Cloud and Sky Brightening Development (CS-06)

Final Report June 2025

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RRAP Cloud and Sky Brightening Development (CS-06) Final Report June 2025

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Location	**Traditional Owner Group**
Heron Island, One Tree Island and Gladstone	PCCC TUMRA, Gidarjil
Whitsundays	Ngaro
Broadhurst Reef and Davis Reef	Bindal and Manbarra

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1 Executive Summary

The Great Barrier Reef (GBR) is experiencing escalating stress from anthropogenic climate change, with increasing sea surface temperatures driving repeated mass coral bleaching events. Marine heatwaves, exacerbated by clear-sky conditions and high solar irradiance, pose an existential threat to coral reef ecosystems including on the GBR. The Reef Restoration and Adaptation Program (RRAP) Cooling and Shading Sub-program, Project Cloud and Sky Brightening Development (CS-06) aims to assess the feasibility of Marine Cloud Brightening (MCB) and Marine Sky Brightening (MSB) as interventions to reduce solar radiation and mitigate bleaching stress. This report summarises progress from 2020 to 2025, encompassing development of nozzle technology, engineering for field deployable seawater atomisation systems, and the world's first outdoor MCB experimentation to investigate aerosol-cloud-radiation interactions with respect to MCB.

The project sought to progress the technical understanding of MCB across four areas of research and development:

1. Engineering development: Establish and optimise seawater atomisation nozzles capable of generating submicron sea salt aerosols in sufficient quantities suitable for cloud condensation nuclei (CCN).
2. Systems integration and scaling: Iteratively upscale prototype spray systems to increase particle flux, enable outdoor research and advance the technology towards operational feasibility.
3. Aerosol and plume characterisation: Quantify plume dispersion, vertical transport, characterise the artificial sea spray aerosol and cloud microphysical responses to controlled sea spray injections over the GBR.
4. Model and data integration: Combine empirical *in situ* collected field data with computational and both surface and satellite remote sensing analyses to document aerosol-cloud interactions and compare these with numerical modelling on the scale of the experiment.

A dedicated nozzle testing facility was constructed at Southern Cross University (SCU) along with a temporary sister facility at the University of Cambridge. The nozzle laboratories enabled systematic assessment of a range of potential seawater atomisation technologies, including effervescent nozzles, electrospray technologies, superheated systems, Rayleigh jet arrays, and acoustic nozzles. Effervescent nozzles have continued to be the highest performing and most mature technology, capable of producing particle fluxes in the order of 10^{13} s^{-1} per nozzle with a large fraction of particles in the desired 30 - 800 nm dry diameter range. Alternative technologies tested show promise of creating more monodisperse sprays at lower energy requirements, but with orders of magnitude lower number production rates. These more monodisperse technologies face scale up challenges to develop systems that consist of millions or billions of individual nozzles that can operate robustly at sea. Computational Fluid Dynamics (CFD), including the novel *evdFoam* solver, provided new insights into internal flow regimes and droplet breakup dynamics providing valuable insights for potential further improvement of the effervescent spray technique in terms of energy efficiency, size distribution and upscaling to higher total production rates.

Iterative development of the Aerosol Radiation and their Interactions Experimental Laboratory (ARIEL) seawater atomisation system over the course of the project increased the output, robustness, and refined the standard operating procedures. Progressive, modular engineering upgrades increased the total sea spray flux generated by an order of magnitude. The current prototype produces ~10^{15} s^{-1} sea salt aerosols using 320 kilowatts (kW) of energy. Further innovation is required to achieve implementation scale production rates, currently estimated to be a target of around 10^{16} s^{-1}. The system has now been demonstrated over several hundred operating hours at sea and shown to be a reliable method of sea spray aerosol production. There remains considerable scope for improvements in energy efficiency and output of the system, which are a focus of ongoing research.

Between 2020 and 2025, five major MCB field campaigns were conducted with federal regulatory approval from the Great Barrier Reef Marine Park Authority (GBRMPA) at various locations within the Great Barrier Reef Marine Park (GBRMP). Initial trials demonstrated successful generation of submicron aerosols detectable over twelve kilometres (km) downwind and showed the aerosol size distribution to be like that measured under laboratory conditions. Subsequent campaigns progressively scaled output and integrated multi-platform sampling strategies as the scale and objectives of the experiments expanded. Measurements confirmed that evaporative cooling did not inhibit vertical plume rise as was previously speculated in the literature. Instead, plumes consistently reached cloud base heights (800 - 900 metres) under typical trade-wind and low-wind speed doldrum type atmospheric conditions. Coordinated observations using drones, surface-based Light Detection and Ranging sensors (LiDAR), vessel platforms and the instrumented SCU Cessna 337 aircraft yielded the first direct evidence that engineered sea spray aerosols could perturb cloud microphysics *in situ and* confirmed the underlying hypothesis of microphysical changes consistent with the Twomey effect. These datasets represent a world-first empirical validation of MCB principles, and strong evidence of the applicability of MCB over the Great Barrier Reef.

High-resolution plume dispersion simulations and Large Eddy Simulations (LES) validated field observations, confirming that wind speed and atmospheric stability are key drivers of plume behaviour. Satellite retrievals of cloud condensation nuclei (CCN), corroborated against *in situ* measurements, revealed background concentrations of 50 - 200 cm^{-3}, conditions conducive to effective MCB. Satellite-based retrievals of cloud microphysical properties during experiments also showed strong evidence for the Twomey effect downwind of the spraying source. Integrated model and observational approaches constrained the expected radiative forcing and informed site selection and deployment strategies, advancing predictive capability for regional interventions.

The RRAP Cloud and Sky Brightening Development Project (CS-06) represents a groundbreaking advancement in climate intervention research, delivering the first outdoor experimental validation of MCB and MSB technologies within a federally funded and regulated research program with broad social support for conducting the research. The findings demonstrate that engineered sea salt aerosols can be generated efficiently, transported to cloud base and perturb cloud microphysics under natural atmospheric conditions prevailing over the GBR during summertime. However, substantial uncertainties remain regarding scalability, the potential for unintended environmental impacts and how cloud microphysical processes beyond the Twomey effect will be impacted. Some cloud indirect effects could have radiative impacts both positive (enhanced cooling) or negative (a reduction in the total estimated amount of cooling). Ultimately, the impact to all these processes needs to be adequately understood to estimate the total net forcing for a given situation.

Future research should prioritise the refinement of nozzle and spray technologies to achieve higher output, improved spray droplet size distributions and reduced energy demand. Further field experimentation will be needed, both to expand the characterisation of MCB under diverse meteorological regimes and different sea spray size distributions and implementation scenarios. Larger and longer experiments will create a contiguous region of perturbed boundary layer aerosol to study the evolution of cloud micro and macro physical properties following the initial perturbation. Research is needed to evaluate the efficacy (benefits) and potential for unintended impacts (risks) of various deployment strategies. Along with improved ecological modelling to increase the confidence in the link between atmospheric interventions and long-term coral health outcomes as well as the apparently strong synergies between atmospheric interventions and other reef adaptation strategies and management approaches. There remains further work to be done on the development of governance frameworks in consultation with Traditional Owners, regulators and stakeholders with increased and wider ranging social engagement.

In conclusion, while MCB and MSB cannot substitute for urgent global emissions reductions, they may provide a viable regional, temporary intervention to reduce coral bleaching intensity during acute thermal stress events. These technologies have the distinct advantage of theoretically being implementable at a scale commensurate with the size of the ecosystem, while also being applicable at smaller regional scales. The RRAP Cloud and Sky Brightening Development Project (CS-06) has answered many critical initial questions around the viability of such interventions by experimentally confirming key underlying hypotheses and advancing the engineering know how and technological readiness levels to enable the commencement of outdoor *in situ* studies. Complex multi-institutional multi-platform outdoor field campaigns were conducted annually for the duration of the project to rapidly advance knowledge and experience. This report summaries at a high level the research undertaken to meet the key agreed objectives and provides preliminary results. The detailed analysis of the extensive observations collected and their dissemination in the peer-reviewed literature is ongoing.

2 Background and Justification for the Research

Coral reef ecosystems are globally significant biodiversity hotspots that support fisheries, coastal protection, tourism, and cultural heritage for millions of people (Moberg and Folke 1999). Despite their ecological and economic importance, coral reefs are among the ecosystems most vulnerable to climate change, particularly to warming oceans and marine heatwaves driven by anthropogenic greenhouse gas emissions (Hoegh-Guldberg 1999; Hoegh-Guldberg et al. 2007; Hughes et al. 2017a; Hughes et al. 2017b; Hughes et al. 2018). The Great Barrier Reef (GBR), the largest coral reef system on Earth, has already suffered repeated mass bleaching events in 1998, 2002, 2016, 2017, 2020, 2021, 2022, 2024, with escalating severity and increasing frequency (Hughes et al. 2017b; Hughes et al. 2019; Spady et al. 2025). Mass coral bleaching events on the GBR occur during extended periods of anomalously high sea water temperatures leading to the expulsion of symbiotic zooxanthellae and, if prolonged, large-scale coral mortality. Physiological stress is exacerbated during clear skies and elevated solar insolation (Ellis et al. 2024; Ellis et al. 2025), which occurs on the GBR during doldrum conditions (Richards et al. 2024). Model projections indicate that without significant intervention, severe bleaching may occur annually across much of the GBR by the mid-century (van Hooidonk et al. 2016).

The urgent threat posed by climate change to coral reefs has prompted exploration of interventions by the Reef Restoration and Adaptation Program (RRAP) to temporarily reduce heat stress on reefs, which may buy time for emissions reduction and ecological adaptation (Bay et al. 2019; Harrison et al. 2019; Harrison 2024). Among the proposed cooling and shading approaches, Marine Cloud Brightening (MCB) is a potential solar radiation management (SRM) technique to regionally reduce incoming solar shortwave radiation and thus cool surface waters while also reducing light intensity (Harrison 2018). The concept relies on the atomisation of seawater to produce submicron sea salt aerosols, which act as cloud condensation nuclei (CCN), increasing droplet number concentrations in low-level marine clouds (Latham 1990; Latham et al. 2012). This process enhances cloud reflectivity, a phenomenon known as the Twomey effect (Twomey 1974) and can, under suitable conditions, also extend cloud lifetime, cloud fraction and reduce precipitation efficiency (Albrecht 1989). The sea spray aerosols also scatter sunlight, a shading effect which could under certain circumstances provide as much shading as the perturbation to cloud optical properties (Ahlm et al. 2017). Targeting this direct atmospheric aerosol scattering effect rather than clouds is sometimes referred to as Marine Sky Brightening (MSB) and may also be applicable over the GBR (Harrison et al. 2019; Harrison 2024).

The scientific basis for MCB and MSB is rooted in decades of research into aerosol-cloud-radiation interactions. Observations of ‘ship tracks’, lines ofcloud formed by aerosol emissions from ships and observed by satellite provided early analogues for MCB. Satellite and field studies revealed that enhanced CCN concentrations in ship exhaust plumes can increase cloud droplet numbers, reduce droplet size, and brighten clouds (Durkee et al. 2000; Possner et al. 2018). Improved microphysical understanding of aerosol activation and cloud dynamics has led to increasing recognition of the inadvertent brightening impact anthropogenic aerosol emissions have had on clouds and the degree to which this forcing has offset global warming from greenhouse gasses (IPCC 2007, 2014; Chen et al. 2024). A recently mandated reduction in oceangoing ship fuel sulfur content has led to substantially reduced global cooling that was present from inadvertent MCB. This regulatory action has been linked to the recent spike in global temperatures and accelerating climate change (Quaglia and Visioni 2024; Yoshioka et al. 2024; Yuan et al. 2024), and to exacerbating bleaching stress on the GBR (Ryan et al. 2025). It is now well established that increased aerosol concentrations lead to higher concentrations of CCN, overall net increase to cloud albedo, and reduced shortwave solar radiation reaching the earth’s surface.

Latham (1990) first proposed the deliberate introduction of additional CCN produced from seawater to modulate cloud albedo for the purpose of further offsetting planetary warming due to greenhouse gas emissions. Theoretical and modelling studies in the early 2000s explored the potential of MCB as a climate intervention to cool the earth. Model simulations have examined its possible influence on sea ice, rainfall patterns, and regional climate variability, highlighting both potential benefits and risks (Rasch et al. 2009).

Modelling studies suggested that MCB could, if deployed judiciously to large regions of the most sensitive marine clouds, reduce coral bleaching risk by cooling tropical reef waters (Latham et al. 2013; Latham et al. 2014). Although, these proposed applications were termed 'regional' and the application areas considered covered major portions of entire ocean basins and were still of a scale to impact global weather and climate processes, thus have been considered a form of 'geoengineering' (Shepherd et al. 2009). Modelling studies of MCB have underscored the uncertainties in scaling up, from process-level understanding to climate-relevant outcomes, and highlighted the importance of natural meteorological variability, background aerosol characteristics, and cloud regime properties in determining MCB effectiveness (Alterskjær et al. 2012; Latham et al. 2012; Wood and Ackerman 2013; Goren and Rosenfeld 2014; Wood 2021).

Compared with modelling efforts, there has been a paucity of laboratory research and engineering investigations to assess the feasibility of generating aerosols in the required size range and quantity for MCB and how MCB could feasibly be implemented. Submicron sea salt aerosols of greater than 30 nanometre (nm) diameter are considered desirable for CCN activation without overly promoting undesirable microphysical responses such as drizzle enhancement or cloud thinning (Connolly et al. 2014; Wood 2021). Effervescent nozzles, which mix pressurised air and seawater, emerged as a promising technology for producing large numbers of particles with appropriate size distributions (Cooper et al. 2014). Alternative approaches such as electrospray atomisation and super critical seawater were also explored, with theoretical potential to improve energy efficiency or achieve more monodisperse particle populations (Cooper et al. 2013; Neukermans et al. 2014). The early proponents of MCB envisioned deployment using a fleet of wind powered vessels with billions of nozzles of very small orifice size (400 nm) spraying in the Rayleigh jet mode (Salter et al. 2008; Latham et al. 2012; Salter et al. 2014). However, this work was entirely theoretical, subsequent studies were unable to maintain nozzles of this fine size without clogging (Cooper et al. 2014). The proposed method of deployment, a novel bespoke vessel design remains entirely untested.

The suggestion by Harrison (2018) that MCB could be used intermittently during marine heatwaves at the regional scale of the GBR (<0.1% of the earth's surface) represents an implementation orders of magnitude reduced in scale from those considered previously. Although the underlying technological concept is the same, the significant difference in the nature and intent of the intervention raises both opportunities and challenges compared with previously proposed scenarios of MCB implementation. The localised and intermittent nature of the application lead to an inherently different environmental risk profile than continuous intervention at a scale intended to alter global climate. The activity could be undertaken entirely within the exclusive economic zone (EEZ) of Australia, and the maritime logistics of deployment in a coastal region with generally low wave energy are favourable compared with the remote open ocean. The Great Barrier Reef Marine Park (GBRMP) is a federally managed marine conservation area leading to simpler regulatory and governance considerations. Conversely, obtaining sufficient radiative forcing over a smaller area is more challenging and although the clouds over the GBR are expected to be sensitive to MCB (Anthony et al. 2019; Harrison 2024; Zhao et al. 2024), there is only low occurrence of marine stratocumulus clouds (Zhao et al. 2022) which are widely considered to offer the highest potential radiative forcing from MCB (Latham 1990).

Despite the considerable amount of theoretical research on MCB over the last 35 years, the uncertainties around MCB feasibility, efficacy and risk remain substantial, in part due to the absence of any previous outdoor experimentation directly evaluating the MCB concept (Diamond et al. 2022; Feingold et al. 2024). Key questions include the scalability, energy efficiency, and efficacy of spray technologies, the vertical transport of aerosols into cloud layers under diverse meteorological conditions, and the magnitude and consistency of cloud albedo responses. While ship-track observations demonstrate the feasibility of aerosol-induced cloud brightening, extrapolating from narrow anthropogenic plumes to controlled, large-area interventions remain a challenge (Wood and Ackerman 2013). Ecological and socio-political concerns, including potential unintended environmental effects such as on regional weather patterns, precipitation, and marine ecosystems are only just beginning to receive research attention.

The objective of the Reef Restoration and Adaptation Program Cooling and Shading Sub-program: Cloud and Sky Brightening Development Project (CS-06) was to conduct scientific research and engineering development to assess the technical feasibility and potential efficacy of Marine Cloud and Sky Brightening approaches for the mitigation of coral bleaching on the Great Barrier Reef. Governance, social license and engagement, ethics, and environmental risk of these potential interventions are equally important considerations which are addressed in other projects within the Reef Restoration and Adaptation Program. In this report we provide a brief overview of major findings and outcomes from the period 2020 - 2025 against objectives in the funding agreements. We direct the reader interested in further detail to the RRAP website: gbrrestoration.org.. We note that this work is ongoing and that the extensive datasets collected during the final two field campaigns in 2024 and 2025 are still undergoing quality assurance, post processing, and analysis by the many scientists and institutions involved. Further results will be published as they proceed through the scientific peer review process. An up-to-date list of publications is maintained on the RRAP website https://gbrrestoration.org/rrap-about-us/publications/.

Figure 1: Marine cloud brightening sprayer during operation.

3 Research Objectives and Key Findings

A current list of project outputs are listed on the RRAP website: gbrrestoration.org. Key research objectives and findings are detailed below.

Table 1: Key findings of the Project aligned to the overarching and specific research questions for each sub-project.

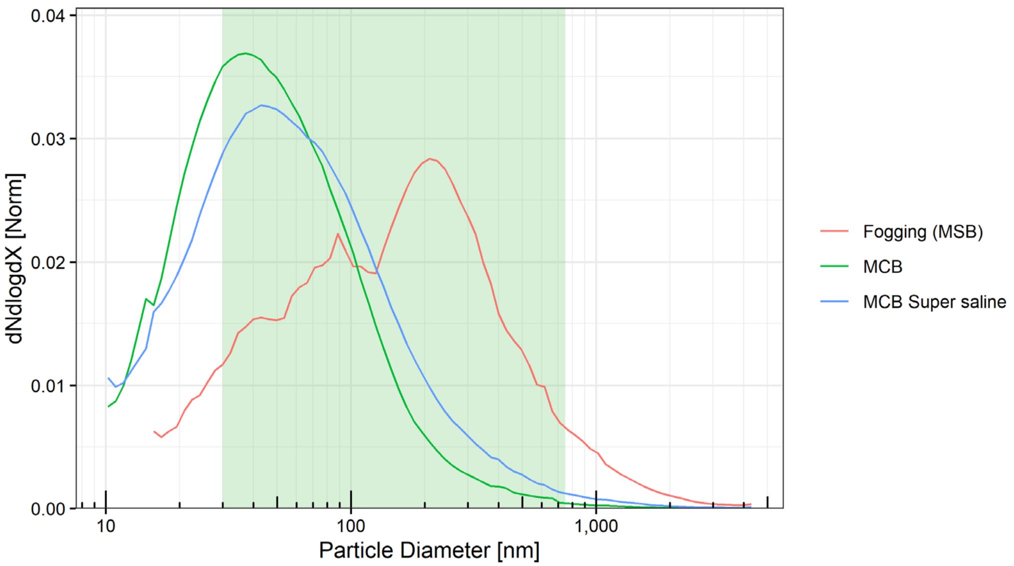
Objective		Key Findings and/or Outcomes
1.	Establish a nozzle testing facility to enable extensive laboratory-based nozzle testing of candidate technology types and nozzle variants with seawater.	A dedicated seawater atomisation nozzle testing facility was developed within an industrial warehouse space, located in Coffs Harbour nearby the Southern Cross University National Marine Science campus. The facility houses two sizes (0.6 and 1.4 metre diameter) of turbulently mixed one-way flow through wind tunnels with variable wind speed (1 - 10 m/s). The tunnels are designed to enable accurate estimation of nozzle droplet production rates and measurement of resultant dry sea salt aerosol size distributions. The sampling system includes adjustable dilution allowing testing of water atomisation nozzles over a very wide range of droplet production rates and droplet size distributions. The tunnels are well instrumented with aerosol sizing and counting equipment, both at the inlet to quantify the background ambient aerosol and downwind of the spraying apparatus to characterise the spray produced by the nozzle under test. Over the course of the project period instrumentation, operating procedures, test plant for operating the nozzles and electronically controlling operating parameters have been continually improved and optimised to allow for rapid testing of a significant number of nozzle variations and operating parameters. Various nozzle supply and testing plant has been constructed to examine the multiple nozzle technologies researched (see objective 4 below). All plant is equipped with industrial grade monitoring equipment to display and log operating parameters such as the required high-pressure air and water for a wide range of nozzle types. Instrumentation now included in the nozzle facility is capable of measuring nozzles producing 10 to 10,000 nm diameter dry salt crystals at rates of up to 6×10^{13} s^{-1}. The nozzle generated seawater spray can also be characterised in the tunnel in the droplet phase, at sizes from 2 - 50 micrometre (µm) diameter. Methodology and further description of the methodology can be found in Harrison et al. (2025) and Medcraft et al. (2025). A second smaller nozzle testing facility has been established at the University of Cambridge, United Kingdom. This facility is being used to conduct initial characterisation and development of new candidate technology types and nozzle variants that might provide higher efficiency and more effective MCB. The facility is currently undergoing expansion and upgrades to enable experimentation of multi-nozzle arrays enabling cross comparisons with similar experiments undertaken at the SCU nozzle testing facility.

Objective		Key Findings and/or Outcomes
		 *Figure 2: The SCU nozzle testing facility. Left) High pressure air and water plant are visible mounted on the trailer in the background and the 1.4 metre diameter wind tunnel on the right. Right) The tunnel fan unit and nozzle chamber, with the super-heated nozzle plant mounted inside the nozzle chamber.*
2.	Design and instrumentation fit out for aircraft, conduct preparatory and test flights	The SCU Cessna 337 serves as an airborne research platform designed specifically for MCB field studies. Despite its relatively compact size compared with other meteorological-aerosol-cloud microphysical research aircraft, the SCU platform is equipped with an extensive array of meteorological, aerosol, and cloud microphysical instruments typically found on much larger research planes (Hernandez-Jaramillo et al. 2024). These instruments enable scientists to collect high-resolution atmospheric measurements critical for understanding cloud processes, aerosol interactions and their combined effects on the marine environment. The instrumented Cessna 337 has proven to be a robust research platform, advancing our understanding of aerosol-cloud interactions over the marine environment (Braga et al. 2025). The aircraft's capabilities have been demonstrated during four RRAP Cooling and Shading Sub-program field campaigns, conducted in the summers of 2022/2023, 2023/2024, and 2024/2025 in Gladstone, Hamilton Island, Gladstone, and Townsville respectively. During these campaigns, the Cessna 337 played a crucial role in gathering in-situ measurements of cloud microphysics, aerosol size distributions and meteorological conditions. The data collected is essential to evaluating the effectiveness of MCB techniques, offering valuable insights into how cloud microphysical processes can be perturbed with additional sea salt aerosol to potentially enhance cloud albedo to in the future reflect more sunlight and mitigate the effects of climate change on the GBR. Since the detailed description of the aircraft setup in Hernandez-Jaramillo et al. (2025b) and ahead of its most recent missions, the aircraft underwent significant upgrades. These were designed to enhance its capacity to fully support the complex multi-role flight missions which are required to perform in the RRAP Cooling and Shading Sub-program. These upgrades included improvements to the avionics instrumentation on the aircraft, an additional instrument for redundancy, installation of a hyperspectral sensor, additional inlet monitoring instrumentation, and improvements to scientific instrument mounting systems.

Objective		Key Findings and/or Outcomes
		A comprehensive avionics system update was undertaken, aimed at improving flight safety, efficiency and both pilot and science mission situational awareness as well as navigational capabilities. The modernised avionics not only provided better navigation and communication tools for the pilots and scientific crew but also streamlined scientific data acquisition processes, ensuring precise coordination during the complex flight patterns required for cloud sampling. An additional improvement was the integration of a second independent cloud droplet probe (CDP) from Droplet Measurement Technologies (DMT). Being the critical instrument for MCB research, this probe was installed to add redundancy to the existing cloud combination probe (CCP), increasing data reliability and allowing for cross-verification of cloud droplet measurements. The CDP measures the size and concentration of cloud droplets, which is essential for assessing cloud microphysical response to meteorological conditions and aerosol-cloud interactions. To further enhance the aircraft's flexibility, additional quick-release instrument mounting systems were designed and installed, allowing for much more rapid installation and removal of delicate instrumentation such as condensation particle counters (CPCs), the Scanning Mobility Particle sizer (SMPS) and other instrumentation from cabin racking system. This design improvement provided flexibility in adaptation of the instrumentation configuration to meet mission-specific requirements, offering greater versatility for various types of atmospheric research. Another critical upgrade involved the addition of a dedicated computer station in the front seat of the aircraft. This new system enables the flight mission scientist to manage missions more efficiently by providing real-time data visualisation and analysis. Within this system, the scientist can track the detection of plumes and monitor cloud droplet concentrations during flights, enabling dynamic adjustments to flight paths and sampling strategies as needed. The integrated software system custom developed by the team at SCU collects data from the main instruments, processes it, and displays live plots of key parameters alongside the aircraft's flight track. This real-time feedback loop has significantly improved the team's ability to respond to evolving atmospheric conditions during missions. New relative humidity probes were installed inside the pod to monitor the efficiency of the inlet drying system at numerous points throughout the aerosol sampling system. Accurate tracking of relative humidity is crucial for ensuring that aerosol particles are adequately conditioned before measurement, preventing biases in size distribution data due to unwanted water uptake or loss. This negates the need for assumptions about the aerosol composition to determine dry equivalent size. This upgrade enhances the reliability of aerosol measurements strengthening the scientific integrity of the collected data. Following these enhancements, the Cessna 337 supported two field campaigns. The first took place in December 2024 in Gladstone, where the upgraded aircraft gathered critical data on background cloud microphysical properties over the reef to inform modelling and MCB system design studies. The second campaign occurred from February to March 2025 in Townsville, focusing on studying cloud responses to MCB spray injections and further assessing the feasibility of MCB techniques. Both campaigns benefited immensely from the aircraft's improved instrumentation and real-time data capabilities, solidifying its role as a versatile and effective airborne research platform for the Australian atmospheric sciences community.

Objective	Key Findings and/or Outcomes
	 *Figure 3: The flight mission scientists aircraft panel pre and post avionics upgrade. Left) Steam gauges and ad-hoc science displays using tablets in the cockpit. Right) The upgraded panel with modern avionics and panel mounted navigation and science displays.* Through these upgrades and successful field deployments, the SCU Cessna 337 has established itself as a cutting-edge tool for atmospheric research, with a distinct advantage of being able to fly lower and slower than other aerosol-cloud microphysical aircraft platforms. This capability is essential for small scale atmospheric perturbation research such as initial outdoor MCB field experimentation. The combination of advanced instrumentation, real-time data processing, and adaptive design makes it a valuable asset for studying complex aerosol-cloud processes. As research into MCB and other climate intervention strategies progresses, the Cessna 337 will continue to contribute vital data and insights, pushing the boundaries of our understanding of the atmosphere and its role in climate regulation.

Objective		Key Findings and/or Outcomes
		 *Figure 4: The SCU Cessna 337G Aircraft. Left) Underwing view of the reef from the SCU research aircraft during the 2025 field campaign. Right) The SCU aircraft showing the underwing instrument pod.*
3.	Continued optimisation of the existing effervescent nozzle concept, through laboratory experimentation, testing new conceptual designs, and CFD modelling to elucidate key nozzle parameters impacting the	Systematic testing of various effervescent nozzle designs has been conducted across several variations to internal and external geometry, orifice diameter, operating pressures and Gas to Liquid Ratios (GLR). Remarkably, the results indicated negligible changes to the size distribution in produced sea salt aerosols for the majority of this testing. However, there were significant differences in number particle production rate and energy required to produce the particles. An increase in particle production rate with increasing pressure and GLR's was observed. This indicated that to increase the number production of the current effervescent technology, we should operate at the maximum pressure and GLR available. These results informed the systems designs for the current effervescent nozzle-based Aerosol Radiation and their Interactions Experimental Laboratory (ARIEL) spraying system used in outdoor field experiments of marine cloud brightening.

Objective	Key Findings and/or Outcomes
spray size distribution and quality	Increasing the salinity of the water being atomised was investigated in the laboratory. Higher salinity increases the size of the salt crystals produced from each droplet sprayed, but not necessarily in accordance with mass conservation as one would expect. This phenomena has been previously reported by Cooper et al. (2014), who was unable to explain the observation. By increasing the salt concentration from 32 parts per thousand (ppt) to 110 ppt, the median particle size was increased from 35 to 45 nm dry diameter with an observed widening of the size distribution (Figure 5). This observation suggests that the higher salinity may be affecting the physics of droplet breakup. Spraying at higher salinity does successfully increase the number of particles produced within the target marine cloud brightening range, as shown in Figure 5.  *Figure 5: Normalised particle size distribution from field campaign in 2024 for three modes of particle generation. Green shading indicates a MCB target range of 30-800 nm dry diameter.* Computational fluid dynamics (CFD) modelling of the effervescent mixing was carried out to investigate the various flow regimes within this highly dynamic dual phase compressible flow regime. The CFD modelling investigation used three different solvers—*interFoam*, *compressibleInterFoam*, and a new solver called *evdFoam*—to simulate two-phase (liquid-gas) flow in and around spray nozzles. These solvers model how liquid and gas mix and flow together, each with different levels of detail. The results show that *evdFoam* is capable of accurately distinguishing between key internal flow regime patterns, such as slug flow and annular flow, which were confirmed to be related to different gas to liquid mass ratio conditions. At higher GLRs, some blurring of results

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occurs due to volume diffusion in the model. Nonetheless, comparisons with experimental images (shadowgraphs) confirm that evdFoam captures the major flow features seen in real tests (Figure 6).

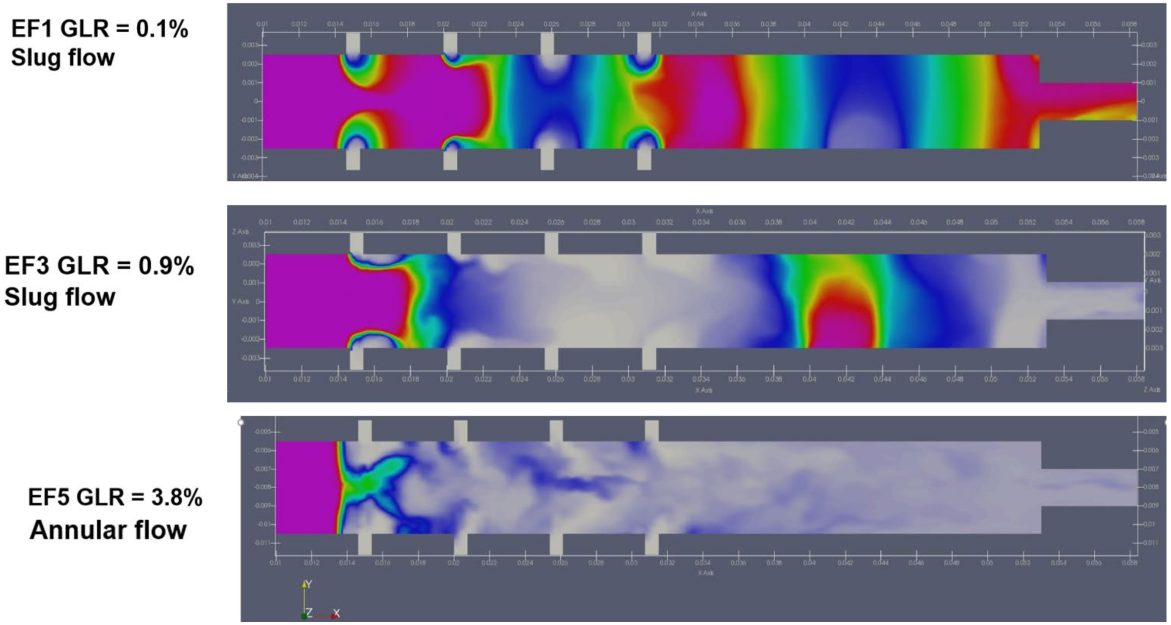

Figure 6: Flow profiles under different GLRs.

A separate set of simulations using interFoam at lower pressures explored how nozzle design and operating conditions affect the initial mixing of air and water. These tests identified the main causes of unstable (oscillating) spray behaviour and suggested design tweaks that could reduce these effects. For example, directing the liquid flow more smoothly or along the nozzle's axis can lead to quicker jet breakup, though it may also introduce some long-lasting flow variations. One ongoing challenge is accurately predicting droplet sizes and distribution downstream of the nozzle. To address this, the team is developing a Lagrangian particle tracking method for evdFoam, which follows individual droplets through the spray. This will help improve understanding of how liquid breaks up and disperses between the dense spray near the nozzle and the fine mist further away. Validation tests using detailed simulations of a turbulent jet confirm that evdFoam can reliably predict how liquid volume and surface area change along the spray. Future work will focus on expanding evdFoam's capabilities for compressible flows and improving its ability to model detailed droplet formation and spray structure.

Effervescent spray atomisation continues to be the best performing technology for producing MCB suitable sea salt particles, and the only nozzle technology demonstrated at scale. Over multiple iterations of MCB field testing using the effervescent concept, the output
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Objective		Key Findings and/or Outcomes
		performance has been iteratively improved through a combination of scale up, engineering improvements, and tweaking of operational parameters (flow, pressure, and GLR). A further increase in output efficiency of around one order of magnitude in particle production rate is highly desirable to minimise energy requirements for a deployable MCB intervention. Meanwhile further improvement of the spray droplet and resulting aerosol size distribution could theoretically increase the effectiveness of MCB by maximising the net cloud albedo response.
4.	Development of electro spray, which is highly monodisperse and energy efficient but requires research and development (R&D) in micromachining to achieve scale	Research into the electrospray method has progressed significantly, furthering knowledge of the feasibility of upscaling this technology for marine cloud brightening. Electrospray nozzles can produce highly monodisperse droplets within the desired size range for cloud brightening. However, there is only a small body of literature applying the method to saline solutions. Figure 7 shows a simplified schematic of the electrospray experimental configuration which was developed. Figure 8 shows representative images of prevalent modes of Taylor cone observed thus far. The optimum mode for monodisperse droplets is the cone-jet mode which has now been achieved consistently with a 3.5% saline solution without the need for surfactants. The cone-jet mode involves the formation of a so-called Taylor cone immediately downstream of the nozzle exit, where uniform droplets are ejected from the tip of the Taylor cone. The spray behaviour and operating modes have been characterised using direct imaging and spray current measurements. A theoretical performance algorithm has been developed that characterises saline electrosprays with respect to key variables such as applied voltage, liquid flow rate, nozzle diameter, and electrode arrangement. Figure 9 shows operating bounds within which the desired Taylor cone (in the stable cone-jet mode) is formed – deviations from these bounds can lead to either corona discharge or ion evaporation. Figure 10 shows the remarkable reduction in power requirements by opting for smaller droplet sizes, nozzle diameters, and electrode separations. Such tentative findings from the theoretical algorithm will be consolidated and validated in future experiments. Crucially, this work will provide a systematic framework to characterise saline electrosprays without surfactants. This serves as a valuable baseline from which solutions more representative of seawater can be tested. Once the parameter space is sufficiently characterised, measurements of particles produced by the electrospray nozzle design can occur.

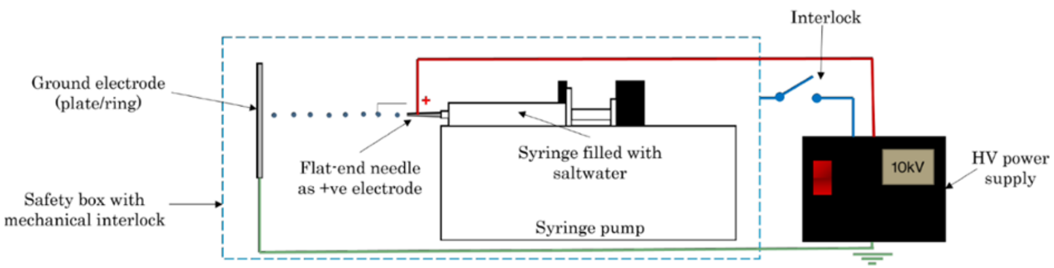


Figure 7: Simplified schematic of the electrospray experimental configuration.

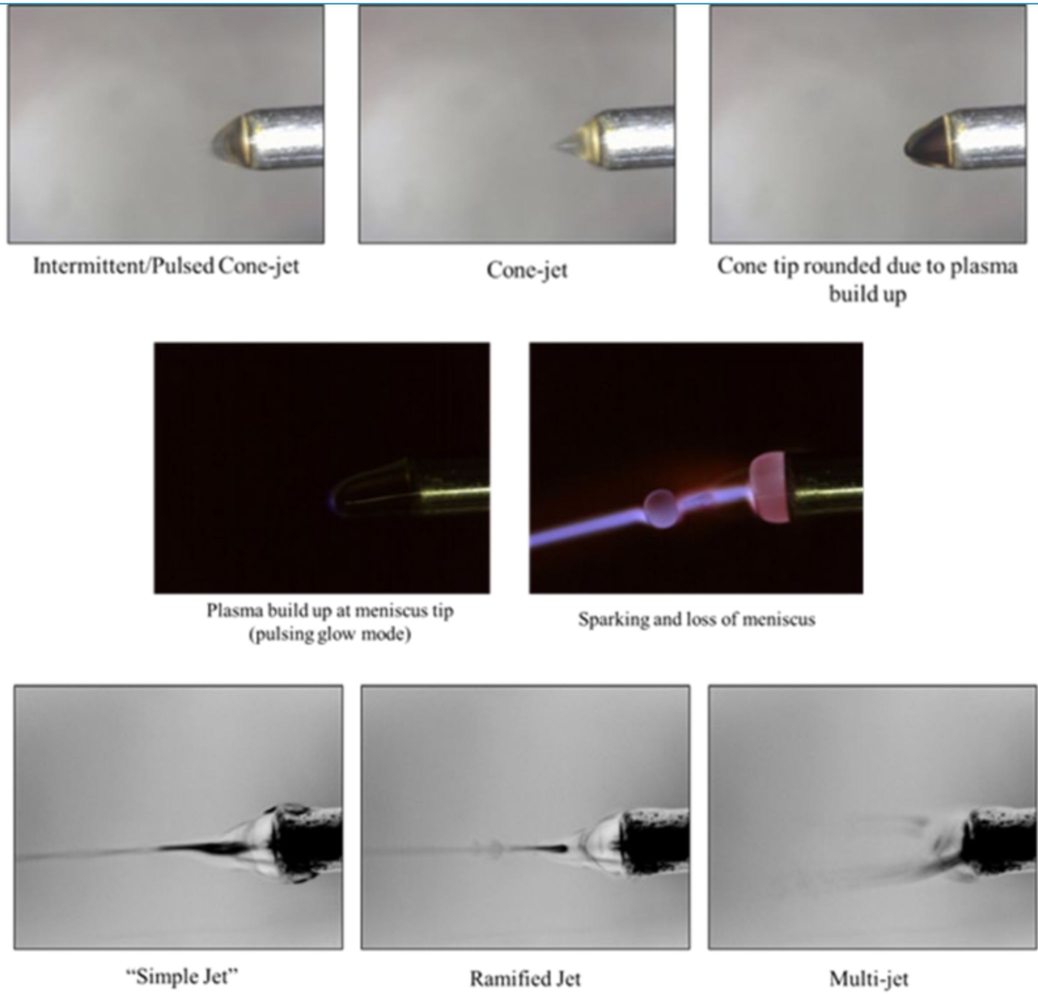
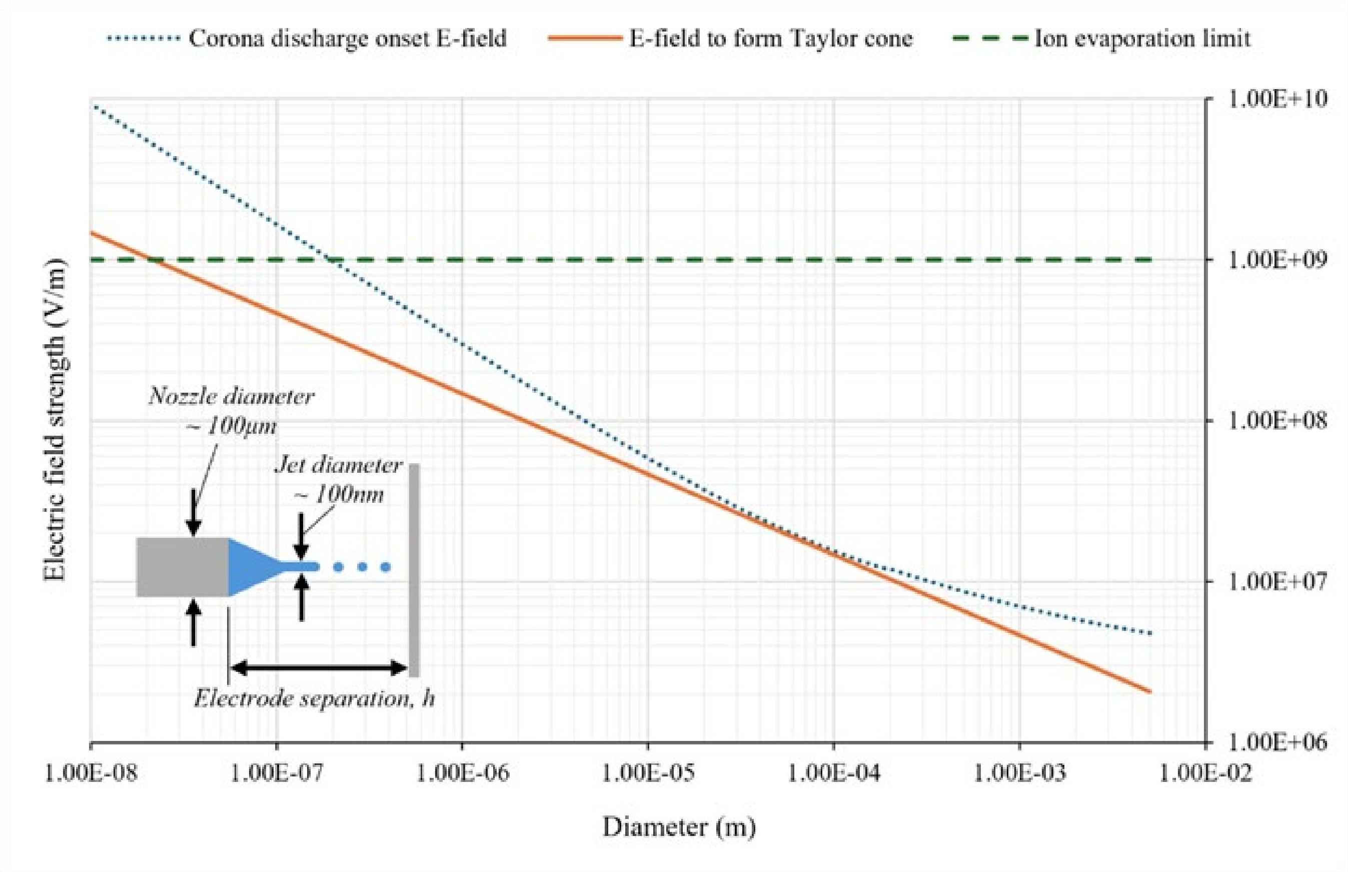
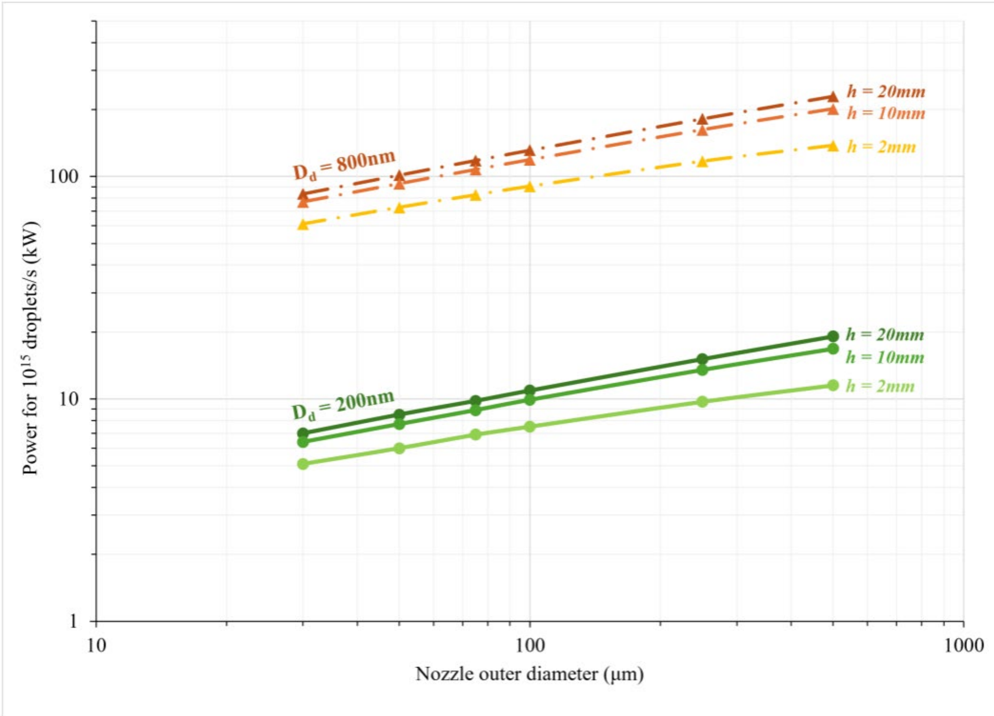


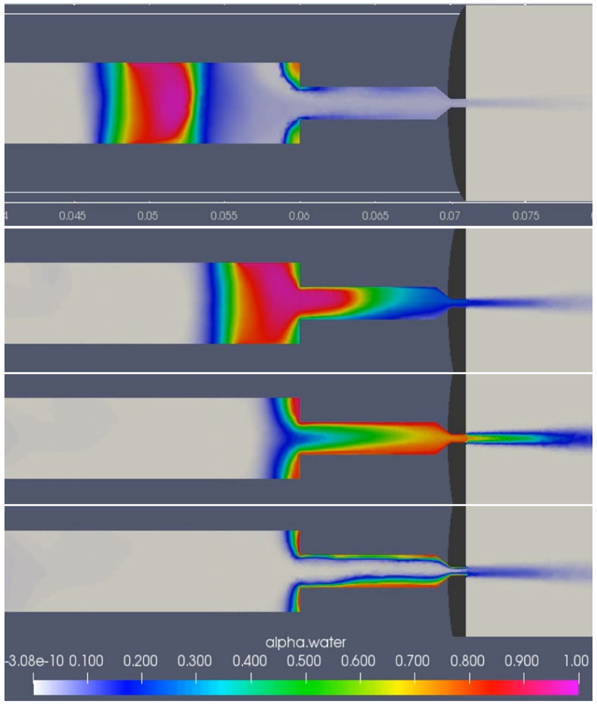
Figure 8: Representative microscopic images of the operating modes and general behaviour of saline electrosprays.

Objective	Key Findings and/or Outcomes
	 *Figure 9: The behaviour around a conductive cylinder containing 3.5% sodium chloride (NaCl) saltwater, including the onset of corona discharge, the onset of Taylor cone formation, and the ion evaporation limit. E-field denotes electric field strength, and the cylinder is characterised by its diameter.*

Objective		Key Findings and/or Outcomes
		 *Figure 10: Power requirement as a function of nozzle outer diameter for specific droplet diameters (Dd: 200 and 800 nm) and electrode separations (h: 2, 10, 20 mm).*
5.	Sequentially evaluate alternative spray generation options such as ultra-high-pressure water, superheated water, sonic nozzles using the nozzle characterisation and testing facility	Although the current effervescent technology used in the ARIEL spraying system has proved suitable to enable the worlds' first outdoor experimentation examining MCB aerosol-cloud interaction, it may not be the ideal technology for implementation. The current ARIEL system produces around 10^{15} s^{-1} aerosol, while it has been suggested that for implementation the production rate should be around 10^{16} s^{-1}. While it would be possible to scale up the existing system by brute force this would require a considerably large plant footprint and around 3.5 megawatts (MW) of energy. Although possible this would likely limit MCB deployment to dedicated vessels which is not considered a suitable or affordable implementation method for the GBR. The objective is to find more efficient nozzle technology that can reduce the energy required per suitable MCB aerosol produced by at least a factor of ten, and to also improve the resulting cloud condensation nuclei size distribution to obtain the maximum possible albedo increase in cloud for a given quantity of spray. To achieve these objectives, alternate spraying technologies are assessed in the nozzle testing facilities.

Objective	Key Findings and/or Outcomes
	Flash boiling nozzle Flash boiling nozzles have been developed on two parallel pathways at SCU and Cambridge. At SCU a batch testing plant has been developed which contains a pressure vessel of finite volume (2.2 litre (L)) in which saltwater is heated and pressurised with high pressure over water. When the vessel has heated to the desired temperature a valve is remotely operated which allows the superheated water to discharge through the nozzle while pressure is maintained during discharge by a regulator supplied by a bank of high-pressure air cylinders. The SCU superheated nozzle testing plant is described in Medcraft et al. (2025). The primary advantage of this approach is that nozzles with a wide range of operational flow range can be tested. In contrast, the testing apparatus developed at Cambridge operates continuously with liquid supplied by a high-pressure water pump and heating applied along a length of supply tubing. While this setup can only test lower flow nozzles, it has the advantage of being able to independently adjust flow and heat which along with the nozzle geometry determines pressure. The highest performing super-heated nozzle tested so far was using the continuous system at Cambridge. The results so far suggest that the highest output efficiency (per unit energy) is at very low nozzle flows, which implies that large numbers of nozzles may be needed for an upscaled system. Using a convergent nozzle (1.75 mm to 0.2 mm), the submicron fraction of the particles produced have a mode of roughly 80 nm and a geometric standard deviation of roughly 1.7 - 2.3 (for liquid temperatures of 180 - 240°C and operating pressures of 24 - 42 bar). The minimum power estimate to produce particles at the desired rate for eventual implementation (10^{16} s^{-1}) is roughly 4 MW – comparable to the power demand of the current effervescent system used in field trials. Due to the lack of energy efficiency gain, this technology has not been expanded for field use yet, although it remains an area of key focus and technological development. A further major concern with all superheated nozzles tested to date is that mass conservation analysis reveals that only about 5 - 10% of the salt mass sprayed is accounted for as aerosols in the sub-micron range. This suggests that super micron aerosol is also produced by the nozzles. Since super-micron aerosol is known to promote processes that can dim clouds, the nozzle geometries currently tested are not considered superior to the effervescent nozzles currently in use. Nevertheless, theoretical extrapolations from previously published results suggest considerable promise for these nozzles so they remain under investigation by the research team. **Rayleigh jet** An external medical technology company has agreed for their nozzle arrays to be tested with 3.5% saline solutions. Preliminary measurements of a 100-pore array (pore size: 1.6 µm) show a typical particle mode size of 160 nm and a geometric standard deviation of 1.26 - 1.40. The estimated power demand to produce particles at the desired rate (10^{16} s^{-1}) is roughly 1.5 MW. These estimates meet optimal criteria for cloud brightening and as such this technology appears promising and is still being actively investigated. The greatest concern with this approach is the requirement for ultra filtration and potentially other precautions or interventions to keep the very small orifices from clogging under real world conditions. Research is underway to ascertain if continuous filtration at this level is practical.

Objective		Key Findings and/or Outcomes
		Sonic nozzles Ultrasonic nozzles were briefly tested for their ability to produce droplets at rates and sizes applicable for MCB. Despite literature and manufacturer claims, initial testing revealed that off-the-shelf nozzles did not meet either the production rate or size targets for MCB. As such, this nozzle technology has not undergone continued development to date.
6.	Computational fluid dynamics modelling of the nozzle atomisation process	Three different solvers have been used to conduct the CFD simulations. These solvers are used with the aim of performing high fidelity simulations of interfacial flows. To explore jet break up with affordable computational resources, we employ large eddy simulation (LES) such that the large eddy scales are resolved with the grid and the smaller scales (sub-grid scales) modelled with closure models. Among the three solvers, the first is used as a conventional Volume of Fluid (VOF) approach with a standard incompressible solver called *interFoam*, second is its compressible version named *compressibleInterFoam* that incorporates compressibility which is essential for high pressure choked nozzle simulations. These standard solvers are common in multi-phase flow simulations, but there are a few limitations. To capture very small liquid elements, very fine grids and high computational cost are required due to the infinitely sharp interface topology and complex interface dynamics. When the fields are under resolved (as they always are in practical simulations of real engineering-scale configurations such as the MCB nozzles), the discrete solution of the volume fraction exhibits numerical diffusion which smears the interface and affects liquid break up predictions. Thus, such numerical simulations of jet atomisation are highly mesh dependent. The research community has found that this issue may be partly addressed by an artificial interface compression term to sharpen the interface or through an anti-diffusion flux corrected transport (FCT) scheme. However, problems remain with grid dependence, and this motivated our development of a novel LES method named Explicit Volume Diffusion (EVD). It has been implemented in a solver called *evdFoam*, with closures developed for sub-volume flux, stress, and the volume averaged surface tension force. It is based on a volume averaging concept with more accurate treatment of interfacial dynamics compared to standard modelling found in *interFoam* and *compressibleInterFoam*. As part of the present project, we have also introduced the coupling of the Eulerian-based EVD method with a *Lagrangian* particle tracking approach to predict spray statistics more accurately.

Objective		Key Findings and/or Outcomes
		 *Figure 11: Example of CFD modelling exhibiting flow regime transition from slug flow to annular flow at the contraction region of the nozzle.*
7.	Construct higher production rate seawater atomisation technology, implement land and ocean-based testing	The seawater atomisation technology and associated plant have been continually developed by the RRAP Cooling and Shading Sub-program team. The Aerosol, Radiation, and their Interactions Laboratory (ARIEL) system has been developed from a total sea salt aerosol output of ~ 10^{14} s^{-1} to ~10^{15} s^{-1} over the course of the project. The original prototype consisted of 100 nozzles arranged using a bicycle spoke manifold arrangement. This was supplied by a single large high pressure high flow air compressor. Subsequently the system was expanded to 320 nozzles in a 5 x 64 nozzle tower configuration and the air supply updated to three air compressors. Ultimately, a second cloud cannon unit was integrated giving a total of 640 nozzles supplied by six air compressors. The outcomes of outdoor testing of the various iterations of the ARIEL system are detailed below under Objective 9.

Objective		Key Findings and/or Outcomes
8.	Plume modelling of the expected dispersion of the plume under various atmospheric conditions for comparison to field results and to inform sampling strategy	A review of plume dispersion applicable to marine cloud brightening was completed and is provided in Hernandez-Jaramillo et al. (2025a). Initial plume modelling sought to quantify the rate of vertical mixing of the plume towards cloud base and compared to field studies undertaken in 2021, which provided the first empirical evidence on the atmospheric dispersion of artificially generated sea spray aerosols (SSA) for MCB (Hernandez-Jaramillo et al. 2023). Using both drones and crewed aircraft, plume behaviour was investigated across near- and far-field domains under a variety of atmospheric conditions. It was demonstrated that under typical boundary layer trade wind conditions over the Great Barrier Reef, evaporation of the MCB plume did not hinder the vertical mixing of the plume towards cloud base. In the near-field (up to one kilometre), drone-based measurements demonstrated consistent vertical mixing of the SSA plume, reaching altitudes of up to 150 metres under moderate to low wind conditions. Observations revealed that evaporative cooling from atomised seawater did not suppress vertical dispersion, contrary to previous modelling predictions. Instead, atmospheric stability and wind velocity emerged as key factors controlling plume rise and dispersion. Comparison with the Briggs Plume Rise Model indicated that model predictions underestimated the observed plume height, particularly under stable conditions.

Objective	Key Findings and/or Outcomes

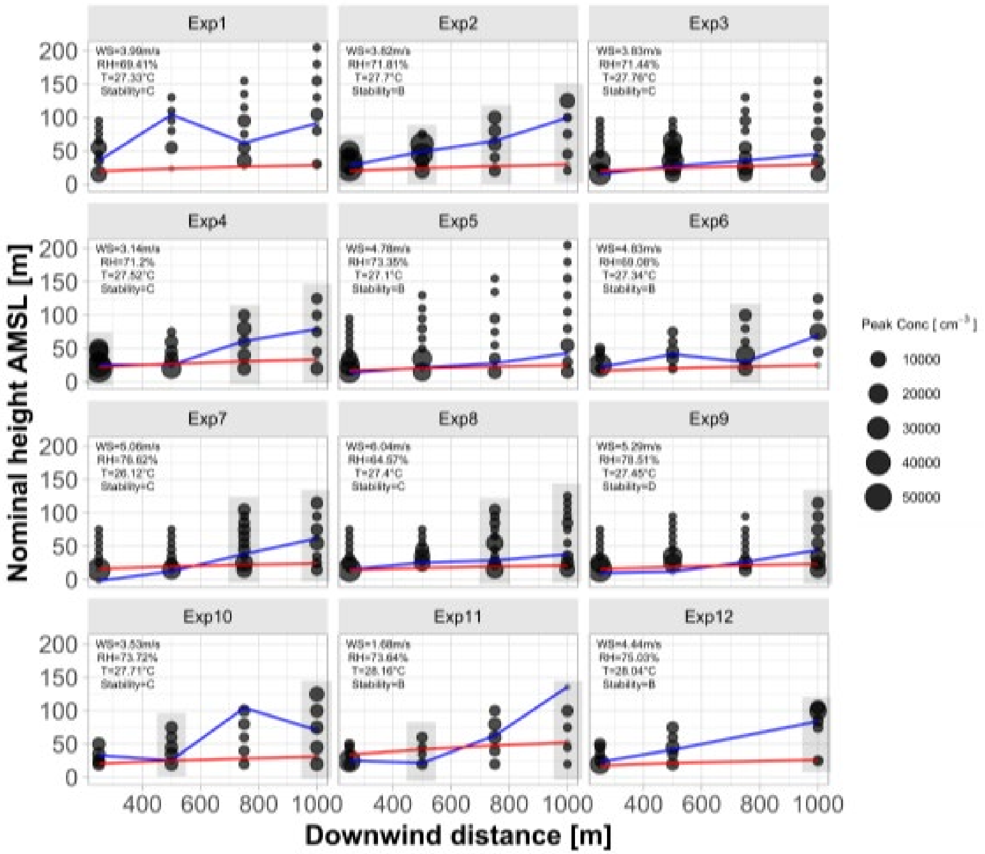


Figure 12: Plume centroid rise compared to predictions from the Briggs Plume Rise Model. Adapted from Hernandez-Jaramillo et al. (2023).

In the far-field (1 - 10 km downwind), aerosol dispersion was assessed using airborne platforms. Aircraft detected the SSA plume reaching cloud base heights (~825 - 900 metres) under both anchored and moving vessel scenarios. The moving vessel strategy, which aligned the sprayer with the prevailing wind, proved especially effective by concentrating aerosols in a coherent column beneath cloud base. Under these conditions, artificially generated SSA clearly exceeded background marine aerosol levels and maintained distinct vertical profiles consistent with expected cloud condensation nuclei behaviour.

Further plume modelling has been undertaken using Large Eddy Simulation (LES) modelling. The modelling investigated the dispersion of a MCB generated sea salt aerosol plume in a trade wind cumulus cloud regime initiated using measurements from one of the RRAP Cooling

Objective		Key Findings and/or Outcomes
		and Shading field campaigns. The dispersion of the plume was investigated across a range of horizontal wind speeds to inform on the most applicable sampling strategy and gain insight into the potential effectiveness of MCB under commonly occurring atmospheric conditions over the GBR. This work found that increasing wind speed increased the rate of vertical dispersion of the plume and higher wind speeds led to greater penetration of the plume into the cloud layer above.

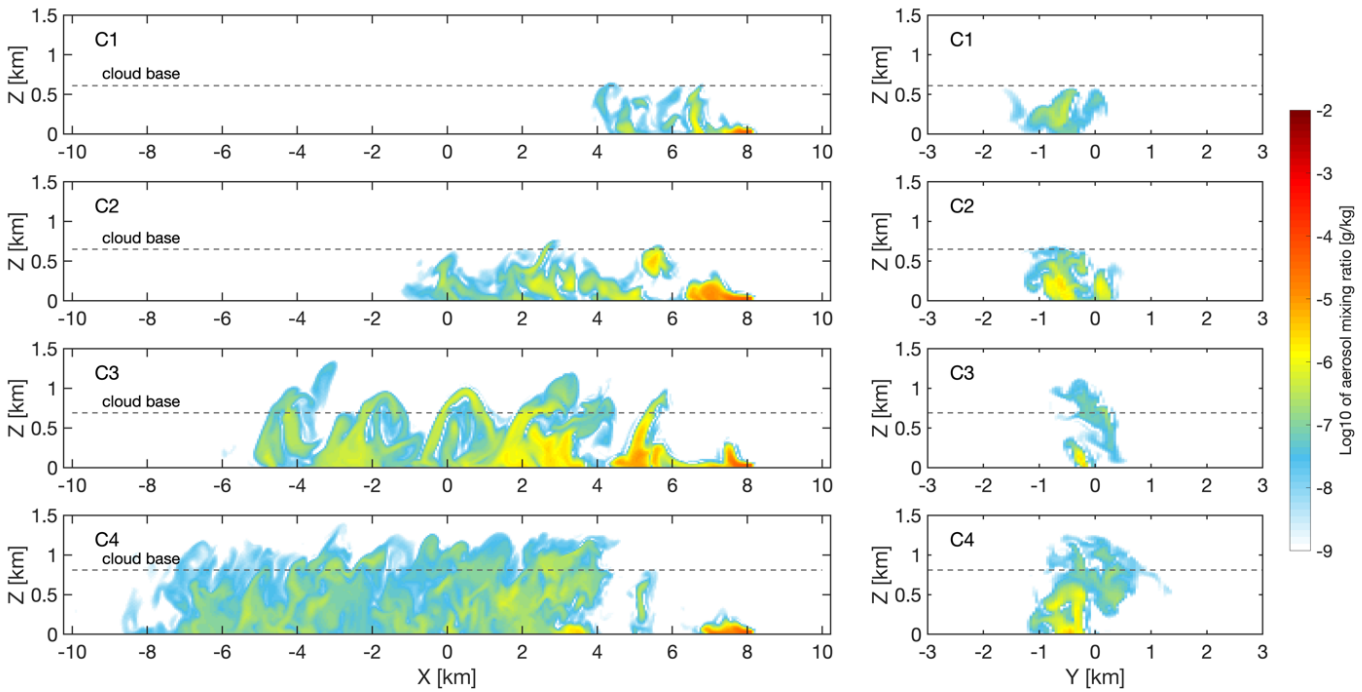


Figure 13: LES modelling of the sea salt spray spreading vertically in a trade wind cloud regime simulated over the Great Barrier Reef. The panels show the spread over 45 minutes under increasing wind speeds from top to bottom (S Chavez and D Harrison, in review).

Objective		Key Findings and/or Outcomes
9.	Field trials of various prototype hardware configurations for producing the spray of	A series of iterative engineering upgrades have been completed to advance the readiness of MCB technology for outdoor experimentation and towards ultimate scale up for potential implementation to mitigate coral bleaching on the GBR. The first prototype sprayer, V22Cloud1, was developed in collaboration with Ron Allum Deepsea Services (RADS) and EmiControls by retrofitting a V22 dust suppression unit with 100 custom-built effervescent nozzles. This system successfully demonstrated the proof-of-concept for in the field

Objective	Key Findings and/or Outcomes
atomised seawater droplets	atomisation of seawater for MCB in 2020, producing an estimated 2.7 × 10^{14} droplets per second with a mode dry aerosol diameter around 40 nm. This experiment demonstrated that the aerosol size distribution produced at sea under real world conditions from 100 nozzle fan driven array matched that of a single nozzle characterised under laboratory conditions. Following the 2020 trial, the system was upgraded for improved output and manufacturability. The number of nozzles per sprayer was increased to 320, achieved by implementing a new tower-style manifold system. The original 14-part nozzle design was replaced with a simplified cartridge nozzle retaining the same internal geometry, significantly reducing costs and complexity. This new design was deployed during the 2021 field campaign (one compressor, V22Cloud2.1) and the 2022 campaign (three compressors, V22Cloud2.2). Additionally, an integrated Programmable Logic Controller (PLC) system for real-time display and logging of operational parameters was integrated into the system. This scale spray system generated a plume that was detectable at more than 12 km downwind with production rates 2.6 - 3.7 times higher than V22Cloud1, moving the technology a step closer towards enabling outdoor MCB cloud perturbation studies. To support increased output and redundancy, V22Cloud3 was developed for the 2023 field campaign by introducing a second independent sprayer with an additional three compressors. Further enhancements for WHS and system reliability led to V22Cloud4, trialled in 2024. Upgrades included improved air filtration, venting upgrades to lower operating temperatures, enhanced monitoring systems, and better water filtration.

Objective		Key Findings and/or Outcomes

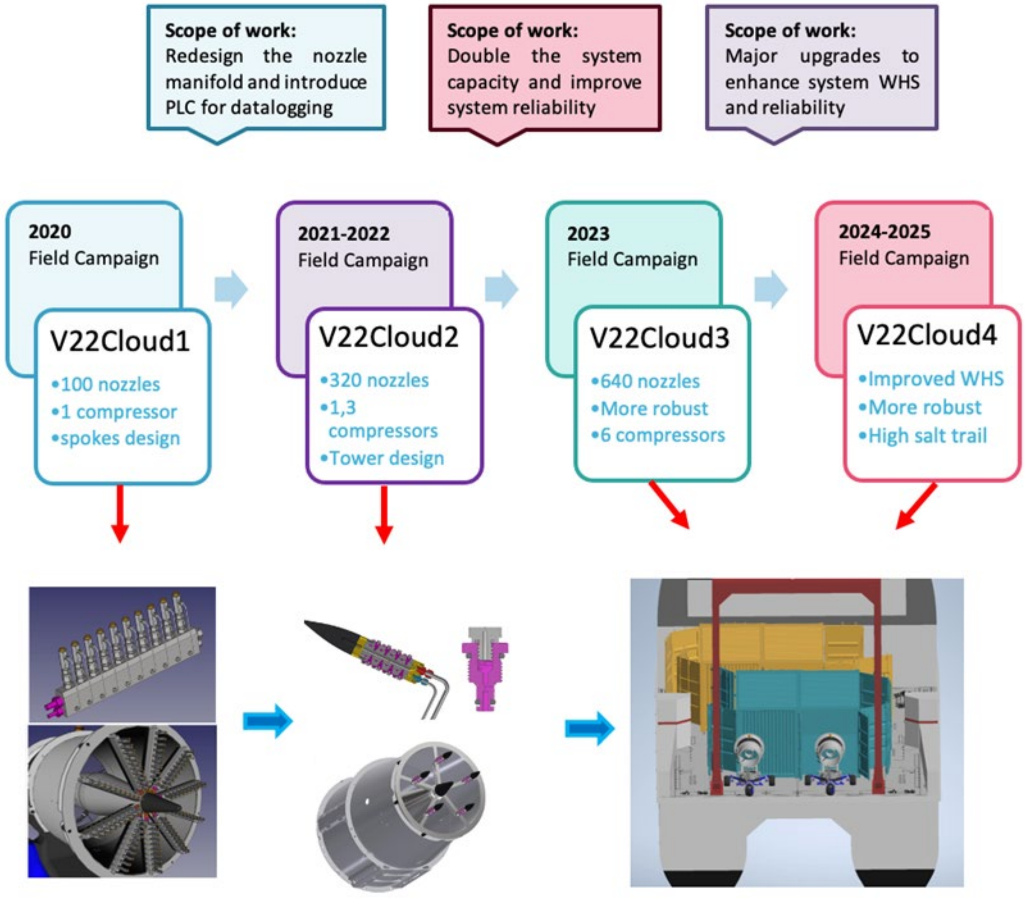
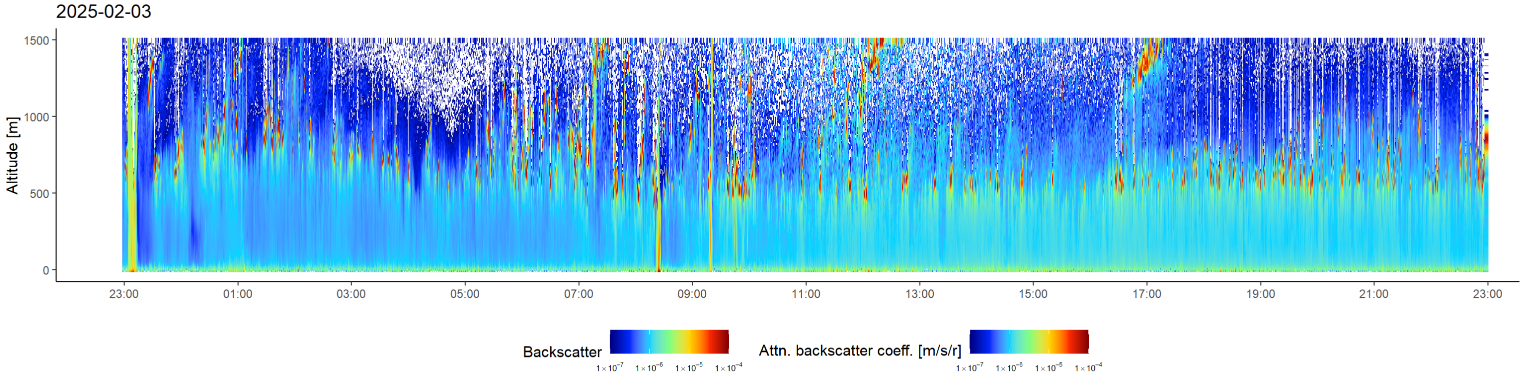
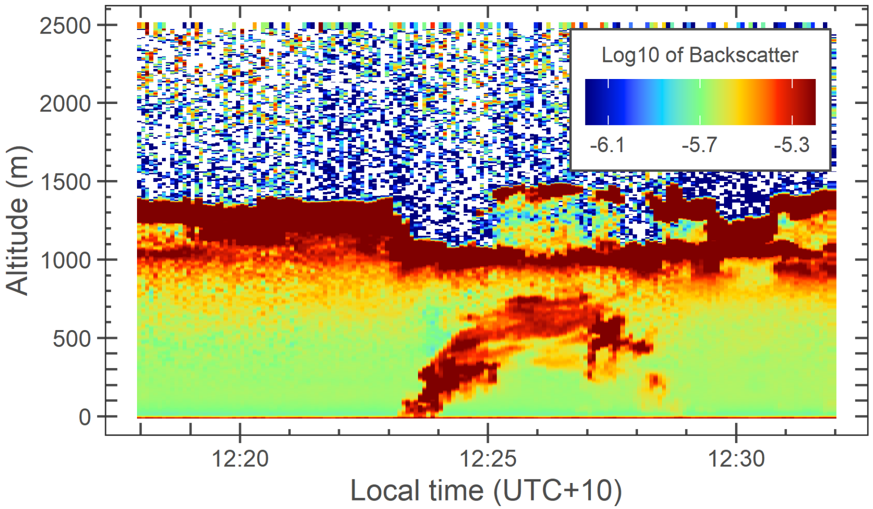
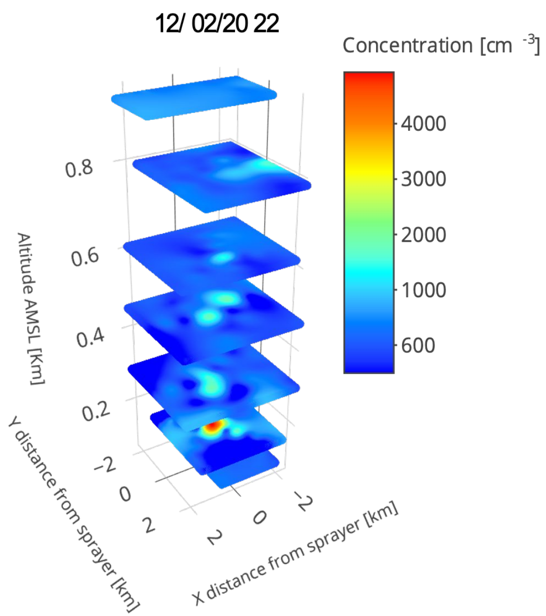


Figure 14: Overview of engineering upgrades and upscaling of the ARIEL MCB droplet generator over the life of the project.

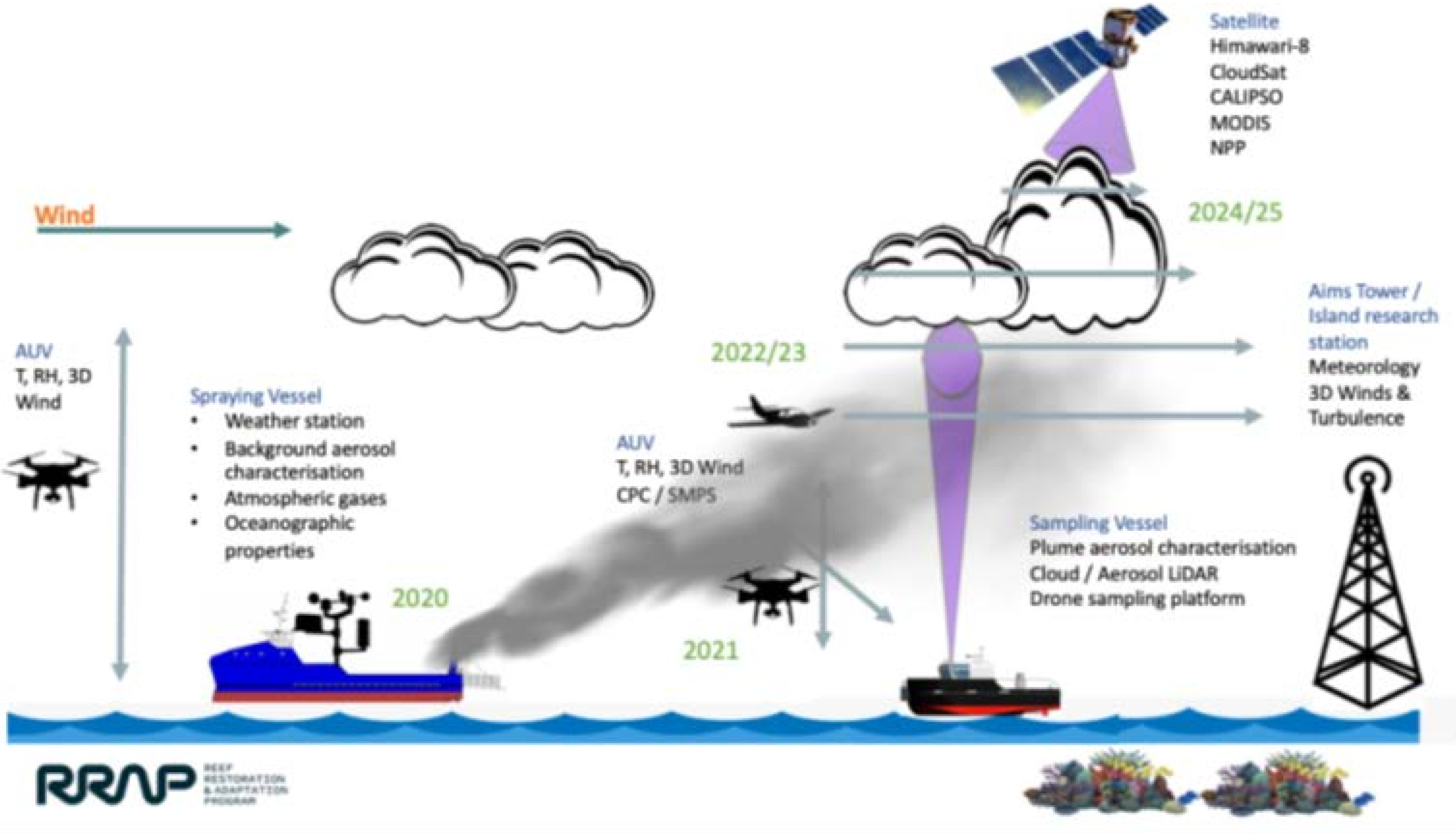
10.	Satellite remote sensing analysis in support of field trials	Our newly developed methods for satellite retrievals of CCN were validated against shipborne measurements over the GBR. We used two completely independent methods. The T-re method had a root mean square error (RMSE) of 33 CCN cm^{-3}. A by-product of this method is the adiabatic fraction (f_{ad}). When the τ-re method was corrected for the f_{ad}, it yielded a significantly improved accuracy, with an RMSE of 25 cm^{-3}. The application of the methodology for mapping the CCN over the entire GBR reveals that background CCN concentrations range

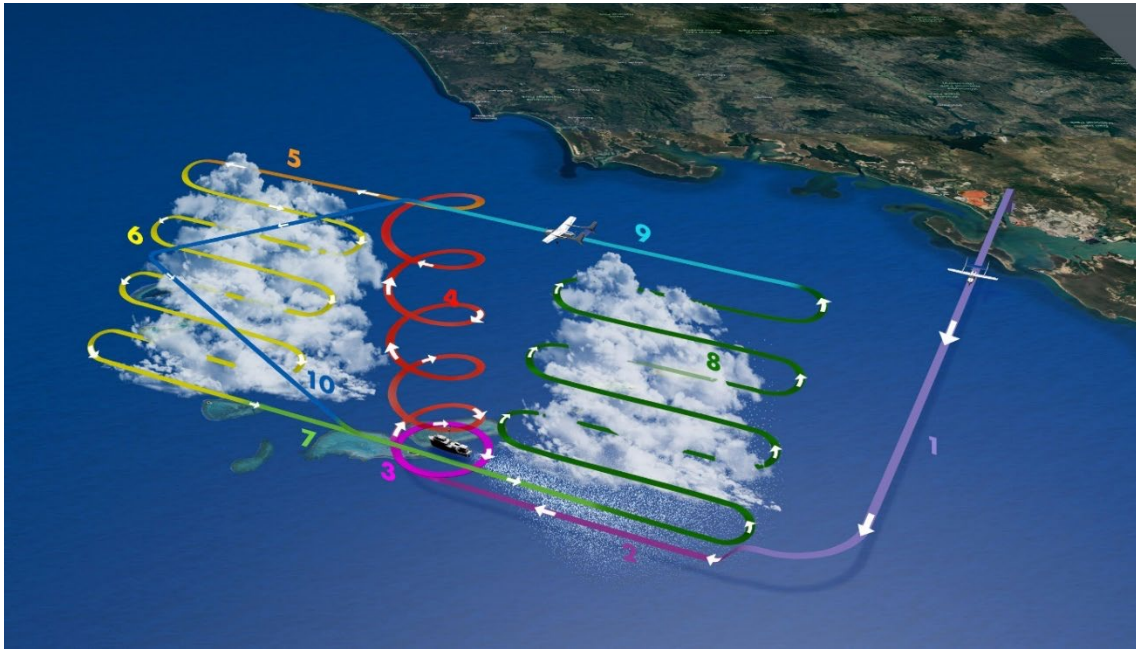
Objective		Key Findings and/or Outcomes
		from approximately 50 to 200 cm^{-3}, while activation supersaturations (S) vary from 0.3% to 0.7%, respectively. The most common value is near 100 cm^{-3}, and S is near 0.4%. The CCN concentrations over land are significantly higher, particularly in densely populated areas. Usually adding CCN such that the concentration exceeds 200 cm^{-3} starts to saturate the cloud drop concentrations of marine boundary layer clouds, as it is beyond the aerosol-limited regime. This indicates that the background CCN is sufficiently low to enable MCB due to the Twomey effect, except for when the air mass originates from over land. However, the cloud fraction effect is thought to saturate at much lower concentrations of about 60 to 100 cm^{-3} (Rosenfeld et al. 2019; Hu et al. 2021). Meaning that the potential for additional negative radiative forcing due to the cloud cover effect (second indirect) might be limited. This research is essential for initiating regional clouds and MCB atmospheric simulations with the correct background CCN, as the MCB results are very sensitive to the background.
11.	Surface based LiDAR measurement of aerosol, plume, and cloud properties	Surface-based LiDAR measurements of the plume and background conditions have been carried out over six major MCB field campaigns on the Great Barrier Reef, within the Townsville, Whitsundays, and Capricorn Bunker regions. Additionally, a LiDAR ceilometer is currently installed at the One Tree Island Research Station as part of a long-term (greater than one year) background meteorology, aerosol, and clouds monitoring program (Figure 15).  *Figure 15: Surface based LiDAR measurements of the atmosphere over One Tree Island, Southern Great Barrier Reef. The plot shows a day of typical trade cumulus (low scatted cloud) passing over the site at around 500 metre altitude for most of the day.* Measurements during field campaigns with the LiDAR focused on mapping the vertical distribution of the plume and observing the plume rise to cloud base. As the sampling vessel was moving and intentionally targeting sampling underneath clouds accurate estimates of cloud cover fraction is not possible during these missions. Given that the project team has discovered a large discrepancy between satellite derived estimates of low cloud cover and low cloud cover estimated by the Australian Bureau of Meteorology weather forecasting and reanalysis models a long-term monitoring station with LiDAR Ceilometer has been deployed on One Tree Island in the southern GBR. These background measurements of aerosol and cloud properties over the GBR have and will continue to allow for atmospheric model validation

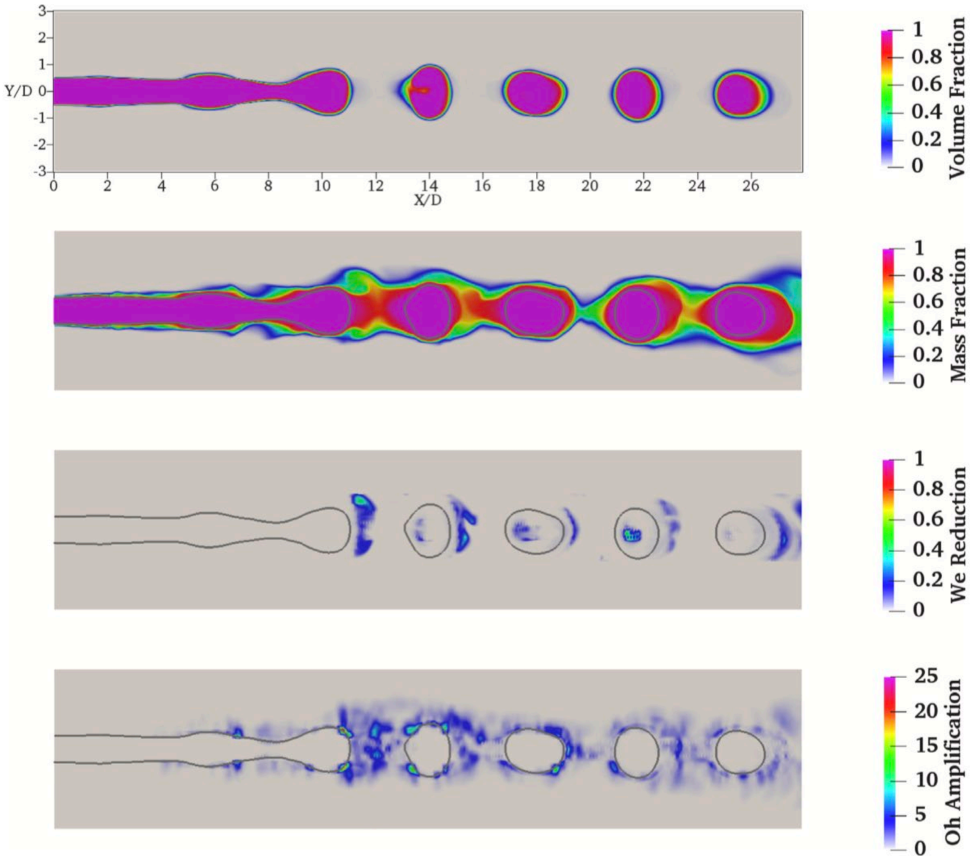
Objective		Key Findings and/or Outcomes
		and ground truthing. Additionally, these long-term measurements will be linked to particle concentration in the future to estimate the background aerosol climatology over the southern GBR. Plume measurements consistently showed plume rise beneath low clouds, suggesting uplift of the plume into the targeted low marine boundary layer clouds (Figure 16). This information was used in real time to direct aircraft and vessel sampling strategies. The LiDAR measurements have also been used to investigate plume width and vertical dynamics at varying distances downwind from the spray generation.  *Figure 16: LiDAR backscatter of the produced MCB aerosol plume extending up to cloud base height during the 2022 February field campaign.*
12.	Field investigation of dynamic plume behaviours, characteristics, and dispersion under varying atmospheric conditions	In early MCB field trials *in situ* data was collected that is critical to understanding nearfield aerosol dispersion. A key concern of MCB surface-based spraying technology has been whether evaporative cooling near the source produces a negatively buoyant plume that hinders vertical aerosol transport. To address this, we conducted the first *in situ* characterisation of nearfield dispersion from a point source using effervescent nozzle technology. Results demonstrated consistent vertical mixing of the plume to heights of approximately 150 ±5 m at 1 km downwind, with mixing depth influenced by wind speed and atmospheric stability. No evidence was found that evaporative cooling from the 0.068 kg/s water flux significantly limited vertical dispersion (Hernandez-Jaramillo et al. 2023). This outcome was attributed to the small droplet sizes and low flow rates achieved with the effervescent spray system.

Objective		Key Findings and/or Outcomes
		Subsequent field campaigns characterised the vertical and horizontal extent of the MCB plume including mapping the extent of plume just below cloud base as it is uplifted into cloud. Furthermore, the size distribution of the plume was characterised just below cloud base after undergoing advection and dispersion. These results are summarised in the publication by Hernandez-Jaramillo et al. (2025b).  *Figure 17: Interpolated aerosol number concentration of the sea spray plume generated by a moving vessel, created from aircraft transects at multiple heights up to cloud base (Hernandez-Jaramillo et al. 2025b).*
13.	Development of aircraft and vessel-based measurement and sampling techniques. These will need to develop as the technology scales and influences a larger	The development of advanced aircraft and vessel-based measurement and sampling techniques is essential for accurately assessing the effects of MCB as the technology scales. As MCB operations expand both horizontally across larger oceanic regions and vertically through different atmospheric layers, instrumentation must evolve to capture key data on aerosol dispersal, cloud microphysics, and radiative effects.

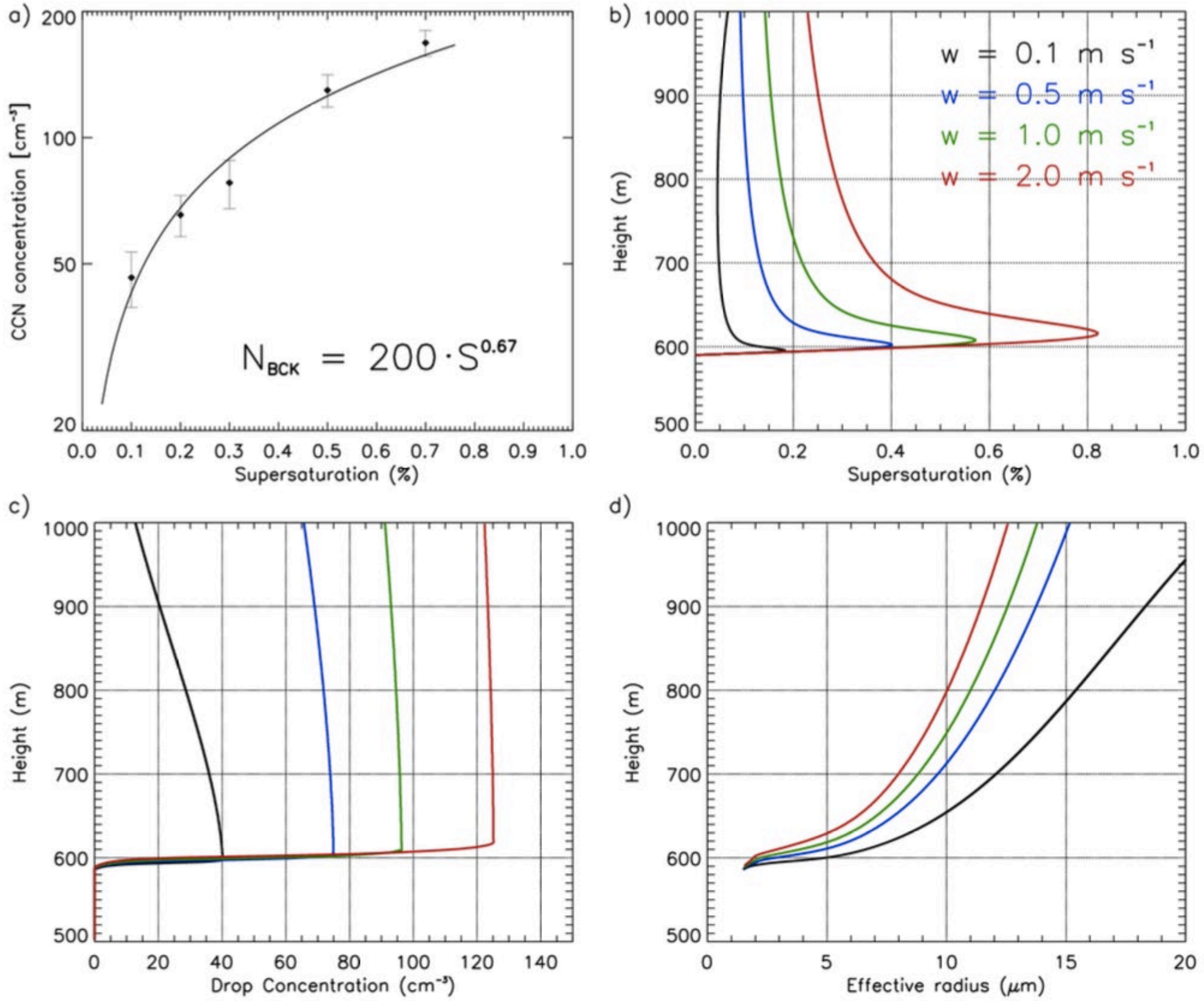
Objective		Key Findings and/or Outcomes
	area horizontally as well as extending vertically.	Over the life of the project the measurement and sampling strategies have evolved from nearfield characterisation of the plume dispersion using instrumented drones (Eckert et al. 2023; Hernandez-Jaramillo et al. 2023; Eckert et al. 2024; Ryan et al. 2024) to meteorological, and aerosol-cloud interaction studies using aircraft (Hernandez-Jaramillo et al. 2024; Braga et al. 2025; Hernandez-Jaramillo et al. 2025b). The SCU research aircraft was developed as a comprehensive meteorological, aerosol, cloud microphysics, and remote sensing instrumentation platform with a focus on supporting marine cloud brightening research (Hernandez-Jaramillo et al. 2024). The aircraft is equipped with cloud microphysical instrumentation for in-situ sampling of cloud droplet size distributions, aerosol concentrations and mapping of cloud albedo using a broadband hyperspectral sensor. Meanwhile, vessel-based systems continuously monitor sea salt aerosol generation, plume dispersion, and surface-level meteorological conditions, ensuring a comprehensive understanding of how injected particles interact within the marine boundary layer. As MCB efforts scale, integrating multi-platform measurement strategies will be vital to track both localised and larger-scale atmospheric responses. The vertical dimension presents unique challenges, as aerosol-cloud interactions extend into different atmospheric layers, requiring coordinated sampling from surface ships, drones, and aircraft. Additionally, satellite remote sensing has played a complementary role providing broader spatial context for ground and airborne measurements.

Objective		Key Findings and/or Outcomes
		 *Figure 18: Evolution of the RRAP Cooling and Shading MCB sampling strategy as the experimental program progressed over multiple annual campaigns (Harrison et al. in-prep).*
14.	Preparation for major field trials, including refinement of sampling techniques, on-land testing, setup calibration and operation of airborne platforms,	Five major MCB field trials have been conducted during the first five-years of RRAP. Campaigns were conducted offshore Townsville in the region of Broadhurst Reef, in the Whitsundays near to Hamilton Island, and in the region of Heron Island offshore Gladstone. Campaigns required considerable co-ordination and planning, typically involving multiple research vessels, drone operations, aircraft operations, and background atmospheric research teams stationed across one or more island research stations.

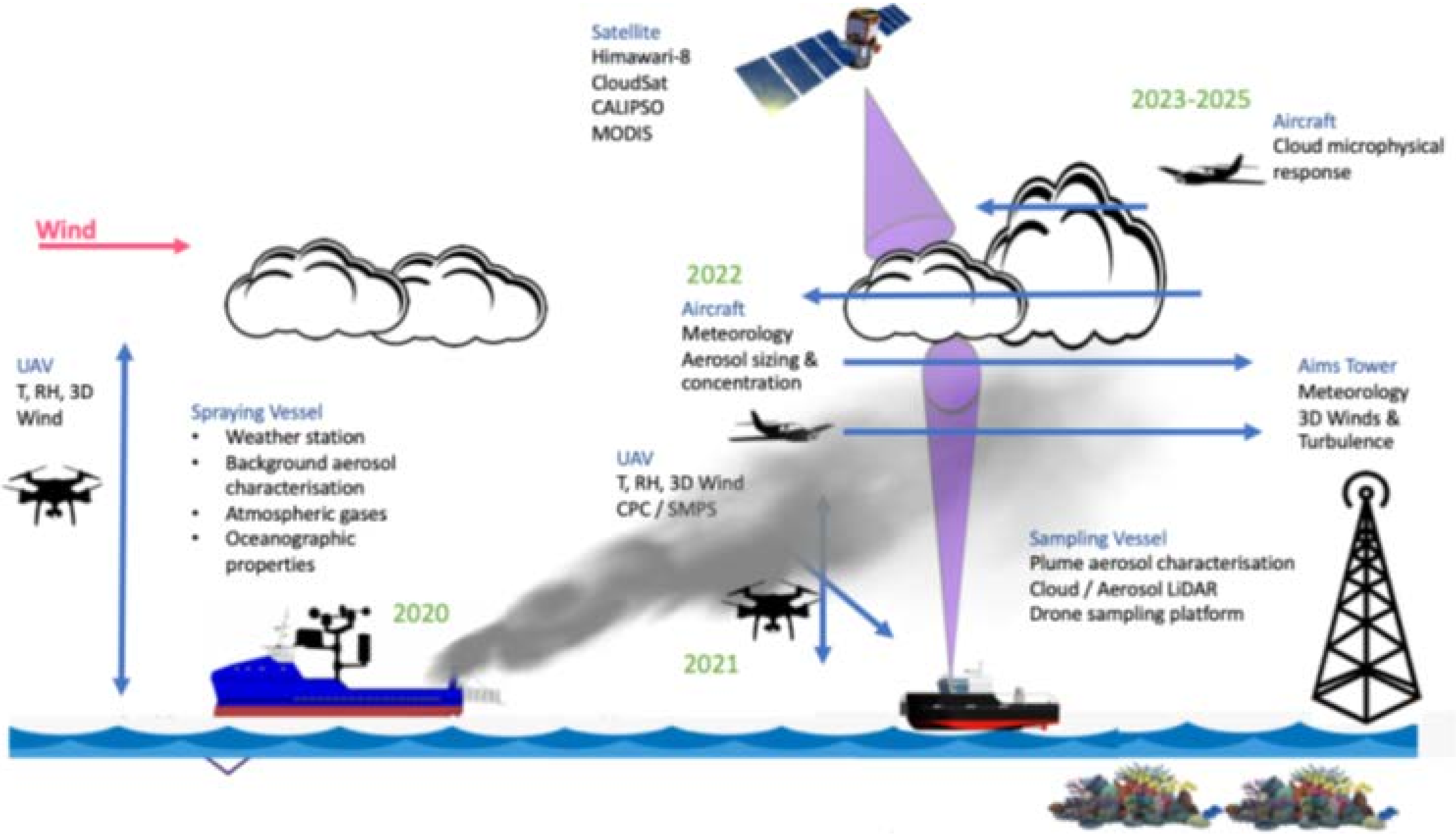
Objective		Key Findings and/or Outcomes
	satellite analysis and site selection, planning (all partners)	Pre campaign planning included producing whitepapers for sampling strategies, refinement of aerosol sampling techniques, completion of on-land system testing, calibration of instrumentation and upgrades and operational readiness preparation of airborne platforms. Satellite data analysis and meteorological assessments have been used to inform site selection, while collaborative planning with all project partners has ensured logistical alignment and scientific integration across the multi-institutional and multi-disciplinary components. Research permits have been obtained for all fieldwork in the marine park from the Great Barrier Reef Marine Park Authority. These preparatory efforts have positioned the team for successful execution of the large-scale field campaign with a commitment to safety and inclusion of Traditional Owners in fieldwork being high proprieties in the organisation of the field campaigns.  *Figure 19: An example aircraft sampling strategy for the 2023 field campaign.*
15.	Computational fluid dynamics modelling as required to support engineering development	Due to the complexity of the flow within a nozzle, experimental measurements by themselves are generally not sufficient to determine the optimal design and operation of a spray nozzle. Computational Fluid Dynamics (CFD) provides a complementary tool to analyse multiphase flows under a wide range of configurations through the generation of very detailed data sets. Computational Fluid Dynamics works by discretising the partial differential equations governing fluid flow onto a grid, that is a network of many small computational cells which approximates the physical geometry of the system under investigation. Together, the experimental and CFD approaches can be used to

Objective	Key Findings and/or Outcomes
of nozzles and spraying prototypes	design nozzles which meet all requirements for MCB. To produce 10^{16} s^{-1} droplets with a monodisperse distribution with a diameter between 120 and 800 nm (30 - 200 nm dry salt crystal diameter) for the minimum amount of energy possible.  *Figure 20: Instantaneous planar images of modelling parameters showing the predicted droplet breakup from a liquid jet, adapted from Yu et al. (2024).* To achieve these aims, it is essential to have a solid understanding of the flow regimes inside and outside the nozzle and the transitions between these regimes under different flow conditions. The flow regions of interest here are both the internal flow within the nozzle and the external flow of the spray. Atomisation itself can also be divided into two regions: the primary atomisation region (where interaction

Objective		Key Findings and/or Outcomes
		between the liquid and air phases generates shear along an interface and deforms the liquid into large droplets and ligaments) and the secondary atomisation region (where larger droplets and ligaments breakup and evaporate into smaller sizes). The internal flow is a two-phase mixing problem within the nozzle. To make a good prediction of the external flow where the spray forms and eventually becomes an atmospheric plume, it is essential for the solver to capture the correct flow behaviour within the nozzle, such as bubbly flow, slug flow and annular flow depending on the internal nozzle geometry and the operating conditions. The mixing of the liquid and air within the MCB nozzle, which appears to be a complex process that can be affected by various factors was examined. The shape of the leading edge of the liquid stream is a crucial factor that can cause oscillatory growth of interface instabilities, leading to undesirable oscillations, large liquid fragments and negatively impacting nozzle performance. To control the desired air-water state at the nozzle exit, the location of the roll-up phase of the interface instability along the axial direction of the nozzle can be varied. A shorter distance to the exit can avoid fully blocking the air passage, while a longer distance can favour liquid-air mixing to produce a more uniform liquid film or effervescent stream. The operation variation suggests that an axial liquid jet with a radial injection of air, for instance, produces a very compact jet break-up region with a fast decay along the axial direction of the liquid fraction. However, simulations suggest that this configuration may be susceptible to long-time transients, ultimately leading to less uniform spray generation. To avoid interference with the air flow caused by up and down flapping of the liquid sheet, a flow blurring configuration with external mixing may be a potential avenue. By incorporating external mixing, the nozzle's performance can be improved, and the production of a more uniform spray can be achieved. The development of the model code is described in the RRAP publication by Yu et al. (2024), and is further described with respect to droplet breakup and atomisation in Yu et al. (in-press, Applications in Energy and Combustion Science).
16.	Work with modelling team to underpin fieldwork with multiple scale atmospheric modelling to constrain expected response of cloud microphysical and radiative properties	The multi-institutional modelling team has supported fieldwork throughout the project with multi-scale atmospheric modelling. This work is detailed in the accompanying report for the RRAP Environmental Modelling Project (CS-03). Collaborative efforts have enabled the integration of observational data into both regional and process-scale models, helping to constrain the expected response of cloud microphysical and radiative properties to MCB interventions. This modelling work has informed site selection, guided deployment strategies, and provided valuable context for interpreting field measurements, thereby strengthening the scientific basis for ongoing and future MCB field trials. An example of cloud parcel modelling used to constrain the expected cloud microphysical response as a function of updraft speed is shown in Figure 21.

Objective	Key Findings and/or Outcomes
	 *Figure 21: a) Mean concentration of CCN as a function of supersaturation (S) for background conditions (between 31000 s and 36000 s after 00 UTC; see Figure 2). Twomey`s formula is shown for the CCN spectra. The error bars indicate the standard deviation of measurements in each S. b) Vertical profile of supersaturation near cloud base for different prescribed updraft speeds (indicated by colours in the upper-right). c) and d) Simulated number concentration of droplets and cloud droplet effective radius for different cases, respectively.*

Objective		Key Findings and/or Outcomes
17.	Conduct multiple vessel – multiple aircraft atmospheric perturbation experiment to assess efficacy of large-scale cooling and shading	To assess the potential of MCB as a large-scale Cooling and Shading intervention, coordinated multi-platform atmospheric perturbation experiments were conducted across Years 2 to 5 of the Project. These involved the deployment of vessels for aerosol generation and sampling, alongside fixed-wing aircraft and Unmanned Aerial Vehicles (UAVs) equipped with meteorological and cloud microphysics instrumentation. During each campaign, sea salt aerosols were released from a primary spray vessel while a secondary sampling vessel, aircraft, and UAVs tracked the resulting plume and cloud response. This integrated approach enabled simultaneous *in situ* and remote sensing observations of aerosol dispersion, cloud albedo changes, and shortwave radiative forcing across various atmospheric conditions and geographic locations in the central and southern Great Barrier Reef. The experimental approach and its evolution across the yearly summertime field campaigns throughout the project is illustrated in Figure 22.

Objective	Key Findings and/or Outcomes
	 *Figure 22: Indicative sampling design of the RRAP MCB field campaigns. Years indicate the year that sampling platform was added to the measurement campaign. Output of the spraying system was increased iteratively over the duration of the project (from Harrison et al. in-prep).* The use of multiple platforms enhanced the spatial and temporal resolution of measurements, allowing for robust evaluation of MCB efficacy. These experiments provided critical insight into the consistency of cloud responses to aerosol injections, the influence of background meteorology, and potential secondary effects, such as cloud lifetime and precipitation changes. Collectively, these findings have advanced understanding of the feasibility and scalability of MCB as a climate intervention to reduce coral bleaching risk.

Objective		Key Findings and/or Outcomes
18.	Analysis and interpretation of the data to the extent possible in the time frame	Initial assessments have been completed across key datasets, including aerosol properties, meteorological conditions, and radiative measurements. Results from earlier year field campaigns have been published while later year results remain in review and in-prep, due to the significant amount of time required to process, quality control, collate, analyse, and write up results from major multi-platform multi-institutional field campaigns. A very large quantity of *in situ* measurements of cloud properties and their response to the MCB added aerosols have been collected in 2024 and 2025. It will take some time for these to be fully analysed and combined with the datasets collected onboard the two research vessels, as well as the surface and satellite based remote sensing observations. The majority of assigning individual datapoints, collected by the aircraft within-clouds, to the presence or absence of the MCB aerosol plume has been completed. As a result, some initial findings and results are now available, showing evidence of the expected cloud response to MCB seeding signature. An example is provided in Figure 23. It is evident that the seeded clouds contain a much larger number of droplets for the same total cloud water content. This means the same amount of water is distributed over a greater number of particles, resulting in a larger number of smaller cloud droplets. These results confirm the ability of the current MCB equipment to generate the predicted brightening responses in low cloud over the

Great Barrier Reef. Ongoing analysis will provide statistically robust insight into the strength of the cloud microphysical response and the factors which are influential in controlling its magnitude.

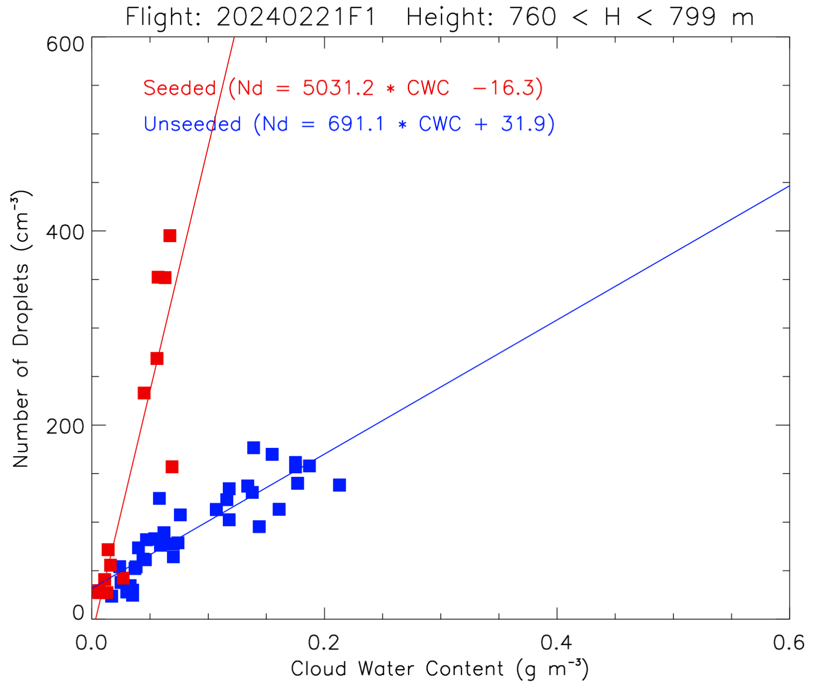


Figure 23: An example of the dramatically changed relationship between cloud liquid water content and the concentration of cloud droplets between MCB seeded and unseeded adjacent clouds, from aircraft transects between 760 and 799 m altitude.

As with the aircraft data, analysis of satellite observations (Figure 24) of cloud microphysical response to the MCB perturbations is also preliminary and ongoing. However, the results processed so far have shown encouraging responses in some cases, suggesting that under the right conditions, particularly lower wind speeds, the current MCB prototype and experimental approach are sufficient to detect the cloud response from space. Nevertheless, due to the methodology, the statistical power of this approach is significantly lower than the *in situ* measurements collected by aircraft.

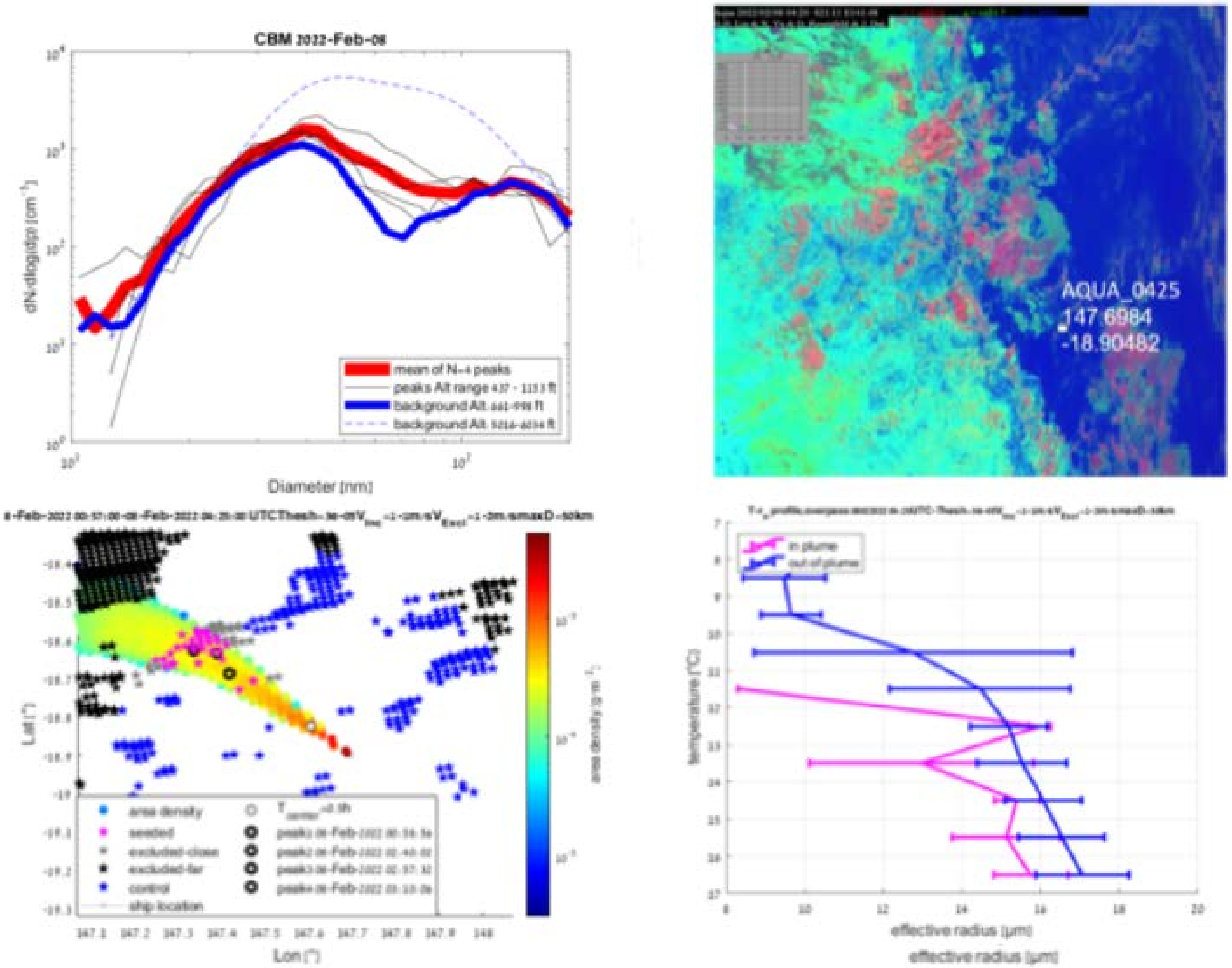


Figure 24: Satellite retrieval of cloud droplet effective radius for pixels within and away from the MCB plume during an MCB experiment on the Great Barrier Reef in 2022 (top left). Aircraft measured size distributions for plume and background aerosols (top right). Microphysical RGB image of the relevant overpass and ship location (bottom left). Image showing the retrieved cloudy pixels and those deemed to be

Objective	Key Findings and/or Outcomes
	within the plume using a simple expanding bubble plume model (bottom right). Vertical profile of cloud droplet effective radius for within and without cloud properties. As they have become available, these preliminary results have been used to inform model parameterisation, evaluate system performance, and identify emerging patterns in aerosol-cloud interactions. This analysis provides a solid foundation for more detailed interpretation and supports ongoing refinement of MCB intervention strategies. It also underpins publications that have already been submitted, as well as a number that are currently in preparation.  *Figure 25: Marine cloud brightening compressor repairs during field trials on the Great Barrier Reef 2023.*

Adjustments to key research objectives

Table 2: Variation in the Project over time.

Initial Research Question	Explain when, how and why the research question changed
No adjustments to report	

4 Future Research Recommendations

The past five years of marine cloud brightening (MCB) research conducted by Southern Cross University and RRAP partners has provided a robust foundation for understanding the operational, meteorological, and radiative characteristics of engineered sea spray aerosol plumes in atmospheric conditions over the Great Barrier Reef. Building on these advances, the following recommendations are proposed to guide the future direction of MCB research, development, and deployment:

1. **Refinement and scaling of spray systems**
   Further engineering innovation is required to improve the energy efficiency and scalability of the ARIEL seawater atomisation system. Future work should focus on improving the current effervescent technology as well as explore alternative nozzle technologies which may offer higher energy efficiency, improved droplet size distributions, and higher output in simpler and smaller plant. Several promising technologies have been investigated during this project and should be researched further including electrospray (Taylor cones), superheated spray (Flash boiling), and Rayleigh jet breakup.

2. **Expanded outdoor experiments and modelling to further understand cloud processes**
   To better quantify the broader environmental effects of MCB, observations collected during the outdoor field campaigns should be further investigated with high-resolution atmospheric modelling, including cloud-resolving models and large-eddy simulations. Extensive in-situ datasets have been collected over the course of this project and in the two most recent campaigns using the SCU aircraft extend to comprehensive datasets covering a full suite of meteorological, aerosol, cloud microphysical, and radiative measurements suitable for validating high resolution modelling. Priority should be given to understanding the interactions between MCB plumes and natural cloud formation processes under a wider range of meteorological conditions and contexts relevant to the GBR atmosphere.

3. **Long-Term Monitoring and Baseline Data Acquisition**
   Establishing a consistent, long-term aerosol and cloud properties monitoring framework across multiple reef locations is needed to provide essential data for developing a climatology to inform estimates of the overall efficacy of MCB and marine sky brightening (MSB) on the reef. Such a monitoring network will also be required to differentiate MCB signals from natural variability. Preliminary work has been undertaken to establish a proof-of-concept station on One Tree Island in the Southern GBR. Expansion to a network of permanent in situ and remote sensing instruments for aerosol, cloud, and radiation measurements, along the length of the GBR operating both during and outside of active spraying periods is a medium-term goal and would provide value to the atmospheric sciences community far beyond this project. This is especially important given the strong links our research has uncovered between meteorological processes and mass coral bleaching events on the reef (see RRAP Atmospheric Survey (CS-01) Final Project Report).

4. **Assessment of Ecosystem and Climate Feedback**
   Future studies should further investigate the downstream effects of MCB/MSB induced changes in cloud properties on local weather patterns, surface heat fluxes, and ecological processes in coral reef ecosystems. The foundational work for these studies has been completed with the establishment of a suite of appropriate and verified models over a range of domain sizes, resolutions, and approaches (See RRAP Environmental Modelling (CS-03) Final Project Report). Coordinated biophysical monitoring will help determine whether short-term reductions in solar irradiance translate into measurable benefits for coral health and reef resilience over the longer term. A systematic identification of the potential unintended impacts of atmospheric intervention over the GBR for bleaching mitigation is a high priority for future research.

5. **Operational Feasibility and Deployment Strategies**
   Further work is also needed to evaluate the operational feasibility of MCB at larger spatial and

temporal scales. This includes determining suitable deployment scenarios and operational windows, evaluating infrastructure and logistics requirements, and identifying conditions under which MCB would be most beneficial, cost effective, and lowest risk. Simulated deployment scenarios should be explored to inform adaptive operational strategies under current and future climate conditions.

6. **Regulatory, Ethical, and Governance Considerations**
   As field trials advance, parallel efforts must continue to develop governance frameworks that ensure transparency, accountability, and social licence. This includes working with Traditional Owners, reef managers, policymakers, other stakeholders and the broader public to co-design engagement processes and the future research program and establish clear consent and oversight mechanisms as the research further progresses. For further information on these aspects the reader is directed to the RRAP Stakeholder and Traditional Owner Engagement (ENG-01) Final Project Report, as well as the RRAP Cooling and Shading Sub-program Management (CS-04) Final Project Report.

7. **Intervention Synergies and Integrated Solutions**
   The MCB and MSB interventions should be evaluated alongside other reef adaptation interventions and traditional management approaches to assess potential combined or complementary effects. Ecological modelling undertaken by RRAP highlighted the potential for very strong synergies when multiple interventions were applied simultaneously (Condie et al. 2021). Integration with local shading approaches such as fogging (Harrison 2024), coral restoration efforts, other RRAP interventions, water quality improvement programs, or efforts to control crown of thorns starfish outbreaks may offer synergistic benefits that enhance overall reef resilience and protection outcomes.

Figure 26: Reflecting on the marine cloud brightening plume during low wind conditions on the Great Barrier Reef 2025.

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Figure 27: Sun-tinged clouds over the Great Barrier Reef during marine cloud brightening field trials in the Great Barrier Reef 2025

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