DOE-NOAA
MARINE CLOUD BRIGHTENING
WORKSHOP REPORT

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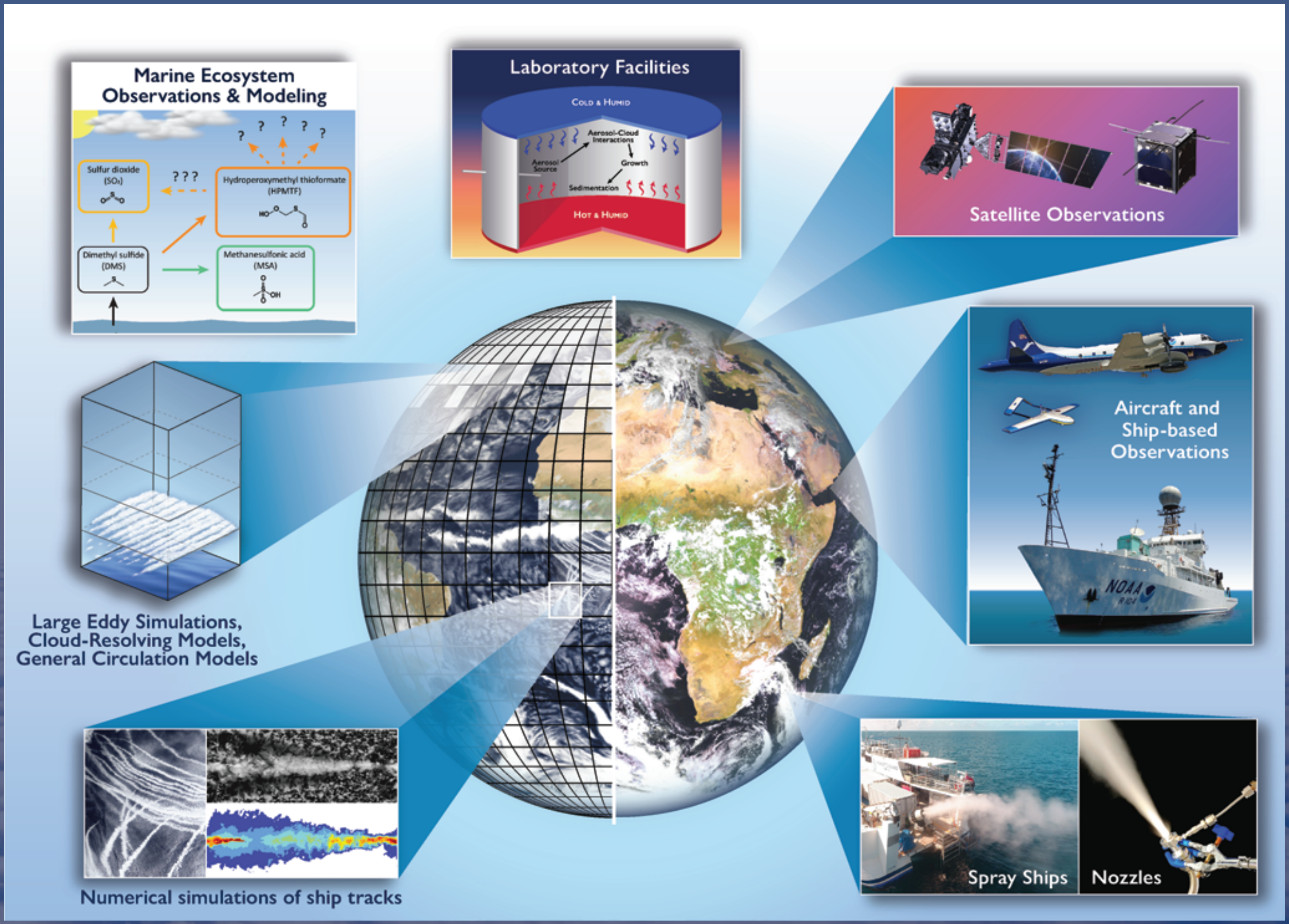

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November 2022

DOE-NOAA Marine Cloud Brightening Workshop

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Executive Summary

Marine Cloud Brightening (MCB) refers to the deliberate injection of aerosol particles into marine clouds to increase their reflection of solar radiation to temporarily cool the planet while decarbonization efforts are pursued. A workshop was conducted to assess the state of knowledge in the field of MCB, and to provide a possible research path toward reducing unknowns in key components of the underlying physical science. This three-day workshop took place in April 2022 and was jointly sponsored by Department of Energy (DOE)'s Atmospheric System Research (ASR) program and the National Oceanic and Atmospheric Administration (NOAA). The workshop focused on identifying key physical science knowledge gaps necessary to answer the following driving questions:

1. Is MCB feasible over sufficiently large regions and is implementation practicable for long-enough durations to avert the worst impacts of global warming?
2. If practicable, what will be the regional impacts of such MCB interventions?
3. Do we have adequate systems in place to detect and quantify the effects of such interventions?
4. What physical and engineering science challenges must be resolved satisfactorily before we can consider embarking on MCB?

To address these questions, current knowledge gaps in several aspects of the physical system were called out, as summarized below:

1) *Cloud microphysical knowledge gaps:*
    a) Aerosol emissions cause changes to cloud amount through changes in precipitation and evaporation and are known to sometimes enhance and sometimes offset cloud brightening. Improved understanding of these offsets and their prevalence is essential.
    b) The efficiency with which aerosol particles can be delivered into clouds to enhance cloud drop number concentrations is uncertain.
2) *Meteorological-aerosol co-variability knowledge gaps:*
    a) There is a need to identify and quantify the frequency of occurrence of regions that are highly susceptible to aerosol injections – typically environments supporting thin, layered clouds with low background aerosol concentrations – and to determine whether local responses scale up well enough for a significant regional and global radiative effect.
3) *Large-scale knowledge gaps:*
    a) There is a lack of adequate tools to assess how small-scale perturbations to cloud brightness might affect larger-scale circulations, and the extent to which these might contribute to regional changes in precipitation and radiative forcing of the climate. Furthermore, the timescales of these feedbacks are poorly quantified.
4) *Detection-related knowledge gaps:*
    a) Given the relatively small aerosol-cloud brightening signals, there is a need to assess how long it would take to detect MCB-related brightening against the background of meteorological variability, and to ascertain whether detection times are short enough for strategies to be changed in response to changing conditions.
    b) The adequacy of current and planned future space-based detection systems needs to be determined.

Some practical ways to address these gaps discussed at the workshop are organized here in terms of a progression from those employing methods that are currently available, to those that require substantial development. All proposed approaches can be viewed as essential components of an MCB research program:

1. Satellite/reanalysis studies of susceptible cloud regimes and their frequency of occurrence to address how well the radiative effect of a small-scale MCB experiment will scale up to the planetary scale.
2. Routine modeling of real cases to evaluate and refine models, together with model intercomparison projects at the full range of scales from the cloud scale on up to the global scale.
3. A small-scale field program to assess the generation of particles at the surface and their delivery into clouds.
4. Leveraging satellite, aircraft, and surface remote sensing to investigate the detectability of changes in cloud albedo within the domain of the deliberate seeding experiment.
5. Laboratory experiments and new facilities to enhance the fidelity of model physics.

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1. Introduction and Motivation

Climate Intervention (CI), or Geoengineering, has been proposed as a means to buy time for humankind to decarbonize the economy and preserve and restore natural ecosystems, thus avoiding the worst impacts of climate change (NRC, 2015). The primary approaches are Carbon Dioxide Removal (CDR), which directly addresses the increase in CO_2 as it is the major cause of climate change, and Solar Radiation Management (SRM), which subsumes a variety of techniques that aim to reduce the amount of heat absorbed by the Earth system. Within SRM, the two leading approaches are Stratospheric Aerosol Injection (SAI), the injection of reflective particles into the stratosphere to reflect some fraction of incoming solar radiation, and Marine Cloud Brightening (MCB), the injection of aerosol particles into low-level, liquid marine clouds that typically cover large areas of subtropical oceans, as a means of increasing their reflectance of solar radiation. This report addresses the latter.

In their 2021 report (NASEM 2021), the National Academies of Science, Engineering, and Medicine (NASEM) identified research recommendations for MCB. Research to date on this topic has been limited, largely due to concerns about such work competing with achieving progress on climate change mitigation. NASEM recommended that the U.S. implement a “robust portfolio of climate mitigation and adaptation,” which specifically included MCB research. The NASEM report recommended that research cover three broad, interconnected areas, to be pursued simultaneously, to address Solar Geoengineering (SG) research: (i) context and goals, (ii) impacts and technical dimensions, and (iii) social dimensions. The impacts and technical dimensions include research on technology for particle generation, atmospheric processes, and climate effects. In addition, the report recommended considering deliberate, outdoor experiments that involve releasing substances, if such experiments could be argued to be needed to advance understanding, and if they were carried out in such a way as to have negligible effects on climate.

An important aspect of the recommended research plan was an embedded strategy for terminating MCB research at the point it was shown to be infeasible. To illustrate how such a research plan might work, Diamond et al. (2022) proposed designated check points for six research themes that were associated with specific exit ramps. These research themes are 1) Generation and delivery of appropriately sized particles, 2) Local cloud adjustments, 3) Spatiotemporal scale of susceptible clouds, 4) Signal detection, 5) Impacts on marine ecosystems and coastal communities, and 6) Large-scale circulation and precipitation response. These themes provide a possible structure for a research program across many scales, disciplines, and tools.

Work on aerosol-cloud interactions addressing climate change more broadly than the MCB question has shown that adding aerosol to marine clouds can increase cloud reflectivity in some circumstances (e.g., Haywood and Boucher, 2000), as in the case of ‘ship tracks’ – bright linear features observed in satellite imagery indicating that ship-stack effluent has mixed into the clouds above (Figure 1) – and also in individual pollution tracks (e.g., Toll et al. 2019). The existence of these ship tracks forms the foundation of proposed MCB. The method rests on the idea that injecting more aerosol particles into a cloud will produce more cloud condensation nuclei (CCN) on which droplets can form and – all else equal, specifically cloud liquid water – brighter clouds. Yet there is large uncertainty regarding where and by how much cloud reflectance (albedo) can be modified at regional-to-global scales, and whether feedback processes that affect cloud liquid water and cloud cover will mask or amplify cooling. This large uncertainty stems from a lack of proper representation of the small-scale underlying processes in many models, particularly climate models, and inadequate observations to constrain these processes. More details about MCB as it was first proposed can be found in Latham (2009), Latham et al. (2012), and Wood et al. (2017).

The purpose of this workshop was to identify specific uncertainties as research targets, providing a first step in implementing the NASEM recommendations, and to consider a wider variety of perspectives than were considered by Diamond et al. (2022). The workshop’s guiding questions were constructed to allow broad consideration of the state of knowledge and its missing components, novel ways to address gaps and challenges, and a path forward.

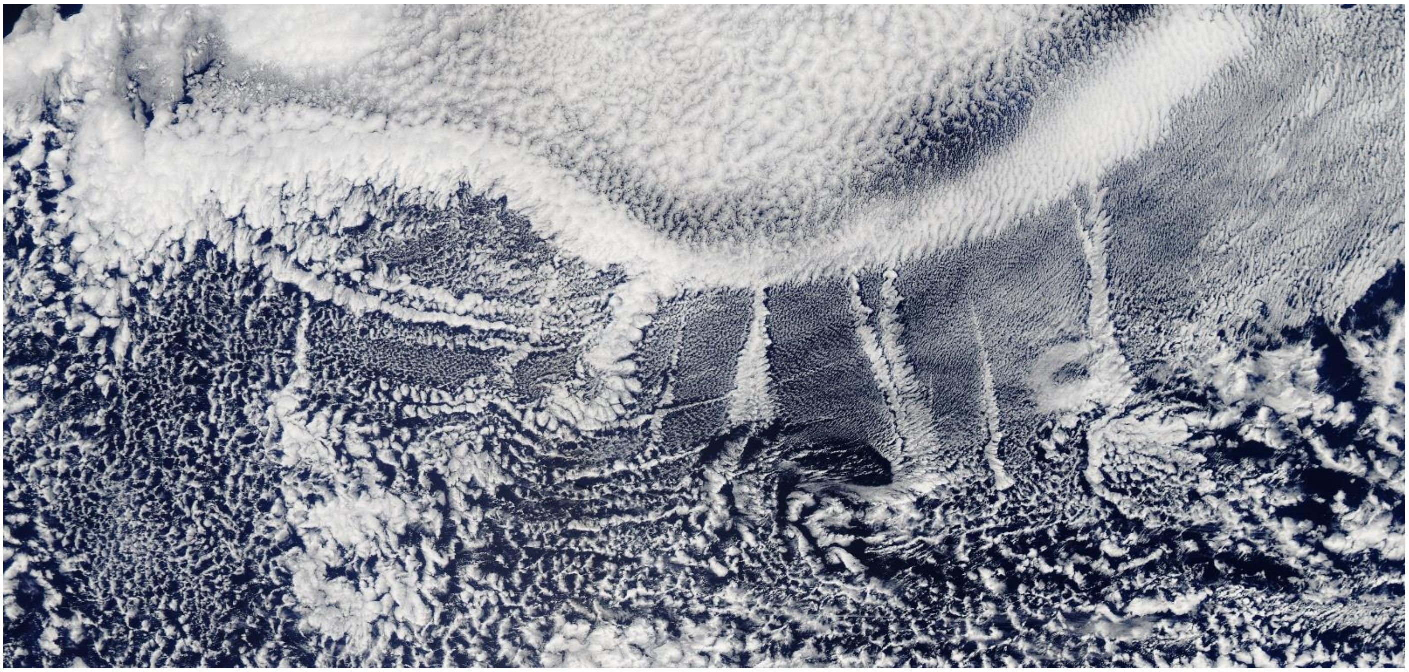

Figure 1: The Moderate Resolution Imaging Spectroradiometer (MODIS) on Aqua satellite captured this natural-color image of several ship tracks extending northward on August 26, 2018. The ship tracks are caused by particles emitted by the ships, entering the clouds and causing microphysical changes. The clouds were located about 1,000 kilometers (600 miles) west of the California-Oregon border. The reflection of solar radiation from this scene is higher than it would have been in the absence of the ship tracks. Credit: https://earthobservatory.nasa.gov/images/92686/summer-ship-tracks-in-the-pacific

2. Workshop Format

The workshop idea was conceived in Fall 2021 by the co-chairs along with the managers of DOE and NOAA programs. The initial draft of the workshop attendees and workshop dates were selected in December 2021. Invitations were sent to participants in January 2022, with almost all invitees responding affirmatively.

Described below is the workshop format. All participants were asked to share a two-page white paper addressing the workshop's four guiding questions prior to the meeting. Each breakout session had two discussion leads, and two rapporteurs. The discussion notes from each breakout session were available for viewing to all attendees throughout, and after the workshop.

Details on the workshop agenda, discussion leads, and rapporteurs are in Appendix 1.

Hosts: Department of Energy/Atmospheric Science Research and NOAA/OAR

When: April 11-13, 2022, 8:30 am to 12 pm Central Time each day.

Where: Virtual

Invitees: Approximately 30 scientific experts covering expertise in aerosol-cloud-radiation interactions and program managers from NASA, NOAA, NSF, and DOE.

Desired Outcome: Workshop report and possible peer-reviewed document reviewing critical issues, assessing knowledge/knowledge gaps, and suggesting a research roadmap for MCB research that focuses on physical science questions but is also cognizant of social science considerations.

Topic Areas: Clouds, Aerosol, Turbulence, and Radiation as they pertain to MCB.

Skill Sets of Attendees: Measurements (in-situ and remote), modeling at a range of scales, laboratory studies, field measurements, and satellite and surface-based remote sensing.

Format: Three days of discussions, three hours/day, with minimal presentation of slides; All participants were asked to share a two-page white paper addressing the workshop's four guiding questions prior to the meeting (See Section 3); Four breakout sessions (one per guiding question, with three groups of 10 each); Initial groupings by scale and groups mixed across scales later on. (Appendix D.)

Other: By invitation only. No recordings. Invitees committed to engage in the entire meeting and to write a report/paper.

3. Guiding Questions

Four guiding questions pertaining to physical aspects of MCB were presented to participants at the time of solicitation of the white papers. The questions listed below were also the focus of and for discussion during breakout sessions.

Question 1: What do we know and what are the main knowledge gaps?

Question 2: What are novel ways to address gaps?

Question 3: What are the biggest challenges?

Question 4: What are the 'must haves' for an MCB research program?

This section constitutes the heart of the report and synthesizes the key findings from the white papers, keynote presentations, panel remarks, and discussions during the workshop. Note that the document synthesizes Questions 1 and 3 to improve the flow of discussion but retains Questions 2 and 4 as stated. The discussion leads and rapporteurs from each breakout session summarized the respective discussions that are synthesized below.

3.1 What do we know and what are the main knowledge gaps, and what are the biggest challenges?

The influence of aerosol particles on marine clouds has been the focus of much research since its first documentation (e.g., Conover, 1966, or Twomey, 1977). In the intervening decades, a vast body of knowledge on aerosol-cloud interactions and their implications for climate forcing has been acquired (e.g., Kreidenweis et al. 2019). Increased cloud droplet numbers in low-level liquid-water clouds due to additional aerosol particles have been observed at individual pollution track scales to continental scales (Toll et al. 2019; Trofimov et al. 2020; Diamond et al. 2020; McCoy et al. 2017; McCoy et al. 2018; Malavelle et al. 2017). MCB is a special case of aerosol-cloud interaction that presents particular knowledge gaps and challenges on a range of topical areas within the atmospheric sciences. The knowledge gaps and challenges occur at the aerosol/droplet scale; through cloud-scale turbulent processes; mesoscale responses in the form of cloud organization, adjustments in cloud cover and condensate loading; regional scale cloudiness, and global scale circulations, all of which need to be resolved prior to MCB deployment. MCB for CI-focused research differs from traditional aerosol-cloud interaction research in the following ways:
(i) most current research focused on ship-tracks or urban plumes is largely assumed to involve sulfate aerosol particles, produced by combustion and aging processes, and covering a range of sizes. In contrast, MCB will generate sea salt particles of pre-selected sizes from the aerosolization and evaporation of ocean water spray. The different chemical composition of the seeded aerosol (sea salt vs. sulfate) results in different hygroscopic properties that control the deliquescence and efflorescence of the particles, which may affect how the particles are activated, and how droplets grow in cloud; (ii) Ship-tracks or urban plumes generally produce continuous aerosol perturbations applied at times set by ship traffic, with no attempt to control the effects on cloud properties. For MCB, sea salt spray might be generated at pre-selected times of the day, for a set duration, and repeated at set intervals during different seasons and at locations determined to have the potential to optimize cloud brightening, and (iii) generation of salt aerosol from ocean water will not result in secondary aerosol production downwind by precursor gases, which is typical in urban plumes. However, the large quantities of salt haze droplets that will be produced might have impacts on the marine ecosystem.

In addition to these differences between planned deliberate perturbation experiments and existing analogues, marine clouds exhibit significant variability in cloud albedo. This can be attributed to changes in parameters external to the cloud system such as meteorological conditions, which determine turbulence, radiation, and surface fluxes, and changes in internal properties, such as rain, evaporation, and entrainment. The challenge of attributing albedo changes to aerosol and/or other meteorological drivers has been a long-standing issue. This is partly due to a lack of coincidental, detailed observations of all important variables for a range of perturbations in each variable, and partly due to a lack of statistically robust approaches to sampling and analysis of the naturally co-varying variable space.

We expand on what we know and our knowledge gaps, and main challenges related to MCB in the following four thematic areas:

3.1.1 Aerosol and Cloud Microphysics

MCB-related gaps and challenges in the realm of aerosol and cloud microphysics exist in the engineering challenge of generating desired aerosol particles and transporting them to the cloud. There is also a physical knowledge gap of the cloud response to these aerosol particles. The major knowledge gaps are summarized below:

a) *Nozzle design and generation of particles of desired size distribution*. There exists an engineering challenge of creating particles of optimal size – preferably with a narrow size distribution without Giant Cloud Condensation Nuclei (GCCN), or CCN on the order of micrometers in size – and having the ability to adjust that size to match local conditions. While significant progress has been made on this front (Cooper et al. 2013; 2014), challenges still remain, especially related to undesirable GCCN (Garner, PARC, personal communication). Ongoing work is investigating whether seawater needs to be filtered to prevent the clogging of nozzles.

b) *Matching optimal injected particle size to cloud/meteorological conditions.* The optimal aerosol composition, size, and concentration for eliciting the desired cloud microphysical response are poorly known and will require significant effort to resolve. It is likely that different conditions will call for different particle-size distribution injections to optimize brightening and to avoid (to the extent possible) the effects of liquid water losses through evaporation and precipitation. While some recent studies have considered this problem, they have not covered the required state space. Tailoring seeded particle size distributions to cloud state is challenging because the target clouds and meteorology, and therefore the brightening potential, are so variable. Understanding the impact of sub-optimal seeding on brightening is also a substantial challenge. Marine boundary layers are known to exhibit distinct diurnal, synoptic, and seasonal cycles. Hence, meteorological conditions and cloud susceptibility vary widely. To achieve effective MCB, it will be necessary to determine prior to seeding the optimal timing, duration, and seeded particle concentrations for a range of meteorological and cloud conditions.

c) *Ensuring delivery to cloud*. The lofting of aerosol to cloud base, including the timescales of lofting, dispersal, and evolution of the particle size distribution while being lofted, is poorly known. This is partly because it depends on meteorological conditions and partly because sprayer technology is still under development. In a natural environment, the aerosol particles generated at the surface are carried up to the cloud base by boundary layer turbulent eddies. However, the cloud layer is often thermodynamically decoupled from the surface (e.g., Serpetzoglou et al. 2008). In an MCB scenario, it is unclear whether the artificially generated sea salt particles will be readily transported to cloud base because evaporative cooling might influence atmospheric stability, and large moisture fluxes might modify natural surface fluxes. Further, the surface generated particles will be dispersed during transport to the cloud base and be advected by the background winds. This results in uncertainty in the particle concentrations that arrive at cloud base (Wood 2021; Hoffmann and Feingold 2021). Lastly, the generated aerosol particle sizes will evolve in time and space, both in and out of cloud. The spatiotemporal scales of these processes are contingent on particle generation scenarios, and therefore poorly quantified. The magnitude of this challenge is unknown but could be explored with large eddy simulation and/or an outdoor experiment.

d) *Small-scale cloud processes are currently not well-enough understood*, at least in part because they are not easy to observe/measure/quantify. Processes such as the activation of CCN, the role of GCCN and the challenge of measuring them, and small-scale turbulence and entrainment at the cm scale have been explored extensively but are still challenging areas of research (Jung et al. 2015; Schlosser et al. 2020). A microphysical challenge specific to MCB is that droplets generated by nozzles will create salt particles at super-equilibrium sizes; just how much larger than equilibrium will depend on particle size and ambient conditions. This is an important consideration since even small concentrations of GCCN (order 1/liter) can reduce brightening by initiating collision-coalescence, followed by precipitation (Houghton, 1938; Dziekan et al. 2021). Resolving the extent to which some of these small-scale processes might determine the success or failure of MCB should be viewed as a high priority.

e) *Avoiding or mitigating negative impacts on the brightening of clouds*. If one considers the activation process alone, the number of drops will depend on the seeded number and size of salt particles, updraft velocity, and temperature. The problem is compounded by processes such as entrainment of dry air and attendant droplet evaporation, resulting in loss of cloud condensate, which offsets brightening. As discussed above, GCCN can also present a potential mechanism for loss of condensate through precipitation. These so-called liquid water adjustments depend on environmental conditions, and have uncertain timescales associated with boundary layer adjustment processes. New approaches to quantifying these adjustments using Large Eddy Simulation (LES) LES (Glassmeier et al. 2021) and temporally staggered satellite measurements (Gryspeerdt et al. 2022) appear promising, but much work still needs to be done.

3.1.2 Scale adjustments

Aerosol-induced perturbations to clouds at small scales are somewhat uncertain, but how they manifest at cloud and larger scales (mesoscale, regional scale, and global scale) is far more uncertain and particularly difficult to quantify with current models and observations. Marine boundary layer clouds respond to increases in the aerosol concentration by increasing their drop number concentration. In turn, the microphysical changes have knock-on impacts on cloud macro-physical properties (liquid water path (LWP); cloud fraction, cloud depth, cloud boundaries, etc.), broadly known as cloud adjustments. Further, these cloud adjustments can also alter atmospheric circulations at meso- and synoptic scales (Fan et al. 2015). There are several fundamental knowledge gaps and challenges regarding these adjustments, as listed below.

a) *The magnitude, duration, and spatial scale of increased cloud albedo* in response to hypothesized seeding is not well-quantified. Moreover, given a constantly evolving atmospheric state, the resulting adjustments will be contingent on external meteorological forcings. Determining whether the change in cloud albedo can be attributed to changes in aerosol properties, or other factors like changes in boundary layer turbulence, cloud mesoscale organization, etc. is a persistent challenge.

b) *The lack of robust quantification of local cloud adjustments*, especially the co-evolution of cloud fraction and LWP. Modeling studies have shown these adjustments to be highly scale- and situation-dependent (e.g., Porch 1990; Wang and Feingold 2009). However, observations to quantify adjustments are lacking (Gryspeerdt et al. 2019, 2022). It has been proposed that one of the more likely pathways to successful MCB would be to seed particles prior to precipitation, typically in the early morning hours, thus enhancing and extending their cloud fraction and LWP into the daylight hours. This would provide a more effective increase in upward shortwave flux as the sun rises higher in the sky (Wang and Feingold 2009, Jenkins et al. 2013). Given the meteorological contingencies, it is unclear if an increased aerosol concentration can reliably suppress precipitation and enhance cloud cover and condensate.

c) *Cloud adjustment timescales*. Cloud liquid water and cloud fraction respond to aerosol perturbations at much slower timescales than the initial brightening signal. Both positive and negative adjustments have been identified, with the former in weakly precipitating conditions, and the latter in non-precipitating conditions. Understanding adjustment timescales relative to the aerosol lifetime, while considering the diurnal cycle and changing meteorological boundary conditions, is a significant challenge.

d) *Modifications to the background atmospheric state.* It is unclear to what extent and at what spatial and temporal scales deliberate seeding will perturb the background aerosol fields, and whether that will translate into changes in boundary layer thermodynamic and dynamic fields (e.g., Durkee et al. 2000), and atmospheric chemical composition (Horowitz et al. 2020).

e) *Model limitations*. Large-scale models are inherently limited in their ability to resolve key physical processes and mesoscale circulations, with the possible exception of cloud resolving model (CRM) scales. There is no single model that can cover the range of scales from microphysical through LES, regional, and global, which means that inferences need to be stitched together from multiple modeling frameworks. Model intercomparison studies typically show significant differences between models of a given scale. The provenance of these differences is usually unclear. In complex systems of this kind, it is often combinations of process representations that drive differences rather than any single process, making it challenging to identify errors or inadequacies in physical representation.

f) *Large-scale impacts.* Although MCB is proposed to be applied locally, the resulting changes in the radiation field will likely result in changes in large-scale circulation patterns and precipitation fields at far-removed locations. Current knowledge of these downstream remote impacts largely comes from highly idealized climate model simulations that are unable to resolve the small-scale aerosol-cloud interactions and their radiative effects (e.g., Jones et al. 2009, Rasch et al. 2009, Hill and Ming 2012). Further, there is no robust way to evaluate these model simulations since even agreement with existing observations is no guarantee that model projections into the future will be correct (e.g., Muelmenstaedt and Feingold 2018). Hence, it is crucial to fully understand the large-scale remote impacts due to MCB.

3.1.3 Aerosol-meteorological co-variability

Aerosol effects on clouds are contingent on meteorology. Both aerosol and meteorology can be thought of as “cloud controlling factors”, and it is challenging to identify whether the changes in cloud albedo are due to changes in aerosol or due to changes in meteorology, unless one of these can be controlled (Russell et al. 2013). Of importance is that the relationship between these cloud controlling factors and cloud amount is not unique; in other words, many different combinations of these factors can yield the same cloud properties. Knowledge gaps and known challenges are summarized below:

a) *Quantifying regional co-variability between meteorology and aerosol.* Aerosol and meteorology covary based on larger scale circulations. The challenge is to understand this co-variability, and to quantify how susceptible clouds will be to perturbation regionally, seasonally, and even within the diurnal cycle. This means a reliance on (ever-improving) model reanalysis and satellite data.

b) *Identifying regions that are most susceptible*. A challenge is to assess just how frequently susceptible clouds occur, what their areal coverage is, and the nature of the co-occurring aerosol conditions. The chances of successful MCB will increase if susceptible conditions co-occur with clean background conditions.

c) *Optimizing*. To maximize the success of MCB, one has to determine optimal time of day, duration, interval, season, and location of seeding. Very little work currently addresses these issues.

d) *Non-uniqueness.* Ideally, one would like to determine the susceptibility of clouds based on atmospheric soundings and aerosol conditions. However, the relationship between meteorology/aerosol and cloud state is non-unique: many different combinations of these cloud-controlling factors can map to the same cloud state (‘equifinality’). This presents a challenge in being able to predetermine which clouds to target based on ambient soundings and aerosol measurements alone.

3.1.4 Detection of MCB

Monitoring of stratocumulus using spaced-based instruments such as the Clouds and the Earth’s Radiant Energy System (CERES) shows that their albedo, even in the absence of anthropogenic aerosol perturbation, is highly variable. As a result, MCB intervention is essentially a “signal-to-noise” problem. Detection – using existing measurements from satellite, aircraft, and field observations – depends on the location, magnitude, and duration of seeding, and is therefore highly uncertain over timescales of relevance to decision making (Seidel et al. 2013; Diamond et al. 2020).

Fundamental challenges include ascertaining the degree to which clouds will be brightened by intervention, as well as the timeframe over which detection will be established with statistical significance. The challenge is both a measurement one, as well as a challenge of determining causality. Pertinent issues are highlighted below:

a) *Weak signals against a noisy background*. Ship-track studies have shown that cloud brightening often presents as a weak signal in a noisy background. The detectability of brightening will depend on the strength of the signal, the variability in the background cloud brightness, the duration of the signal, and its persistence (Seidel et al. 2013). The variability in cloud albedo in the background state will depend on the state of the atmosphere, time in the diurnal cycle, and synoptic conditions. Very little is known about the detectability requirements for MCB salt-tracks.

b) *Invisible tracks*. Experience from ship-tracks shows that many tracks are essentially undetectable, either because they fall below the detection limit of a sensor, or because they occur in a noisy background. Although very weak, their frequency of occurrence might generate a significant signal. Parallels likely exist for MCB. Automated machine-learning approaches are increasingly being applied (e.g., Yuan et al. 2019, 2022; Manshausen et al. 2022).

c) *Satellite-based detection.* Satellite retrievals of cloud microphysics, often the basis for track detection, may be suboptimal precisely when brightening is more likely. For example, microphysical retrievals such as drop effective radius and cloud optical depth are challenging in broken clouds – conditions under which increases in cloud fraction might provide much of the albedo enhancement.

d) *Geostationary satellites.* By viewing cloud systems with high temporal resolution (order 15 min), geostationary satellites provide tendencies on key geophysical variables, and therefore great advantage over snapshot views from single polar orbiting satellites with their revisit times of 24 h. (Note, pairs of polar orbiters with overpass differences approximately three hours apart, are also proving useful; Christensen et al. 2009.) Nevertheless, retrievals of cloud properties from geostationary platforms are at coarser spatial resolution and they depend on the time-dependent solar zenith angle and viewing angle. Improving retrievals from geostationary platforms will be a challenge. However, it would significantly advance the ability to address other challenges, such as cloud adjustments and their timescales.

e) *Surface-based and in-situ detection.* While the most important measure of the success of MCB is the degree of cloud brightening, a radiative response that is most effectively measured from space, one can anticipate a role for ship-based remote sensing to track the effect of MCB salt tracks on cloud development and, in the case of radar, precipitation formation. Airborne in-situ aerosol and cloud measurements as well as ship-based aerosol measurements should prove useful in establishing causal pathways.

3.2 What are novel ways to address the gaps?

Greater understanding of aerosol-cloud-radiation interactions, boundary layer turbulence, and cloud dynamics are needed to assess the technical feasibility of marine cloud brightening. These topics have been longstanding areas of inquiry within the atmospheric sciences. So far, model simulations and analysis of cloud properties within ship-tracks using in-situ measurements and remote sensing retrievals have been the primary tools for studying MCB. Below are plausible novel ways of addressing-MCB related knowledge gaps, such as those listed in Section 3.1.

3.2.1 Analysis of existing data

Large volumes of high-quality observations of aerosol, cloud, radiation and marine boundary layer fields have been made over the past decades during the course of multiple field campaigns. Cloud microphysical, macro-physical, and radiative properties have also been retrieved using measurements by instruments onboard polar and geostationary satellites. Although the data have been used to further our understanding of aerosol, clouds, and aerosol-cloud interactions (e.g., Feingold and McComiskey, 2016; Myhre et al. 2007), they have so far not been utilized for addressing the MCB-related knowledge gaps listed above. This is primarily due to a lack of coordinated, large-scale efforts to address these gaps and a lack of observations of controlled aerosol perturbations that would represent MCB for climate intervention.

Using meteorological reanalysis for context, these large volumes of existing data can be analyzed to identify MCB target locations where confounding meteorological factors are less likely to obscure cloud responses to aerosol perturbations. Further, the seasonal, and interannual variability of meteorological, cloud, and aerosol fields at these MCB target locations can also be characterized using these existing datasets. In addition to ship-tracks, analogues such as effusive volcanoes (e.g., Yuan et al. 2011; Malavelle et al. 2019) and urban/industrial plumes (Toll et al. 2017; 2019) will present continued opportunity for addressing MCB-related questions (Christensen et al. 2022).

The analysis of existing data will yield useful information on MCB target regions and optimal seasons for intervention (e.g., Zhang et al. 2022). It will not, however, yield the required duration and the net change in reflected radiation due to the intervention. Similarly, analysis of data collected within ship-tracks, volcanic, and urban plumes will further scientific understanding of aerosol-cloud interactions but it will not fully address MCB due to (i) different aerosol types involved in MCB (sea salt) as compared to the volcanoes and urban plumes, (ii) lack of control on the properties of the added aerosol particles, and (iii) lack of sufficiently representative and complete observations in relevant regions.

3.2.2 Laboratory and field studies

Measurements are crucial to any MCB effort. Field experiments using ships, aircraft, and satellites at locations amenable to MCB will be essential to address MCB-related knowledge gaps. The scientific community has deep experience with multi-platform and multi-agency/international field experiments addressing aerosol-cloud-precipitation science (e.g., FIRE-I, MAST, DYCOMS-II, VOCALS, MASE, EPEACE, EUREC4A/ATOMIC, and ACTIVATE; see Abbreviations and Acronyms). Laboratory studies of aerosol-cloud interactions such as those generated in the convection-cloud chamber at Michigan Technological University (Chang et al. 2016) can provide refined understanding of aerosol-cloud physics processes in controlled conditions, leading to better cloud-scale models and therefore better overall understanding. Some novel ideas include:

a) *A long-running, single point emission experiment* at a location where the baseline conditions are amenable to both observations and modeling of MCB will help address cloud responses to aerosol perturbation. This type of experiment, complemented by routine LES modeling and ongoing observations from geostationary satellites, as well as in situ sampling by ground-based, unmanned aerial systems (UASs), and other airborne platforms, will illuminate the efficacy of MCB for a range of meteorological and cloud conditions downwind of that location.

b) *Aerosol perturbation experiments in a convection-cloud chamber* that allows the study of droplet nucleation and growth in a turbulent cloud and is large enough to allow formation of drizzle drops from cloud droplets will help illuminate the fine-scale details of aerosol-cloud-dynamics interactions. The representation of drizzle also allows for investigation of feedback on the aerosol particles themselves, such as aerosol loss rates by scavenging and aerosol modification by processing. Such experiments, coupled with LES and Direct Numerical Simulation (DNS) models, will refine our understanding of these interactions and lead to improved MCB modeling.

c) *A cloud seeding experiment with the addition of a passive tracer* in addition to the aerosol injection to discern the cloud brightening signal from the noise will help alleviate issues related to attribution and detection of MCB (e.g., Ghate et al. 2007; Berg et al. 2011). Such an experiment might also help to identify the occurrence of ‘cloud darkening’ (a reduction in brightness due to liquid water losses that more than compensates for Twomey brightening). The presence of a multiscale observational system during such an experiment could inform cloud-top entrainment rates and other small-scale processes impacting MCB-related changes at the mesoscale.

3.2.3 Modeling studies

Modeling provides important context for field measurements, and field measurements provide important constraints for modeling. Model simulations at a range of spatial scales and complexity are required to fully address the MCB-related knowledge gaps listed above. Fortunately, decades of model development have refined many of the tools required to model MCB, although there does not exist one modeling framework that covers all relevant microphysical and dynamical processes at the full range of scales. The Geoengineering Model Intercomparison Project (GeoMIP) experiments apply MCB cloud radiative perturbations (Kravitz et al. 2011) or impose fixed drop concentration increases (Stjern et al. 2018) in coupled climate models to assess changes in large-scale and mesoscale circulation patterns as one ecosystem. As noted, these models lack detailed representation of aerosol and cloud processes (scales on the order of 10 m). LES models, on the other hand, provide high-fidelity simulations of aerosol-cloud interactions at the cloud scale, albeit for shorter durations (on the order of a few days), and in limited domains (on the order of a climate model grid box). Routine LES modeling paired with detailed observations of aerosol and cloud fields can be used to infer the general phase space of cloud susceptibility at target MCB locations (e.g., following methodologies in Sena et al. 2016; Gustafson et al. 2020; Glenn et al. 2020). Such an effort will also yield information on the optimal number, size, composition, and timing of the seeding. To bridge the scales, a promising approach is to employ a global model using either the multiscale modeling framework (MMF) (Terai et al. 2020) or a regionally refined mesh over the target area to resolve scales ranging from 100s of meters to 1000s of kilometers. Nevertheless, these models still require substantial development before they can be used for dedicated MCB research.

3.3 What are the ‘must haves’ for an MCB research program?

The discussion thus far points to a number of different but related physical science gaps (Section 3.1) in different topical areas underpinning MCB. These knowledge gaps are broadly associated with a lack of physical understanding in the field of aerosol-cloud interactions, and could be addressed using approaches described above in Section 3.2. However, for MCB to be considered viable, some of these gaps will need to be adequately resolved and are here termed the “must haves” for an MCB research program. This research will need to reduce uncertainties in each topic, and in parallel, to ensure that uncertainties are individually and collectively sufficiently small to proceed. The accepted level of uncertainty will likely be conditioned on the specific goals of an MCB effort. For a global MCB effort, tolerable uncertainty might be commensurate with targeted global temperature reductions, and with acceptable regional perturbations in temperature and precipitation and low risk of causing extreme events. Regional MCB uncertainties might be focused on improving the state of a vulnerable ecosystem, such as a coral reef, and accompanied by different uncertainty criteria.

3.3.1 Laboratory experiments and field experiments

3.3.1.1 Laboratory work

To fill in gaps in aerosol and cloud microphysical process understanding, laboratory work will be of value. Models, particularly fine-scale models such as parcel models and LES, will benefit from improvements in understanding of activation, droplet growth, entrainment, cloud processing of aerosol, onset of collision-coalescence, and the role of GCCN in a turbulent environment. The physical rates describing these processes would be revisited as necessary. Few laboratory facilities capable of addressing all of these processes exist at this time. An envisioned cloud chamber facility called the Aerosol-Cloud-Drizzle Convection Chamber (ACDC2) is currently under design for possible future implementation. It is larger than the existing convection-cloud chamber at Michigan Technological University (Chang et al. 2016) and it will enhance turbulence kinetic energy and generate longer droplet lifetimes. This will enable the investigation of the range of liquid cloud processes that are relevant to MCB: activation, droplet growth by condensation, and, importantly, the initiation of collision-coalescence in a turbulent medium, as well as the coupling of these processes to the aerosol (Shaw et al. 2020).

3.3.1.2 MCB analogues and perturbation experiments

Natural and anthropogenic analogues to MCB experiments have been of great value for providing bounds on the radiative effect of aerosol-cloud interactions. These include studies of effusive volcanoes (Malavelle et al. 2019), ship tracks (Conover 1966; Ackerman 2000; Durkee et al. 2000), urban tracks (Toll et al. 2019), and other perturbations of opportunity that minimize confounding meteorological effects (Christensen et al. 2022). Continued study of such events provides further opportunity for MCB-related study.

A number of uncertainties that are not addressed by analogues could be addressed by a perturbation-oriented field experiment that would test various components of MCB at scales on the order of 10s of kms. Such an experiment, if attempted, might comprise a number of important components identified as gaps in Section 3.1:

a) *Use of fit-for-purpose sea spraying technology from an ocean-based platform*. As noted in Section 3.1.1, the size distribution of injected particles will likely need to be optimized to avoid excessive evaporation of cloud water and/or precipitation. A perturbation experiment would provide opportunity to test the ability of nozzles to produce droplets of desired size in the marine environment.

b) *Assessment of vertical mixing in a variety of conditions.* An experiment would ascertain the degree to which these generated droplets would reach cloud base in a variety of conditions. A field experiment applying proposed real-world injection rates over extended periods and in different atmospheric conditions would provide an evaluation of whether evaporation of droplets in the lowest ~ 100 m might adversely influence the atmospheric mixing state and inhibit vertical transport.

c) *Measure essential components of the cloud system.* Aircraft (including drones and other unmanned systems), ground-based distributed remote sensing measurements, and satellite-based measurements would need to measure the microphysical properties of the perturbed clouds, as well as adjacent unperturbed clouds. Stacked aircraft and UASs (Corrigan et al. 2008, Sorooshian et al. 2019) could take advantage of recent instrument advances (Sanchez et al. 2017). The perturbed and unperturbed clouds tracked and observed for several hours will also help assess the local cloud adjustments primarily due to aerosol particles.

d) *Aerosol and microphysics closure.* Closure studies that compare observed drop concentrations to drop concentrations calculated based on measurements of aerosol-size distribution and composition in concert with updraft velocities are an essential component of establishing confidence in our knowledge of the fundamentals of aerosol activation (e.g., VanReken et al. 2003; Sanchez et al. 2016).

e) *Microphysics and radiation closure.* Closure studies that assess the degree to which aerosol and cloud microphysical properties produce similar calculated radiative properties to radiative properties measured directly by ground-based or space-borne sensors (e.g., Quinn et al. 1998; Sanchez et al. 2017) are also needed. Closure represents a rigorous test of our understanding of how the details of aerosol-cloud systems project onto the most relevant integrated measure of the system, namely changes in upward shortwave flux. These studies will also characterize the parameter space for identifying an MCB signal during different cloud and meteorological conditions.

f) *Model evaluation.* Detailed modeling of the cloud system in the control and target regions should accompany the experiment and help assess microphysical responses, cloud fraction and liquid water adjustments, and radiative responses. Simulating the observed changes in the perturbed and un-perturbed clouds by a range of models differing in resolution and physical representation of cloud properties is ideal.

g) *Statistical sampling and analysis.* Atmospheric observations need to sample a realistic range of conditions in order for them to be considered representative for modeling exercises. This requires significant resources, particularly in the case of aircraft measurements.

3.3.1.3 Marine ecosystem studies

An MCB program will generate large concentrations of salt droplets and a haze that might exist for extended periods of time. If it works as planned, MCB will also reflect more sunlight and therefore change the amount of shortwave radiation reaching the surface. The ratio of direct-to-diffuse radiation will likely be affected, with unknown consequences for marine biota production. A research program therefore should investigate:

1. Potential impacts of changes in incoming shortwave radiation on Marine Boundary Layer (MBL) halogen cycle, ozone, and marine biogeochemical cycles (Horowitz et al. 2020);
2. Implications for marine species, coastal vegetation, and human populations living in the seeding-affected zones.

Although the ecological impacts of MCB were outside the expertise of the workshop participants, the general consensus was that they should be characterized satisfactorily prior to embarking on MCB.

3.3.2 The Scale-Up

3.3.2.1 Aerosol-meteorological co-variability

A successful MCB program needs to answer the question of whether local cloud brightening will scale sufficiently to provide a globally relevant impact. Warm marine boundary layer stratocumulus clouds that blanket vast areas of eastern subtropical oceans are considered ideal candidates for MCB. However, the stratocumulus cloud decks exhibit distinct seasonal and diurnal cycles (Klein and Hartmann, 1993; Eastman and Warren, 2014) associated with changes in regional meteorology and covarying aerosol conditions that will affect their susceptibility to aerosol injections. Assessing the scalability of MCB requires a solid understanding of aerosol-meteorological co-variability and will rely heavily on meteorological reanalysis and satellite-based measurements of cloud macro- and microscale properties. Taking into account geographical location, time of day, and season, workshop participants concur it is necessary to assess:

a) *The robustness of susceptibility metrics in target areas, and the potential for brightening.* Do susceptible conditions occur frequently enough and over large enough areas to generate cooling of sufficient magnitude? How many of the world's stratocumulus decks would represent targets? Do these target areas behave similarly in terms of their ability to generate cooling if perturbed?

b) *Predictability of liquid water and cloud fraction adjustments and their timescales.* Aerosol perturbations brighten clouds within 10 minutes of particles entering the cloud, but the clouds then adjust to these perturbations with a much longer timescale. The result may be an offsetting or an enhancement of the original perturbation. Quantifying these timescales is key.

c) Amounts (mass of material), size distribution, durations, and intervals for maximum impact of seeding. Very little research exists on the topic of matching seeding amount/strategy to expected cooling.

3.3.2.2 Modeling at a range of scales

As noted throughout this report, modeling at a large range of scales and focused on different research objectives will play a number of important roles in any MCB research program. The following are "must have" modeling needs:

a) *Routine LES modeling of a broad range of real case studies at the mesoscale (unperturbed and perturbed).* By routine, workshop participants refer to multi-day simulations (order 30 per season, per location) with varying boundary conditions. Routine soundings and other atmospheric measurements provide data that will allow for testing of cloud-scale models on a routine basis as in the DOE/ARM/ASR Large-Eddy Simulation Atmospheric Radiation Measurement Symbiotic Simulation and Observation (LASSO) project (Gustafson et al. 2020). Past experiments should be mined to extend the range of conditions. Initializing LES models with observed initial and boundary conditions (e.g., soundings, surface fluxes etc.) and then confronting the simulated cloud fields with observations for a range of commonly occurring meteorological conditions will improve confidence in the ability of LES models to capture the key cloud fields. Following protocols developed in the LASSO project, ensembles of LES would be run to account for uncertain initial conditions and boundary conditions, and to assess the extent to which uncertainty in meteorology influences detectability. Multi-model ensembles would further establish robustness. In contrast to the LASSO project, which took place in a continental setting, the marine boundary layer environment suffers from a relative dearth of surface in-situ and remote sensing measurements, which will require heavier reliance on reanalysis, ship-based soundings (which requires resources), and satellite retrievals of cloud microphysics, fraction, and radiative fluxes. The data collected during the ARM Eastern North Atlantic (ENA) site located in the Azores, and during previous ship-borne field campaigns (e.g., MAGIC) could provide the initial and boundary conditions necessary for the routine LES modeling.

b) *GCM simulations to assess idealized regional responses to perturbations.* In the tradition of GeoMIP climate model intercomparison exercises, efforts to establish inter-model consistency associated with a variety of seeding scenarios will be valuable. Assessment of regional responses in terms of 'winners' and 'losers' – with respect to variables such as temperature, precipitation, water availability, crop-yields, etc. – are of particular interest. Parallel MIPs of the ‘warming world without MCB intervention’ would provide valuable context.

c) *MIPs at a range of scales.* Expanding the range of MIPs would further help to resolve the provenance of model differences. Models employing refined meshes or multi-modeling frameworks over areas of interest would help to resolve the aerosol-cloud-dynamical processes in the target regions.

3.3.3 Improved detection

Any MCB program will need systems in place to detect the degree of cloud brightening from space- and ground-based sensors. A small number of studies have indicated that perturbations at scales on the order of 10s km in shipping lanes would require five to ten years to detect with existing satellite-based systems (Diamond et al. 2020). Speeding up this process is crucial to determine whether MCB is working as intended, or whether it might need to be modified to achieve different goals. Approaches include:

a) *Refined algorithms or instruments* for retrieving important geophysical variables from space, particularly from geostationary platforms, and leveraging the advantages of polar-orbiting and geostationary satellite measurements. Commensurate with cloud brightening detected by space-borne sensors, a decrease in downwelling solar radiation (darkening) could be identified by ground-based sensors (Wild et al. 2007; Michalsky and Long, 2016; Shupe et al. 2016).

b) *Undetected tracks.* Assessment of their contribution might be done indirectly, i.e., by tracking the particle source over the duration of the perturbation rather than searching for a weak signal in a noisy background. Such an effort might also help to identify the causes of the invisible tracks.

c) *Other detection methods,* such as a passive tracer together with the seeding agent, unique pattern of dispersal, frequency/intensity of dispersal, and knowledge of the salt track location over time might also improve detectability.

4. Closing Remarks

MCB is one of the primary proposed Solar Radiation Management approaches to enhance reflectance of incoming solar radiation to space by seeding marine boundary layer clouds, thereby cooling the planet, and potentially buying time for decarbonization to take effect. A three-day workshop sponsored by DOE/ASR and NOAA took place in April 2022 to assess the state of knowledge in the field of MCB and to provide a possible research path toward reducing unknowns in key components of the physical science. The 30 invited scientists, program managers, and representatives from other agencies brought to the discussions deep knowledge of aerosol-cloud physics, turbulence, radiation, chemistry, and large-scale dynamics. Their skillset ranged from in-situ measurements, modeling at a range of scales, laboratory studies, field campaigns, and satellite and surface-based remote sensing.

Participants spent the majority of time in breakout sessions addressing four Guiding Questions:

Question 1: What do we know and what are the main knowledge gaps?

Question 2: What are novel ways to address gaps?

Question 3: What are the biggest challenges?

Question 4: What are the ‘must haves’ for an MCB research program?

The group identified knowledge gaps at a range of spatial and temporal scales on topics including aerosol and cloud microphysics, local and large-scale scale adjustments, aerosol-meteorology co-variability, and detection of perturbations and their radiative effect. Possible practical ways to close these gaps covered continued study of natural analogues (e.g., effusive volcanoes, ship-tracks), focused field campaigns with controlled perturbations, routine modeling of aerosol-cloud systems at the large eddy scale, modeling intercomparison efforts, and analysis of existing observations and output from reanalysis models. Many of the knowledge gaps exist in areas of study already familiar to the broader field of climate forcing by aerosol-cloud interactions, and the path forward is clearer. Some, like particle generation and delivery to the cloud, include more specific but seemingly manageable MCB challenges. One theme stands out as particularly challenging: the influence of local/regional MCB on global circulation patterns. Changes in these circulation patterns have the potential to create regions of the world that benefit from MCB, and others that might suffer, raising the issue of equity in climate intervention strategies. Regional changes in temperature and rainfall could influence heat stress, water availability, crop productivity, and the ability of communities to thrive. Incorporating such regional responses in global climate models requires a comprehensive and coordinated effort of multiscale modeling, with appropriate constraints from laboratory measurements and field observations as part of an iterative and integrated research process (Figure 2). An understanding of these large-scale manifestations of MCB requires modeling tools that do not currently exist, and models should be able to provide reliable projections of shifts in circulation patterns before an active MCB program is undertaken.

Finally, the workshop focused its efforts on the physical science challenges of MCB. While the broader social, ethical, ecological, and governance aspects of the problem were not directly discussed – primarily because the group lacked expertise in these fields – these issues were on the minds of many participants and informed the discussions indirectly. Clearly a successful MCB intervention must take this broad view of the problem as outlined in the NASEM Report (2021).

4.1 Agency and Interagency Program Perspectives

Both DOE/ASR and NOAA have multi-decade programs in the atmospheric sciences covering topics as far-ranging as radiation, tropospheric and stratospheric aerosol, clouds, precipitation, oceans, and land use. Both institutions engage in and support fundamental and applied research in these topics toward improving the understanding of, and enhancing the stewardship of, Earth’s natural systems. The body of knowledge acquired by these programs provides a solid base for investigating the science underpinning climate intervention approaches and, in the current case, marine cloud brightening.

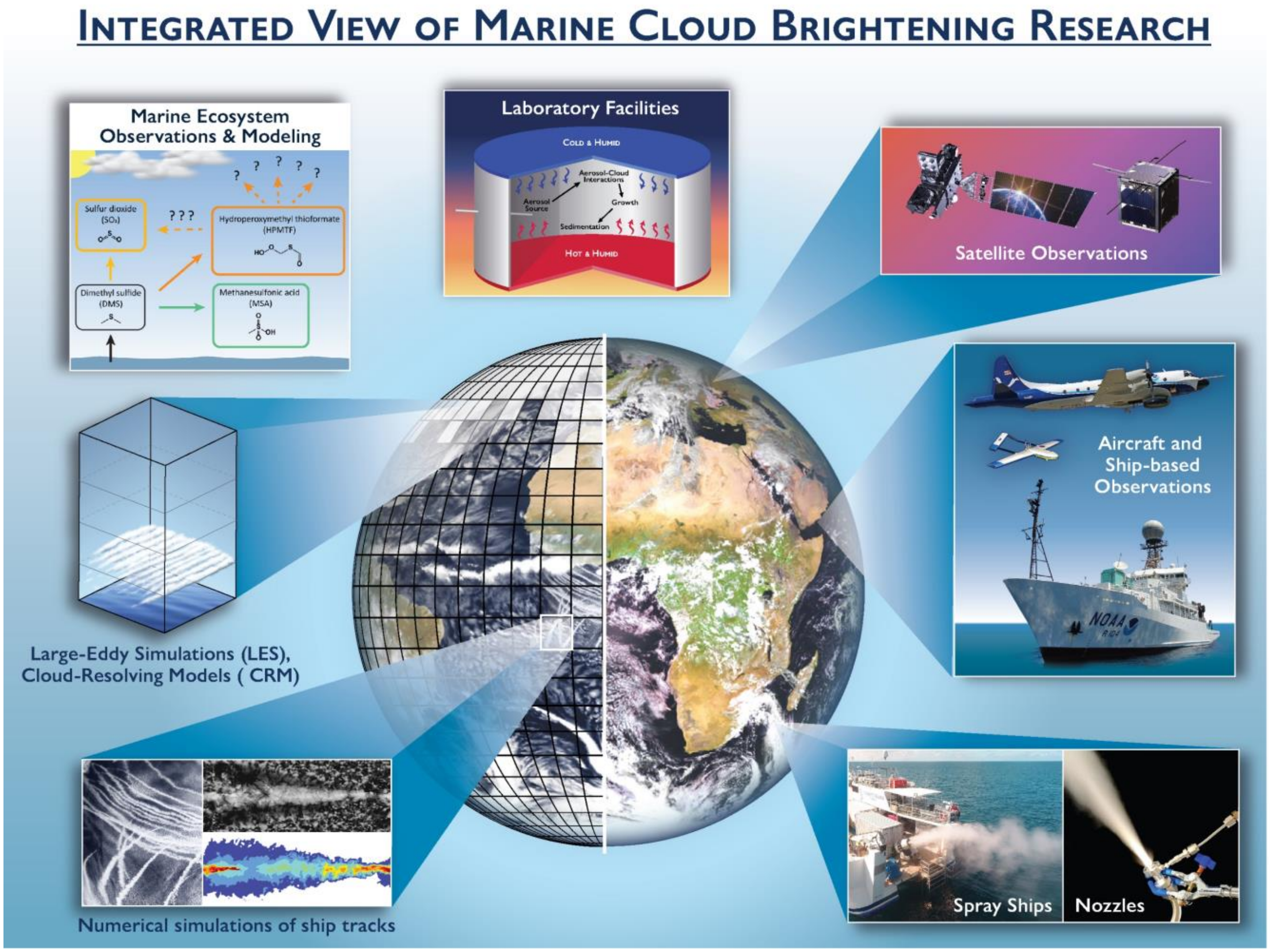

Figure 2: Illustration of an integrated approach to an MCB research program comprising laboratory facilities, field experiments, and modeling. Earth view image is courtesy of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), with modifications to highlight ship tracks and model mesh. (Figure prepared by Chelsea Thompson, NOAA/Chemical Sciences Laboratory.)

4.1.1 NOAA's Earth's Radiation Budget

Congressional appropriations in 2022 provided NOAA no less than the fiscal year 2021-enacted level for continued modeling, assessments, and as possible, initial observations and monitoring of stratospheric conditions and the Earth's radiation budget, including the impact of the introduction of material into the stratosphere from changes in natural systems, increased air and space traffic, and the assessment of solar climate interventions. NOAA was encouraged to develop an interagency program, in coordination with the Office of Science and Technology Policy (OSTP) and other relevant agencies, to manage near-term climate hazard risk and coordinate research in climate intervention and to coordinate with NASA for long- range manned and autonomous in-situ atmospheric observational capabilities. NOAA was also directed, in coordination with NASA and DOE, as appropriate, to improve the understanding of the impact of atmospheric aerosols on radiative forcing, as well as on the formation of clouds, precipitation, and extreme weather.

NOAA was directed to support OSTP, in coordination with DOE and NSF, to provide a five-year plan to Congress with a scientific assessment of solar and other rapid climate interventions in the context of near-term climate risks and hazards. At the time of this workshop report, the OSTP report is in development and should include: (1) the definition of goals in relevant areas of scientific research; (2) capabilities required to model, analyze, observe, and monitor atmospheric composition; (3) climate impacts and the Earth's radiation budget; and (4) the coordination of Federal research and investments to deliver this assessment to manage near-term climate risk and research in climate intervention.

4.1.2 DOE's Biological and Environmental Research

The DOE has received multi-year appropriations from Congress to advance the atmospheric and climate sciences. As part of Congressional direction, DOE focuses its Atmospheric System Research (ASR) portfolio on the physical processes governing cloud-aerosol interactions in the context of the Earth's radiation balance and Earth system predictability. DOE atmospheric sciences also takes advantage of the observations provided by the six observatories of the Atmospheric Radiation Measurement (ARM) User Facility. As a general rule, the ASR program and ARM User Facility are tightly coordinated. More recently, Congress has directed DOE to expand its investments in cloud-aerosol science to take advantage of computational assets unique to DOE, as a means to more rapidly extend our understanding of cloud physics under more perturbed conditions. DOE anticipates that DOE's science and facility investments will increasingly coordinate with other agencies who have similar and complementary interests.

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Appendix A – Abbreviations and Acronyms

ACDC2	Aerosol-Cloud-Drizzle-Convection Chamber
ACTIVATE	Aerosol Cloud meTeorology Interactions oVer the western Atlantic Experiment
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
ATOMIC	Atlantic Tradewind Ocean–Atmosphere Mesoscale Interaction Campaign
CCN	Cloud Condensation Nuclei
CDR	Carbon Dioxide Removal
CI	Climate Intervention
CRM	Cloud Resolving Model
DNS	Direct Numerical Simulation
DOE	Department of Energy
DYCOMS-II	Second Dynamics and Chemistry of Marine Stratocumulus field study
EPEACE	Eastern Pacific Emitted Aerosol Cloud Experiment
EUREC4A	Elucidating the role of clouds-circulation coupling in climate
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FIRE-I	First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment
GCCN	Giant Cloud Condensation Nuclei
GCM	General Circulation Model
LASSO	Large-Eddy Simulation Atmospheric Radiation Measurement Symbiotic Simulation and Observation
LES	Large Eddy Simulation
LWP	Liquid Water Path
MAGIC	Marine ARM (Atmospheric Radiation Measurement) GPCI (GCSS [GEWEX {Global Energy and Water Cycle Experiment, a core project of the World Climate Research Programme} Cloud Systems Study] Pacific Cross-section Intercomparison) Investigation of Clouds
MASE	Marine Stratus/Stratocumulus Experiment
MAST	Monterey Area Ship Track study
MCB	Marine Cloud Brightening
MODIS	Moderate Resolution Imaging Spectroradiometer
MMF	Multiscale Modeling Framework
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Science, Engineering, and Medicine
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
OAR	Oceanic and Atmospheric Research
OSTP	Office of Science and Technology Policy
SAI	Stratospheric Aerosol Injection
SG	Solar Geoengineering
SRM	Solar Radiation Management
UAS	Unmanned Aerial System
VOCALS	VAMOS (Variability of the American Monsoon Systems) Ocean-Cloud-Atmosphere-Land Study

Appendix B – Workshop Agenda

Start Time: 06:30 PT/07:30 MT/9:30 ET/15:30 CET
Meeting Platform: Gather
End Time: 10:00 PT/11:00 MT/13:00 ET/19:00 CET
Social Hour: Starting immediately after the conclusion of the meeting.

Day 1 (9:30 ET to 13:00 ET + social hour)	
9:30 – 10:45	Introduction/Goals/Guiding Principles: Welcome and introductions: 15 minutes Dr. Gary Geernaert, Director, Earth and Environmental Systems Sciences Division, DOE/BER Dr. David Fahey, Director, NOAA Chemical Sciences Laboratory Dr. Gregory Frost, Program Manager, NOAA Earth's Radiation Budget Initiative Summary from small-scale white papers: 15+5 minutes Allison McComiskey Summary from cloud-scale white papers: 15+5 minutes Robert Wood Summary from regional/global scale white papers: 15+5 minutes Andrew Gettelman Questions etc.
10:45 – 10:55	Break
10:55 – 12:25	Breakout 1: Discuss Issue/Question 1 (Groups for all breakouts are listed below)
12:25 – 12:30	Break
12:30 – 13:00	Wrap-up Day 1: Summary and questions/concerns for Issue 1. Report back from note-takers and discussion leads
13:00 – 13:30	Social Hour: Informal Discussions

Day 2 (9:30 ET to 13:00 ET + social hour)	
9:30 – 9:40	Welcome: Things learned from yesterday Grouping changes, suggestions for yesterday's discussions etc.
9:40 – 11:10	Breakout 2: Discuss Issue/Question 2 in a mixed format (Groupings are listed below)
11:10 – 11:20	Break
11:20 – 12:50	Breakout 3: Discuss Issue/Question 3 in a mixed format (Groupings are listed below)
12:50 – 13:00	Wrap-up Day 2: Summary and questions/concerns of Issue 2 and 3. Report back from note-takers and discussion leads
13:00 – 13:30	Social Hour: Informal Discussions

Day 3 (9:30 ET to 13:00 ET + social hour)	
9:30 – 10:00	Welcome: Things learned from yesterday Grouping changes, suggestions for yesterday's discussions, additions for notes, etc.
10:00 – 11:30	Breakout 4: Discuss Issue/Question 4 (original G1, G2, G3 groups). Rapporteurs/Group Leads from the 3 groups present key bullets/ideas on each of the 4 issues/questions and proposed roadmaps
11:30 – 11:40	Break
11:40 – 12:40	Open discussion on Issue #4: Rankings of the bullet points
12:40 – 13:00	Wrap-up: Discussion of proposed research roadmaps/approaches Writing commitments Timetable for writing
13:00 – 13:30	Social Hour: Informal Discussions

Appendix C – Workshop Participants

Name	Affiliation	Role
Shaima Nasiri	DOE	co-organizer
Greg Frost	NOAA	co-organizer
Virendra Ghate	ANL	co-chair
Lynn Russell	Scripps Inst. Of Oceanography	co-chair
Graham Feingold	NOAA/CSL	co-chair
Hal Maring	NASA HQ	attendee/observer
Anne Johansen	NSF	attendee/observer
Victoria Breeze	NOAA	co-organizer
Fabian Hoffmann	LMU	attendee
Allison McComiskey	BNL	attendee
Xue Zheng	LLNL	attendee
Raymond Shaw	Michigan Tech. Univ.	attendee
Matt Christensen	PNNL	attendee
Colleen Kaul	PNNL	attendee
Rob Wood	Univ. of Washington	attendee
Michael Diamond	NOAA/CSL	attendee
Jianhao Zhang	NOAA/CSL	attendee
Prasanth Prabhakaran	NOAA/CSL	attendee
Yi Ming	NOAA/GFDL	attendee
Andrew Gettelman	NCAR	attendee
Armin Sorooshian	Univ. of Arizona	attendee
Sebastian Schmidt	Univ. of Colorado	attendee
Ed Gryspeerdt	Imperial College	attendee
Franziska Glassmeier	TU-Delft	attendee
Matt Lebsock	NASA/JPL	attendee
Johannes Muelmenstaedt	PNNL	attendee
Will Cantrell	Michigan Tech. Univ.	attendee
Peter Blossey	Univ. of Washington	attendee
Velle Toll	Tartu	attendee
Daniel McCoy	U. of Wyoming	attendee
Fan Yang	BNL	attendee
Anna Possner	U. of Frankfurt	attendee
Trish Quinn	NOAA/PMEL	attendee
Jim Haywood	U. of Exeter	attendee
Jessica Wan	Scripps Institute of Oceanography	attendee
Clare Singer	California Inst. Tech.	attendee

Appendix D – Breakout Configurations

Breakout 1 and 4 Group listings

Group 1	Group 2	Group 3
Discussion Leads: Allison McComiskey, Raymond Shaw **Rapporteurs:** Prasanth Prabhakaran, Fan Yang	**Discussion Leads:** Matt Christensen, Franziska Glassmeier **Rapporteurs:** Clare Singer, Matt Lebsock	**Discussion Leads:** Michael Diamond, Andrew Gettelman **Rapporteurs:** Jessica Wan, Jianhao Zhang
Fabian Hoffmann Allison McComiskey Raymond Shaw Colleen Kaul Rob Wood Prasanth Prabhakaran Armin Sorooshian Will Cantrell Fan Yang Trish Quinn Lynn Russell	Matt Christensen Sebastian Schmidt Ed Gryspeerdt Franziska Glassmeier Matt Lebsock Peter Blossey Velle Toll Anna Possner Claire Singer Virendra Ghate	Xue Zheng Michael Diamond Jianhao Zhang Yi Ming Andrew Gettelman Johannes Muelmenstaedt Daniel McCoy Jim Haywood Jessica Wan Graham Feingold

Breakout 2 Group listings

Group 1	Group 2	Group 3
Discussion Leads: Ed Gryspeerdt, Sebastian Schmidt **Rapporteurs:** Coleen Kaul, Fabian Hoffman	**Discussion Leads:** Yi Ming, Trish Quinn **Rapporteurs:** Will Cantrel, Xue Zheng	**Discussion Leads:** Anna Possner, Johannes Muelmenstaedt **Rapporteurs:** Daniel McCoy, Jessica Wan
Fabian Hoffmann Allison McComiskey Raymond Shaw Colleen Kaul Rob Wood Matt Christensen Sebastian Schmidt Ed Gryspeerdt Franziska Glassmeier Lynn Russell	Prasanth Prabhakaran Armin Sorooshian Will Cantrell Fan Yang Trish Quinn Xue Zheng Michael Diamond Jianhao Zhang Yi Ming Virendra Ghate	Matt Lebsock Velle Toll Anna Possner Clare Singer Andrew Gettelman Johannes Muelmenstaedt Daniel McCoy Jim Haywood Jessica Wan Graham Feingold

Breakout 3 Group listings

Group 1	Group 2	Group 3
Discussion Leads: Fabian Hoffman, Velle Toll **Rapporteurs:** Clare Singer, Raymond Shaw	**Discussion Leads:** Armin Sorooshian, Jim Haywood **Rapporteurs:** Jessica Wan, Prasanth Prabhakaran	**Discussion Leads:** Rob Wood, Michael Diamond **Rapporteurs:** Ed Gryspeerdt, Jianhao Zhang
Fabian Hoffmann Allison McComiskey Raymond Shaw Colleen Kaul Rob Wood Matt Lebsock Velle Toll Anna Possner Clare Singer Lynn Russell	Prasanth Prabhakaran Armin Sorooshian Will Cantrell Fan Yang Trish Quinn Andrew Gettelman Johannes Muelmenstaedt Daniel McCoy Jim Haywood Jessica Wan Virendra Ghate	Matt Christensen Sebastian Schmidt Ed Gryspeerdt Franziska Glassmeier Xue Zheng Michael Diamond Jianhao Zhang Yi Ming Rob Wood Graham Feingold