment and detrainment processes depend on factors such as updraft velocity, buoyancy, and relative humidity. Understanding these aerosol dynamics is crucial to evaluating the impact of downdrafts resulting from negative buoyancy fluxes on the dispersion of the MCB plume in the marine boundary layer.

Overall, these studies findings highlight the complex interactions involved in the dispersion of the injected sea salt aerosols and their impact on MCB effectiveness. The findings from this work highlight the importance of considering factors such as aerosol coagulation, droplet evaporation, and the influence of meteorological conditions on the behavior of the MCB plumes.

Further research efforts are necessary to enhance our understanding of negative buoyancy flux in evaporative plumes and its implications for the dispersion within the marine boundary layer. Additionally, the development of advanced modeling approaches that account for the intricate interdependencies between aerosol dynamics, atmospheric conditions, and cloud microphysics will be crucial for refining the estimation of MCB effectiveness on global and regional scales.

6 Airborne measurements of aerosol dispersion

Models have been developed to explore aerosol dispersion, as well as the effects of the interaction between solar radiation and atmospheric particles on global climate, and the formation of cloud droplets or ice crystals from those aerosol particles. A challenge in those models relates to the lack of detailed measurements of particle properties over a broad range of conditions and covering a range of spatial scales to enable validation.

6.1 Aircraft-based studies of particle emissions

Particle emissions from ship engines have been extensively studied due to the impact of those aerosol particles in the marine boundary layer (Durkee et al., 2000c; Frick and Hoppel, 2000; Petzold et al., 2008). Special interest has been shown in the effects of those emissions on the microstructure and albedo of marine stratocumulus clouds. The emission of aerosols that form cloud condensation nuclei from ship engines can cause the formation of ship tracks which are the result of the mixing of aerosol particles throughout the boundary layer in the presence of a cloud layer susceptible to aerosol pertubation (Durkee et al., 2000b). Frick and Hoppel (2000) collected high-resolution aerosol, trace gas, and cloud microphysical measurements from transects of an airship across ship exhaust plumes. Those measurements were used to define the concentration, source strength and size distribution of the aerosol generated by the ships. In-cloud measurements indicated an increase in the number of cloud droplets and a decrease in their radii (Frick and Hoppel, 2000).

The Monterey Area Ship Track (MAST) experiment in 1994 was an aircraft-based study conducted to track particle emissions from ships and measure the effects of aerosol perturbations on the microphysics and radiative properties of marine stratocumulus clouds (Durkee et al., 2000a). Two aircraft were used to measure basic meteorological variables, such as temperature, dewpoint temperature, pressure and liquid water content, as well as cloud and microphysical parameters, and radiation within, above and below clouds. The UW C-131A aircraft was used to investigate the observed increase in ship track albedo resulting from aerosol-cloud interaction while the UK C-130 aircraft performed measurements of turbulence, boundary layer thermodynamic structure, cloud and aerosol microphysics, and multispectral radiation. Their observations evidenced that diesel-powered ships emitting high concentrations of aerosols in the accumulation mode (0.5–2 µm) are substantially more likely to produce ship tracks than ships powered by steam and gas turbines. Diesel-powered ships emit particles with a mode radius between 0.03 and 0.05 µm which are more likely to act as cloud condensation nuclei (CCN). This is in contrast to steam turbine ships that emit smaller particles (mode radius around 0.02 µm), that are less likely to become CCN.

Aerosol microphysical and chemical properties were measured in expanding ship plumes using the DLR aircraft Falcon 20 E-5 (Petzold et al., 2008) as part of the ICARTT-ITOP (Intercontinental Transport of Ozone and Precursors) experiment conducted in 2004. The instrumentation included six Condensation Particle Counters (CPC) with different lower cut-off diameters, Diffusion Screen Separators, a Differential Mobility Analyser (DMA), a thermodenuder with two channels, two optical particle counters (OPC) and a Particle Soot Absorption Photometer. Data from the aircraft observations were integrated with emission studies conducted on ship engines operating under different loads and modelled using a Gaussian plume framework. This approach provided insights into the particle transformation processes during plume expansion, estimating a maximum lifetime for ship exhaust plumes of approximately 24 hours within a well-mixed marine boundary layer.

The Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE) campaign (Russell et al., 2013) combined aircraft, ship and satellite observations along with modeling studies to analyse the effects of aerosol perturbations from three defined sources on marine stratocumulus clouds. Measurements of particle and cloud droplet number, mass and composition were performed from a Twin Otter aircraft while controlled smoke emissions were produced from the research vessel (R/V) Point Sur. During this campaign, measurements of combustion exhaust particles from ships of opportunity, as well as aircraft-released milled salt particles were completed. The results revealed that smoke and ship emissions effectively modify cloud albedo, and that drizzle rates can be increased by the addition of giant salt nuclei.

The impact of ultrafine particles (UFP) on Australian regional water and radiation budgets have been investigated using airborne surveys over Eastern Australia, northern New South Wales and Queensland (Junkermann and Hacker, 2015). Emissions from coal-fired power stations were measured using airborne Lagrangian transects across the plume to determine source strength of primary emissions. Plumes were followed using airborne measurements of concentration and size distributions in real-time during flights. The aerosol and meteorological instrumentation on-board the motorglider ECO-Dimona consisted of scanning mobility particle sizer (SMPS), condensation particle counter (CPC), optical particle counter (OPC), and a BAT-probe for wind, 3D turbulence, air temperature, humidity, and pressure measurements. Coal-fired power stations were identified as the primary source of UFP and possible precursors of CCN, while sugar mills, smelter and shipping along the coast were identified as comparable minor sources of UFP in the region studied.

While direct observations of MCB plumes using aircraft platforms remain limited in peer-reviewed literature, preliminary findings have been presented at conferences, such as the American Geophysical Union Fall Meeting (Harrison, 2023) and XXVIII

General Assembly of the International Union of Geodesy and Geophysics (IUGG) (Hernandez-Jaramillo et al., 2023b), which shared observational data from airborne measurements of MCB-related aerosol dynamics. These emerging studies offer valuable insights into the intricate dynamics of aerosol dispersion, including the effects of ship emissions, sea salt particles, and other anthropogenic sources. Moving forward, integrating observations from airborne measurements with advanced modeling techniques will be essential for refining our understanding of aerosol dispersion processes and their role in climate modification strategies. This continued research will not only enhance our ability to assess the feasibility and effectiveness of MCB as a climate intervention approach but also contribute to broader efforts in understanding atmospheric aerosol dynamics and their impacts on regional and global climate systems.

6.2 Remotely piloted aircraft systems for atmospheric research

Remotely Piloted Aircraft Systems (RPAS), also known as drones (Kelaher et al., 2020a, 2020), have been increasingly used for atmospheric and meteorological research (Anderson and Gaston, 2013; Martin et al., 2011; Mayer et al., 2012). They have been used as measurement platforms for spatial and temporal analysis of the atmospheric boundary layer (Carbajo-Fuertes et al., 2019; Eckert et al., 2023; Hemingway et al., 2017; Hofsäß et al., 2019; Palomaki et al., 2017; Reineman et al., 2013; Witte et al., 2017) due to their versatility, the ability to perform vertical profiles, and their ability to hover at a fixed point. Villa et al. (2019) demonstrated the applicability of drones to characterise the exhaust plume of a ship operating at sea measuring particle number (PN) concentrations and CO_2 concentration. The DJI S800 EVO hexacopter performed transects perpendicular to the plume 20 m from the ship, carrying a Miniature Diffusion Size Classifier (DISCmini) to estimate particle concentrations between 10 and 500 nm of diameter, and a TSI IAQcalc 7545 to measure CO_2 concentrations. Fixed wing drones have also been used to study atmospheric aerosol vertical distributions using an aerosol measurement package, designed and manufactured by Brechtel Manufacturing Inc. The system included a passively pumped isokinetic inlet, a mixing concentration particle counter (MCPC), a three-wavelength absorption photometer and a Multi-Channel Chemical Filter Sampler (Bates et al., 2013). The data collected was intended to assess sources of black carbon (BC) on the Artic and its potential climate impacts.

Hernandez-Jaramillo et al. (2023a) used an advanced Mixing Condensation Particle Counter (9403 aMCPC, Brechtel) and a DiSCmini (testo) onboard drones to characterise the nearfield dispersion of an MCB plume for the first time. Measurements were performed during the Reef Restoration and Adaptation Program (RRAP) Cooling and Shading field experiments in March 2021, in which an MCB sprayer prototype was tested. In this study, the authors positioned the aerosol inlet outside the influence of the propeller downwash to ensure that the sampled aerosols were collected from unperturbed air. Their findings indicated vertical mixing of the plume seemingly contrasted with what some previous modeling studies suggested regarding the impact of evaporative cooling on aerosol dispersion (Jenkins and Forster, 2013; Maalick et al., 2014). Hernandez-Jaramillo et al. (2023a) used an injection rate of 0.068 kg/s of seawater. This is significantly lower than the 7.5 kg/s rate used by Jenkins and Forster (2013) and the 15 kg s/1 rate by Maalick et al. (2014), as well as the 30 kg/s rate suggested by Salter et al. (2008). The lower flow rate in Hernandez-Jaramillo et al. (2023a) results in a lower mass of water being evaporated, consequently reducing the magnitude of evaporative cooling, and thus the associated negative buoyancy.

The integration of drones into atmospheric research has opened up new avenues for obtaining high-resolution spatial and temporal data, enabling more precise observations of complex atmospheric processes. As demonstrated by Hernandez-Jaramillo et al. (2023a), drones provide a valuable means of validating and refining dispersion models, particularly in emerging fields like MCB. This underscores their potential to enhance our understanding of aerosol dynamics and their broader climatic implications.

7 Conclusions

The majority of modeling studies of MCB have focused on the effects of prescribed increases of aerosol salt particles on cloud properties to determine the effectiveness and to estimate the potential impact on climate. Most of the studies are based on global climate models and are intended for global applications, whereas studies of regional applications and specifically for coral bleaching mitigation are still limited. Few modeling studies have considered the processes involved in the dispersion of the sea salt aerosol plume that could potentially suppress the initial plume height and delay the vertical mixing of the particles. However, the dispersion of those aerosol particles requires more empirical experiments to validate modeling studies, and specifically more data to understand what portion of released sea salt particles are incorporated into clouds. Models with finer-scale spatial resolution are needed to resolve sub-grid dispersion processes and correctly estimate the number of particles that could reach cloud heights.

Remotely piloted aircraft systems and crewed aircraft have the potential to be used as measurement platforms to perform sampling along the expanding sea salt aerosol plume intended for marine cloud brightening. Overall, the present review concludes that more empirical experiments are needed to allow validation and improvement of theoretical predictions and models of various complexities. The combination of higher-resolution modeling and empirical field data will contribute to the general understanding of cloud brightening and its feasibility for mitigating mass coral bleaching at management-relevant scales.

Overall, future MCB studies should focus on several crucial areas, including improved spraying techniques to produce suitable particles at a reasonable level of energy consumption, as well as the inclusion of a more detailed representation of the plume dynamics into MCB modeling. This could include the addition of droplet evaporation, buoyancy effects, and turbulence to refine predictions of aerosol-cloud interactions. Larger-scale field experiments are also necessary to understand real-world plume behaviour and cloud responses and validate existing models. Finally, these efforts should be coupled with ecosystem impact assessments to ensure that MCB interventions have no harmful effects on marine and terrestrial systems. Policy and governance frameworks should also be developed to guide decision-making processes regarding the potential deployment of MCB interventions. By addressing these research areas, the feasibility of MCB as a targeted climate intervention for coral reef preservation can be evaluated for future applications.

Author contributions

DH-J: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. DH: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. BK: Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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