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Harrison, D. P., Huang, Y., Woodhouse, M., Schofield, R.,
Chavez, S., Jackson, R., Ryan, R., Zhao, W., Harrison, L., B
raga, R., and Holloway, C.

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This report summarises work undertaken under *Environmental Modelling (CS-03)* in accordance with the Reef Restoration and Adaptation Program’s *Cooling and Shading* Project Agreements. It provides a summarised, point-in-time synopsis of activities, methods, findings and outcomes completed in accordance with the approved project scope up to 30 June 2025.

All information reflects project scope and outcomes as of May-June 2025. Subsequent updates, analyses, or scientific developments are not included. This report should be read alongside any associated and publicly available technical reports, datasets, and publications for full detail. This report does not provide scientific inferences, policy guidance or operational instructions beyond the project’s defined scope and duration.

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The RRAP partners acknowledge Aboriginal and Torres Strait Islander Peoples as the first marine scientists and carers of Country. We acknowledge the Traditional Owners of the places where RRAP works, both on land and in sea Country. We pay our respects to Elders, past, present, and future, and their continuing culture, knowledge, beliefs, and spiritual connections to land and sea Country.

We specifically acknowledge and thank the following Traditional Owners of sea Country that this report relates to:

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

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1 Executive Summary

Within the Reef Restoration and Adaptation Program - Cooling and Shading Sub-program (RRAP C&S) two key interventions: Marine Cloud Brightening (MCB) and Seawater Fogging both involve spraying atomised seawater to introduce additional sea spray aerosols to the atmospheric marine boundary layer. Seawater fogging is a highly localised intervention, seeking to shade corals by creating a fog of humidified seawater aerosols directly over areas of coral reef at scales of up to tens of hectares. Marine Cloud Brightening on the other hand is intended to operate at scales of up to hundreds of thousands of square kilometres. The goal would be to reduce thermal stress on coral reefs by increasing cloud reflectivity over the ocean for prolonged periods (months). By reflecting solar radiation away from the water's surface, MCB and seawater fogging have the potential to cool and shade targeted regions of the reef, mitigating the thermal and light stress that lead to coral bleaching.

As part of RRAP Environmental Modelling Project (CS-03), the RRAP Cooling and Shading Sub-program has developed, configured and evaluated a 'hierarchy' of numerical models to represent a wide range of atmospheric and oceanic environmental processes at domain scales ranging from tens of kilometres to thousands of kilometres, and resolutions from tens of meters to thousands of metres. These include Large Eddy Simulation (LES) models using Cloud Model 1 (CM1), atmospheric models across multiple nested scales using the Weather Research and Forecasting (WRF) model and WRF coupled with chemistry (WRF-Chem), and a coupled atmospheric-ocean-biogeochemical model (ACCESS-EMS-GBR). Together, these models enable simulations and assessments of the potential efficacy, impacts, and risks of marine cloud brightening across different time scales, weather conditions, and implementation scenarios. Confidence in the simulations results from challenging the models with real world measurements during the development phase and having overlapping spatial scales across the hierarchy. The models are referred to collectively as the Cooling and Shading Modelling Suite and enable study of what cannot be tested in the laboratory and field.

The LES model provides fine-scale resolution, capturing processes at scales of tens of meters, which is essential for understanding the behaviour of the sea spray aerosol plumes once they are introduced into the atmosphere. By simulating sea spray injection events from the current experimental prototype or future hypothetical full-scale ocean-based sprayers, the LES model allows research to investigate how wind speeds, boundary layer turbulence, temperature gradients, and humidity affect aerosol dispersion and elevation. These variables are crucial for determining how effectively aerosols can reach cloud condensation levels and contribute to the cloud brightening effect central to MCB.

LES modelling has confirmed that wind speeds play a significant role in the plume dispersion of MCB. For example, simulations have shown that under higher wind speeds such as typical trade winds in the Great Barrier Reef (GBR), aerosol plumes are transported vertically more rapidly and to a greater extent, allowing the particles to serve as cloud condensation nuclei (CCN) and increase cloud density and reflectivity. These findings are significant for understanding and optimising MCB as well as interpreting results of initial field trials such as those described in the RRAP Cloud and Sky Brightening Development Project (CS-06). They suggest that meteorological conditions have important implications for developing deployment strategy of aerosol injections to enhance the cloud shading effects in targeted regions. By providing granular data on plume dispersion and potential CCN formation, LES modelling informs broader strategy considerations for MCB deployment, allowing interventions to be timed with peak efficacy and efficiency.

To investigate the atmospheric processes impacted by MCB, this project employed WRF and WRF-Chem, which in the case of WRF is run at fine enough resolutions to be cloud resolving. These regional scale models bridge the gap between high resolution LES modelling of a single injection site, and the broader continental or subcontinental scale of the ocean-atmosphere coupled models. WRF incorporates a detailed treatment of cloud microphysics, as well as a coupled radiative transfer model and detailed treatment of atmospheric

chemical processes. WRF-Chem additionally considers aerosol microphysics. WRF-Chem and WRF can be used to study how MCB-introduced aerosols behave within the regional climate system, particularly in terms of precipitation dynamics, cloud life cycle, and pollutant movement. WRF simulates MCB using a single variable number representing cloud condensation nuclei, whereas WRF-Chem includes a chemically-speciated and size-resolved aerosol scheme. Through these models, researchers can assess how increased aerosol concentrations alter cloud properties such as droplet number, albedo, optical thickness, longevity, and spatial distribution, providing insights into MCB's potential effects beyond the immediate cooling impacts on coral reefs.

WRF and WRF-Chem findings highlight for the first time the potential benefits and efficacy of MCB in the types of meteorological conditions and cloud structures prevalent over the Great Barrier Reef (GBR). The WRF simulations demonstrated that trade wind cumuli play a critical role in regulating surface energy balance and are sensitive to local forcings such as aerosol loading and sea surface temperature anomalies. Sensitivity experiments revealed that aerosol injections can alter cloud microphysics, enhancing droplet number concentrations, albedo, and optical depth, thereby producing significant localised cooling and shading benefits. These results underscore the importance of carefully considering wind regimes and cloud structures when designing interventions, as mesoscale processes and coastal topography strongly influenced the magnitude and spatial distribution of the cooling effect.

WRF-Chem extended this analysis by explicitly resolving aerosol size and chemical composition, allowing both direct radiative and indirect cloud-mediated effects to be assessed. Simulations confirmed that the efficiency of MCB depends strongly on aerosol size, with dry diameters in the 40–130 nanometre (nm) range producing the most effective cloud condensation nuclei (CCN) responses. Importantly, WRF-Chem revealed broader atmospheric implications, including increased surface shortwave radiation following reductions in ship-sourced sulfur emissions, a regulatory shift in 2020 that may have inadvertently exacerbated coral bleaching risk. Additional experiments highlighted potential downstream effects, such as changes in acid gas concentrations and modest increases in PM_{2.5} (particles with a diameter of 2.5 micrometres or less) when spraying occurred within the GBR. Collectively, the WRF and WRF-Chem findings establish that while MCB is technically feasible and potentially beneficial for reducing coral heat stress, its deployment must be optimised to balance efficacy with minimisation of unintended regional atmospheric and air quality impacts.

The ACCESS-EMS-GBR coupled modelling framework developed in this project represents a significant advancement in the capability to assess the efficacy and potential risks of MCB for the Great Barrier Reef on regional scales. By integrating the Australian Community Climate and Earth System Simulator (ACCESS) atmospheric model with the CSIRO Environmental Modelling Suite (EMS), the system explicitly resolves aerosol–cloud–radiation–ocean–coral–symbiont interactions. The model successfully simulates the impacts of sea salt injections on atmospheric properties, including cloud condensation nuclei formation, cloud albedo, and radiative forcing, while simultaneously capturing feedback on ocean temperatures, light propagation, and coral bleaching risk. Key results indicated that injections of appropriately sized sea salt aerosols (40–130 nm dry diameter) demonstrably increases cloud droplet number concentrations, enhance cloud reflectivity, and reduce downwelling solar radiation at the sea surface. Importantly, these changes were largely confined to the GBR and coastal northeast Australia, indicating that the intervention can deliver localised cooling benefits without adverse impacts on regional meteorology.

The simulations further demonstrated that the intervention's apparent impacts on precipitation were minimal, with changes in mean daily rainfall and total summer precipitation considerably less than the natural interannual variability, even under extreme aerosol injection scenarios. These early findings suggests that MCB can be achieved with negligible alteration of hydrological patterns across the GBR region. The model also incorporated improved representations of biogeochemical feedback, including dimethyl sulfide (DMS) production by reef organisms, thereby allowing assessment of both natural and artificial contributions to atmospheric aerosol loading. Collectively, the ACCESS-EMS-GBR findings provide robust evidence that

regional-scale MCB can reduce thermal and radiative stress on corals during bleaching conditions, with limited risk of unintended large-scale atmospheric impacts. These results establish the coupled model as a critical tool for optimising intervention parameters, such as particle size, emission flux, and spatial deployment, while simultaneously evaluating ecological outcomes for reef ecosystems.

The range of modelling approaches has enabled the RRAP Environmental Monitoring Project (CS-03) to address the specific atmospheric conditions over the reef that influence cloud microphysics, such as droplet size distribution, cloud optical properties, and precipitation behaviour. By incorporating high-resolution observational data from the GBR and surrounding regions collected by the RRAP Cooling and Shading Sub-program, the project has refined its modelling to capture the unique environmental drivers affecting cloud formation in this area. This targeted approach allows for a more accurate assessment of how MCB could alter cloud characteristics in ways that could reduce heat stress on corals. Simulating these interactions leveraging the strengths of multiple modelling approaches offers insight into how interventions might perform under diverse atmospheric conditions and drives understanding of the multitude of micro and macroscale environmental processes involved from nanometre scales of aerosol chemistry interactions through to mesoscale processes of ocean circulation and heat transfer. Ultimately, this depth of understanding not only contributes to developing effective intervention strategies but also informs policies and conservation efforts by highlighting the interplay between atmospheric conditions and reef health, reinforcing the potential of climate interventions as part of an integrated strategy for coral reef resilience.

By employing a combination of modelling approaches and scales, including cloud-resolving models, the project has advanced our understanding of trade wind clouds, atmospheric chemistry, and their interactions with local forcing. These insights are important for assessing the potential of MCB to mitigate coral bleaching events and for informing future climate intervention strategies. Collectively, these findings validate MCB as a promising tool for reef conservation on the GBR. With the planned continued model refinement, these models could be expanded to simulate multi-seasonal and multi-year influences of MCB, allowing researchers to forecast the long-term viability and cumulative effects of aerosol injections on coral reefs and the surrounding ecosystem. Future research will focus on enhancing the spatial and temporal resolution of the models to capture finer-scale ecological interactions. In addition, aerosol injection parameters and chemical scheme optimisation will continue, utilising the extensive meteorological and atmospheric data sets collected during the RRAP GBR Atmospheric Survey Project (CS-01), the RRAP Cloud and Sky Brightening Development Project (CS-06) and the RRAP Fogging Development Project (CS-07), to explore optimal MCB approaches from a technical and risk-mitigation point of view.

The Project's innovative modelling techniques now offer a suite of tools and datasets for collaboration with Traditional Owner groups, policymakers, and environmental organisations, helping to communicate potential benefits and risks while allowing these stakeholders to provide input on intervention timing and location. This project fostered a unique collaboration between Southern Cross University, the University of Melbourne, CSIRO and the Australian Institute of Marine Science, each contributing specialised modelling systems and domain expertise. These efforts have led to the development of a greater understanding of atmospheric and meteorological conditions on the reef and the potential application of successful MCB deployment on the GBR.

2 Background and Justification for the Research

Coral reefs are among the most biodiverse and economically significant ecosystems worldwide, yet they are increasingly threatened by anthropogenic climate change (Hoegh-Guldberg 1999; De'ath et al. 2012; Hughes et al. 2017; Hughes et al. 2018). Rising atmospheric CO₂ concentrations have driven ocean warming, leading to recurrent marine heatwaves and mass coral bleaching events in nearly all tropical reef regions (Hughes et al. 2017). Bleaching occurs when corals, under combined thermal and radiative stress, expel their symbiotic dinoflagellates (Symbiodiniaceae), leading to loss of pigmentation and compromised energy acquisition (Lesser 1997). Without their symbionts, corals become highly vulnerable to disease and starvation, with mortality rates increasing when stress persists. For the Great Barrier Reef (GBR), the world's largest coral reef system, recurrent bleaching events in 2016, 2017, 2020, 2022, and 2025 have prompted research into interventions that can alleviate thermal and light stress on corals during marine heatwave events.

Marine Cloud Brightening (MCB) has been proposed as one such intervention, operating at regional scales by enhancing the albedo of marine stratocumulus and shallow cumulus clouds through the targeted injection of sea salt aerosols (Harrison 2018; Harrison et al. 2019; Harrison 2024). The technique aims to increase available cloud condensation nuclei (CCN), leading to more numerous but smaller droplets, raising cloud reflectivity (albedo) (Twomey 1974) and prolonging cloud lifetime (Albrecht 1989). By reflecting incoming shortwave radiation, MCB could reduce sea surface temperatures, thus mitigating coral bleaching risk (Harrison et al. 2019). Initial global climate modelling studies demonstrated that widespread MCB deployment could offset greenhouse warming, but they also highlighted uncertainties related to regional precipitation and circulation impacts (Bala et al. 2011; Kravitz et al. 2013). For the GBR context, where mesoscale meteorology and complex ocean-atmosphere interactions prevail, regional high-resolution modelling is essential to evaluate feasibility and risk.

Large Eddy Simulation (LES) models have been pivotal in advancing process-level understanding of MCB. LES resolves turbulence and convective eddies at tens-of-metres scale, capturing fine-scale aerosol dispersion, mixing, and cloud microphysics with fidelity that coarser models cannot achieve (Ackerman et al. 2009; Wang et al. 2009). Early LES studies of sea spray seeding demonstrated that the efficiency of aerosol activation depends on plume rise, humidity, and background CCN conditions (Wang et al. 2011; Wood et al. 2012). More recent LES experiments incorporating observational data have refined estimates of optimal particle size ranges for cloud albedo enhancement, highlighting that particles of ~50–200 nm dry diameter are most effective (Partanen et al. 2012). For the GBR, LES provides a crucial foundation to inform nozzle engineering, sprayer design, and experimental deployment strategies by quantifying how plumes evolve within the marine boundary layer under trade wind regimes.

While LES offers high spatial fidelity, it cannot simulate regional scales relevant to GBR-wide cooling. Regional weather and climate models such as the Weather Research and Forecasting model (Skamarock et al. 2008) are therefore employed to simulate mesoscale cloud dynamics and their response to MCB perturbations. WRF has been widely used to study marine stratocumulus behaviour, aerosol–cloud interactions, and boundary layer processes in subtropical oceans (Wang et al. 2011; Yang et al. 2011). Studies using WRF to simulate MCB have demonstrated that aerosol injections can brighten clouds, but the magnitude of albedo change is highly sensitive to background meteorological variability, aerosol size distribution, and vertical mixing (Hill et al. 2009; Stjern et al. 2018). For GBR conditions, where trade wind cumuli dominate, WRF's convection-permitting configurations enable assessment of how seeding influences shallow cumulus cloud fields, which are critical regulators of the regional energy budget and coral bleaching risk (Richards et al. 2024).

To build on the weather simulating capabilities, WRF has been coupled with detailed atmospheric chemistry modules (WRF-Chem), allowing explicit treatment of aerosol size, composition, and transformation processes (Peckham et al. 2017). WRF-Chem simulations and measurements have provided insights into the efficiency of different aerosol sizes for CCN activation, the role of existing anthropogenic and biogenic emissions, and potential side effects such as altered aerosol chemistry and air quality (Pringle et al. 2012; Chen et al. 2019).

The Australian Community Climate Earth System Simulator (ACCESS) suite of models includes global and regional atmospheric configuration. The latter, an implementation of the Unified Model Regional Nesting Suite, can be setup to simulate high resolution weather and aerosol-cloud interactions (Gordon et al. 2023).

The CSIRO Environmental Modelling Suite (EMS) has been configured for the GBR and often referred to as 'eReefs' (Baird et al. 2020). eReefs includes hydrodynamic and biogeochemical components and can simulate a range of inputs and effects on corals and symbionts, including light and heat stress, and coral bleaching. Separately, ACCESS and EMS can simulate the full range of processes relevant for MCB, but would do so in a non-interactive way if not coupled, missing potentially key feedback and interactions between atmosphere, ocean, and biology.

Coupled atmosphere-ocean models have been viable tools at the global climate scale for a number of decades but are rarely implemented at regional scales. Coupled regional models that consider the non-physical circulation components of a system (e.g. biogeochemistry) are yet to be developed. A tool to simulate the coupled atmosphere-ocean-biosphere system of the GBR is therefore absent, and is a necessary development to capture feedback between MCB, cloud radiative forcing, and reef-scale ocean responses. Such a system would allow for simulation of coral bleaching dynamics as a function of both light and temperature, thereby linking atmospheric interventions directly to ecological outcomes (Ellis et al. 2025). Previous coupled studies have shown that regional MCB could achieve significant reductions in surface heat stress without producing large precipitation anomalies (Jones and Haywood 2012; Kravitz et al. 2015).

There is a need for these various modelling approaches to be further developed and optimised to address critical uncertainties surrounding MCB. LES can be used to quantify plume behaviour and droplet activation at fine scales; WRF can provide cloud-resolving insights at the mesoscale; WRF-Chem extends this to chemical and aerosol speciation, including interactions with anthropogenic sources; and a regional coupled atmospheric-ocean-biogeochemistry system can be exploited to simulate the entire system, linking intervention efficacy to bleaching outcomes. Together, the desired suite of tools is necessary to allow robust multi-scale scenario testing, bridging gaps between experimental trials, engineering design, and ecological risk assessment. Such integration is essential given the spatially heterogeneous and climatically variable nature of the GBR, where interventions should be precisely targeted and adaptively managed.

The rationale for this project lies in addressing a suite of research questions that span this modelling hierarchy. Specifically, the project seeks to: (1) use LES to refine experimental design and quantify plume transport and cloud microphysical response; (2) employ WRF-Chem to characterise sources, sinks, and transformations of aerosols in the GBR atmosphere across intra- and interannual scales; (3) apply cloud-resolving WRF and bin microphysics schemes to assess aerosol-radiation-cloud interactions across nested scales; (4) utilise nesting to bridge LES and regional coupled model domains; (5) develop a high-resolution coupled atmosphere-ocean framework for integrated atmosphere-ocean-reef assessments; (6) test scenarios to evaluate potential continental-scale teleconnections and unintended consequences; (7) refine radiative transfer and bleaching sub-routines within eReefs, including DMS feedbacks; and (8) assess in-water efficacy of cooling and shading interventions to reduce bleaching stress.

By systematically applying this multi-model strategy, the RRAP Cooling and Shading Environmental Modelling Project (CS-03) provides a uniquely comprehensive framework for evaluating the feasibility, efficacy, and

risks of MCB as a targeted reef protection measure. The outputs will inform experimental field trials, engineering design of sprayers, governance frameworks, and ecological monitoring, ensuring that any potential deployment is based on rigorous scientific evidence. Ultimately, this research aims to determine whether MCB can form part of an adaptive portfolio of interventions to safeguard the GBR in the face of escalating climate change, while minimising risks to the wider regional climate system.

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
<p>1. Large Eddy Simulation (LES) modelling of fine scale physical transport, convective and cloud microphysics processes to inform experimental design, system design engineering, and assess cloud microphysical response.</p>	<p>The Cloud Model 1 (CM1) (Bryan and Fritsch 2002) was used generate a large eddy simulation configuration representative of a typical summertime trade wind condition over the Great Barrier Reef. The model was configured using data collected during the 2023 field campaign conducted by the RRAP Cooling and Shading GBR Atmospheric Survey Project (CS-01) and the European Centre for Medium-Range Weather Forecasts Reanalysis version 5 (ERA5) reanalysis product. The model was compared with data collected by the SCU aircraft and showed good skill in reproducing the cumulus cloud field observed.</p> <p>Aerosols injected into the atmosphere from a vessel over the GBR ocean were simulated in the model as a continuous source. The aerosol mixing ratio field shows high horizontal heterogeneity as observed in the field (Figure 1). Aerosol availability is dependent on the distance from the source, using an iso-surface to determine the aerosol plume structure each 60 seconds revealed that the plume dispersion and hence overall shape appears to be determined by the population of differently sized eddies in the atmospheric marine boundary layer (AMBL). The increase of aerosol available, in the AMBL due to the dispersion, to be activated into cloud droplets has a complex time evolving three-dimensional structure. The increase of aerosol availability for each grid point was introduced in the parameterisation of activation (Abdul-Razzak and Ghan 2002) used by the Microphysics scheme of Morrison et al. 2005.</p>

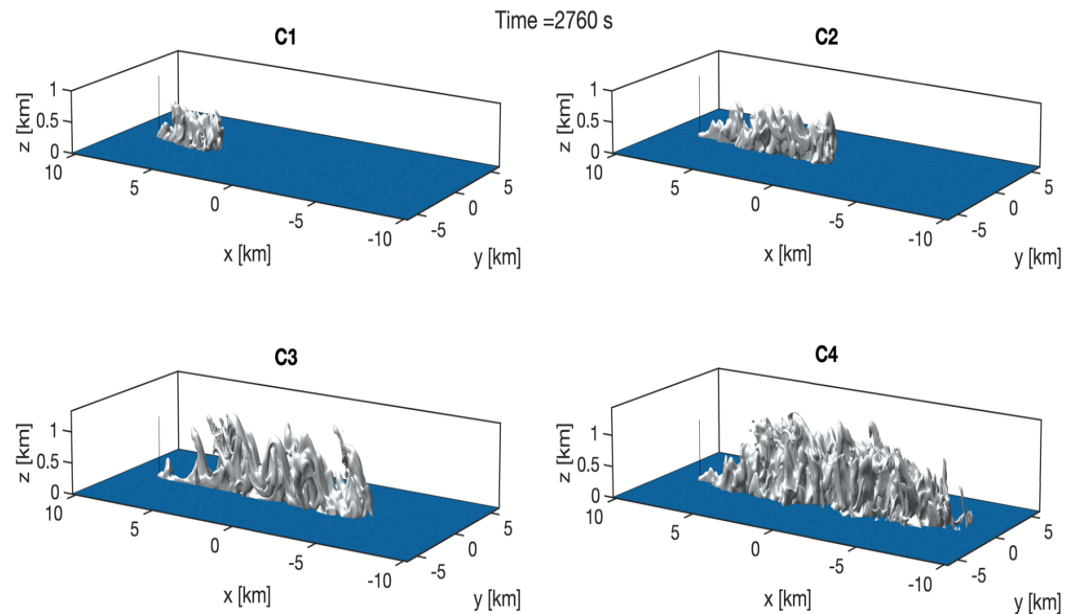
Objective**Key Findings and/or Outcomes**

Figure 1: LES simulation of aerosol mixing ratio field displayed as an isosurface of $0.039 \times 10^{-3} \text{ g Kg}^{-1}$ from a continuous single source after 2760s for cases 1, 2, 3 and 4

On a typical day in the GBR, the sky can be populated with cumulus clouds which are the same clouds simulated by the model in the four cases analysed. In these conditions, the simulated injected aerosols dispersed in the AMLB encompass several orders of magnitude. The spatial variability of the dispersed aerosol concentration can be conveniently captured in Counter Frequency by Altitude Diagram (CFAD).

As the aerosol plume rises, the amount of aerosol greater than $0.039 \times 10^{-3} \text{ g/kg}$ becomes less common with height. The CFAD shows nearly the full height of the plume and helps us measure how high the aerosols reach (Figure 1). Across all four simulations,

Objective**Key Findings and/or Outcomes**

stronger winds lead to the mixing of aerosols more rapidly to higher altitudes and aerosol concentrations between 10 and 100 particles per cubic centimetre.

This means that in windier cases (C3 and C4), more aerosol particles are carried higher into the atmosphere while still at reasonable concentrations, increasing the chance they can act as cloud condensation nuclei (CCN). One reason for this stronger vertical transport could be the presence of larger air eddies mixing the particles upward.

The full description and results of this work are currently under consideration (in-review) for publication.

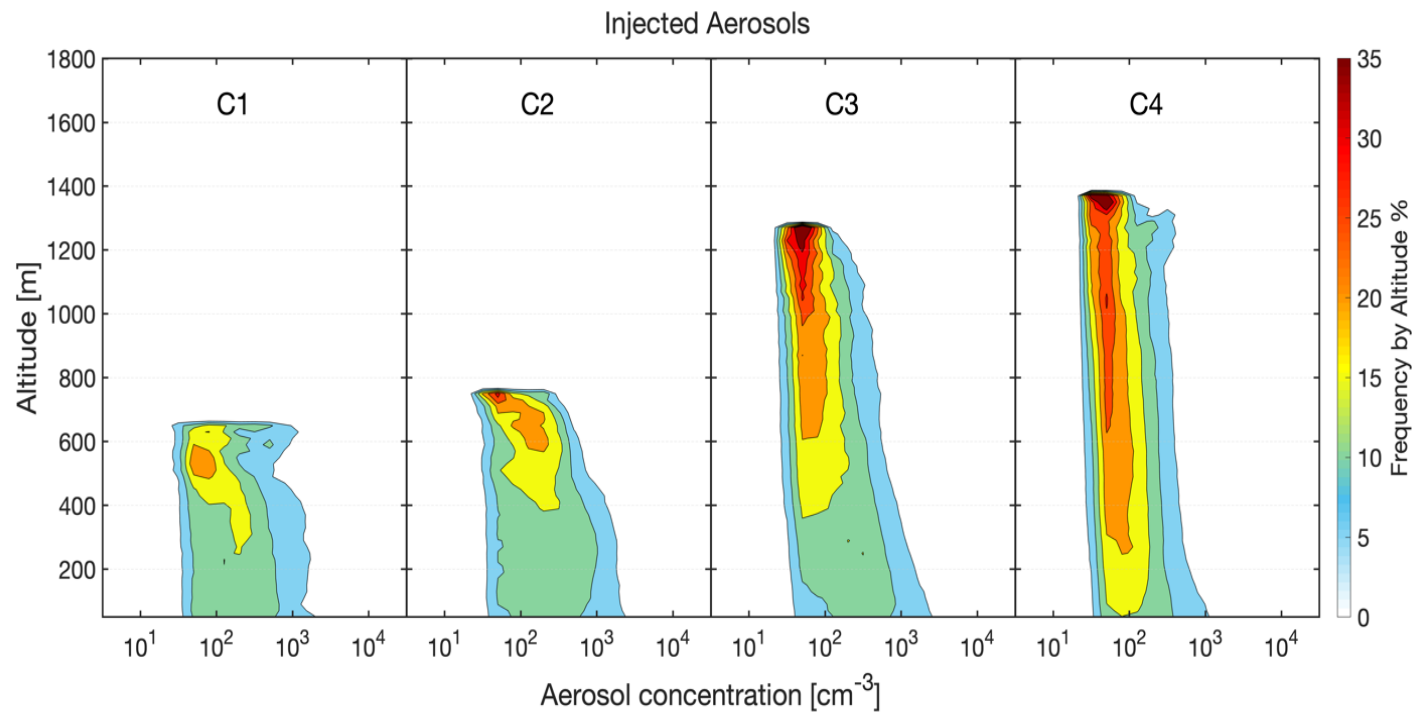


Figure 2: CFAD of aerosol concentration for the simulation period 960-2760s for cases 1,2,3, and 4.

Objective	Key Findings and/or Outcomes
<p>2. Atmospheric marine aerosol modelling to adequately capture source, sink, transformation, and transport processes of the Reef region and intra/inter annual variability.</p>	<p>A regional-scale modelling framework for use over the Great Barrier Reef (GBR) has been developed to consider aerosol source, sink, and transformation processes over the reef. We used the Weather Research and Forecasting Model coupled to chemistry (WRF-Chem). The Weather Research and Forecasting (WRF) model is a numerical weather prediction model that can be used for simulating meteorology at a range of different temporal, horizontal and vertical resolutions. WRF is widely used for meteorological modelling on its own, for which it contains numerous different physical, dynamical and microphysical scheme options. WRF-Chem is a chemistry-enabled implementation of WRF and is ideal for modelling atmospheric chemistry around the GBR, and therefore for the RRAP project, due to its ability to simulate the interaction of gaseous chemical species and aerosols with clouds.</p> <p>In WRF-Chem regional scale simulations covered Eastern Australia and surrounding ocean, including the Coral Sea and GBR. By utilising nested domains of increasingly high spatial resolution, we can target high-resolution and coarse-resolution research questions in different regions. The multi-scale modelling approach also allows MCB tests in small areas of the GBR to be scaled up in both particle number and spatial extent. WRF and WRF-Chem have previously been used for studying atmospheric dynamics, chemistry, aerosols, radiation and clouds in the Great Barrier Reef vicinity (Chen et al. 2019; Nguyen et al. 2019; Fiddes et al. 2021; Fiddes et al. 2022). WRF-Chem was also used previously during the RRAP Concept Feasibility Phase scoping study of marine cloud brightening (Harrison et al. 2019).</p> <p>Simulation Domains</p> <p>WRF-Chem was run for periods and locations coinciding with the 2022 and/or 2023 intensive field campaigns at the Great Barrier Reef. The 2022 field campaign lasted through January and February 2022 around Townsville and the Davies and Broadhurst Reef section of the central GBR. The 2023 campaign lasted through February and March 2023 around Gladstone and the Capricorn Bunker Group of the Southern GBR. The spatial domains are shown in Figure 3.</p>

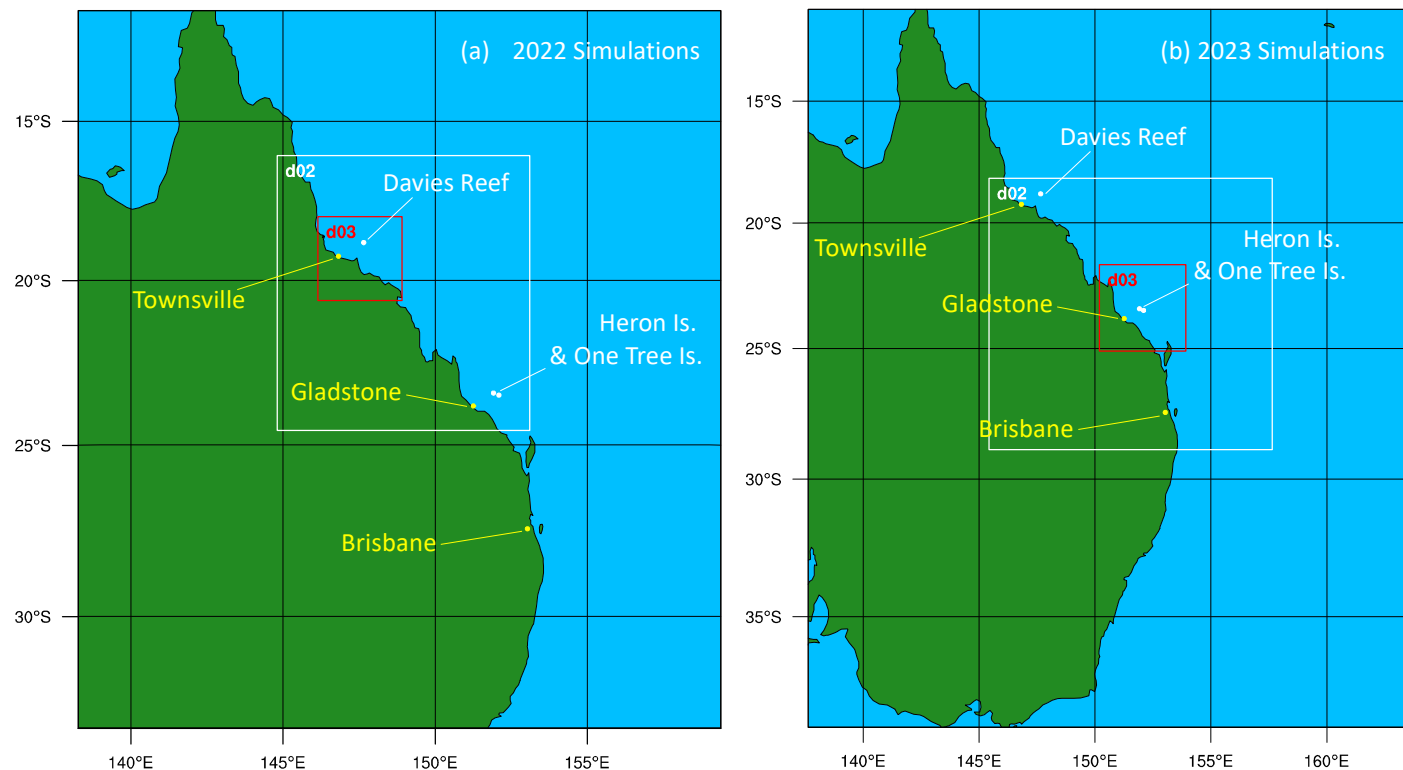


Figure 3: Spatial domains for RRAP Cooling and Shading WRF-Chem simulations over the GBR. (a) for 2022 simulations, the highest resolution domain is targeted over Townsville/Davies and Broadhurst Reefs, and (b) for 2023 simulations, the highest resolution domain is targeted over Gladstone/Capricorn Bunker Group. The outer domain is at 27km resolution, domain d02 at 9km resolution and domain d03 at 3km resolution.

Including the cities of Townsville and Gladstone in the high-resolution domain is useful due to the large number of in-situ air quality observations available in these cities, conducted by the Queensland Government. Background atmospheric data, on aerosols and meteorology, from fieldwork on the ships *RV Magnetic* and *RV Guardian* in 2022 and One Tree Island (OTI) and Heron Island (HI) in 2023, was also able to be used for model validation using this configuration.

Objective	Key Findings and/or Outcomes
	<p>Model validation results</p> <p>The results indicate that the model performs well with respect to simulating wind speed and direction in the Heron Island, Townsville and Davies Reef region, parameters which are crucial for modelling pollutant transport and aerosol formation from sea-spray. WRF-Chem does a good job of simulating temperature in the relative humidity compared to 2022 observations but struggles to capture the diurnal variation of these variables over the complicated environment of Heron Island.</p> <p>Modelled nitrogen dioxide (NO₂), PM10 (particles with a diameter of 10 micrometres or less) and PM2.5 (particles with a diameter of 2.5 micrometres or less) levels are consistent with observations at a Queensland air quality monitoring site in Townsville. However, daily maxima and minima are greater in the simulations than the measurements, indicating that primary air pollutant emission sources are not well constrained in WRF-Chem for this environment. The over-simulation of peak NO₂, particulate matter and ozone, is even more pronounced when looking at the larger urban areas, such as Brisbane. This is consistent with previous studies suggesting that the Emissions Database for Global Atmospheric Research (EDGAR) inventory needs updating, especially in terms of diurnal variation, for Australian anthropogenic emissions (Garg et al. 2022). We compared satellite formaldehyde (HCHO), NO₂ and ozone (O₃) to the domain-wide WRF-Chem output for these species and found that the model overrepresented all three in urban areas but that otherwise, the spatial variation was consistent with observations. This gives confidence in interpreting broad-scale WRF-Chem oxidative chemistry conclusions.</p> <p>Major outcomes</p> <p>We demonstrated the capability of WRF-Chem to provide important information on the role of different particulates in aerosol/cloud/radiation interactions by examining anthropogenic ship emissions in and around the GBR. Results are shown in Figure 4 below.</p> <p>The full description and results of this work are described in (Ryan et al. 2025).</p>

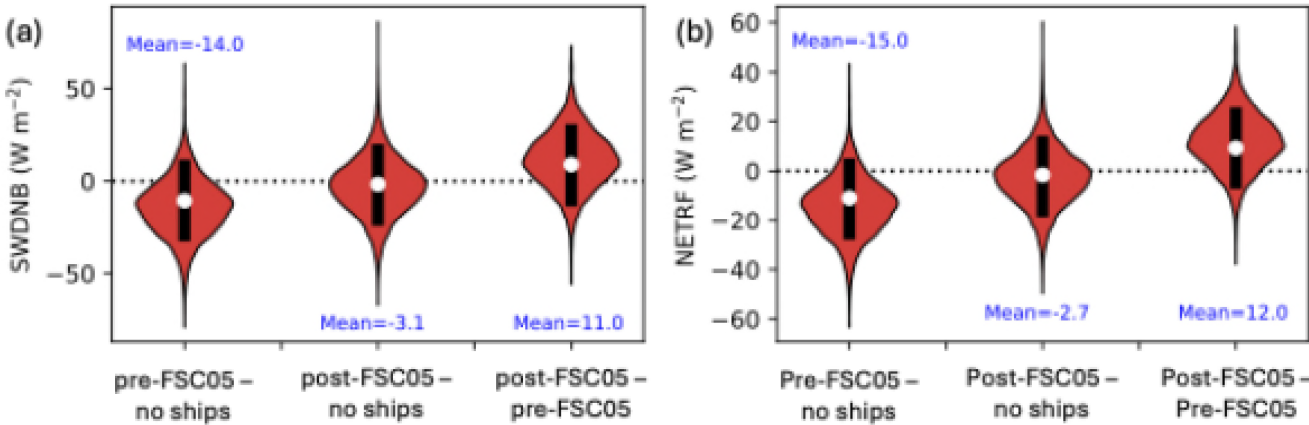
Objective	Key Findings and/or Outcomes
	 <p>Figure 4: Impact of different ship emission scenarios on radiative forcing at the GBR. Results are the difference in (a) downwards shortwave radiation reaching the reef surface and (b) net top-of-atmosphere radiative forcing between simulations with ship emissions and without ship emissions. Results are averaged over 10 days of simulation, daylight hours only. In each panel, the left-hand violin shows the distribution of results for scenarios before ship fuel sulfur content was restricted to 0.5 % (pre-FSC05), the middle violin is for the post-regulation scenario, and the right-hand side shows the difference between pre- and pos-regulation scenarios. The right side of the plot shows the extra radiative forcing hitting the GBR as a direct result of the ship fuel sulfur regulation. We estimate that an increase of 11 Wm⁻² in surface downwards shortwave radiation could equate to as much as three degree heating weeks of extra thermal stress for GBR corals (Ryan et al. 2025).</p>
3. Cloud microphysical modelling employing aerosol and radiation schemes and bin microphysics within a framework which allows multiple scale, domain, and resolution configurations to extend the analysis from experimental to GBR scale.	<p>A series of WRF sensitivity simulations have been successfully conducted to identify an optimal configuration for shallow cloud and precipitation modelling over the GBR. The work provides a baseline setup that supports and guides ongoing modelling efforts and serves as a key resource for future studies in the GBR region using this modelling configuration.</p> <p>Optimised WRF-Chem settings are derived from simulations with WRF and previous WRF-Chem simulations in GBR and other Australian conditions. WRF and WRF-Chem simulations can be run at variable (nested domain) resolutions of 27, 9, 3 and 1 kilometres (km). For computational efficiency, because chemistry adds significantly to the computational requirements, WRF-Chem sensitivity simulations are run at 9 x 9 km only. The WRF / WRF-Chem configuration is summarised below in Table 2.</p>

Table 2: WRF/WRF-Chem configuration

Parameterisation schemes	Option No. (d01, d02, d03)	Comments
Microphysics	mp_physics = 28	Thompson Aerosol Aware scheme
PBL	bl_pbl_physics = 1	YSU PBL scheme
Cumulus	cu_physics = 1 (d01 only)	Kain-Fritsch scheme (d01 only)
Land/Sea surface	sf_surface_physics = 2	Noah Land Surface Model
Short wave radiation	ra_sw_physics = 4	RRTMG shortwave
Long wave radiation	ra_lw_physics = 4	RRTMG scheme
Chemistry Scheme (for WRF-Chem only)	chem_opt = 34	Carbon bond chemical mechanism (CBMZ)
Aerosol scheme (for WRF-Chem only)	chem_opt = 34	MOSAIC 8-bin scheme
Anthropogenic emissions (WRF-Chem only)	emiss_opt = 4	EDGAR emissions with STEAM2 ship emissions

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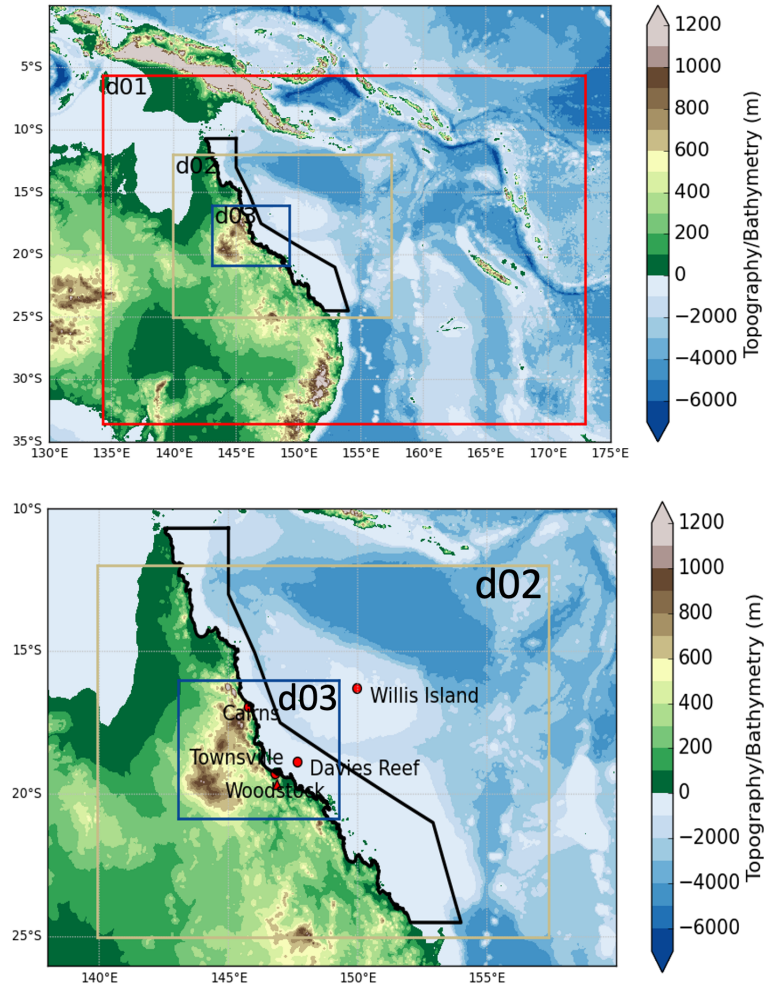


Figure 5: Nested domain configuration applied in WRF model, recent work is using further nesting down to LES scales of several 10s of km domain side length.

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By employing cloud-resolving WRF model with nested domain configuration, the work investigates how trade wind clouds over the GBR respond to local forcings as well as natural processes, like mesoscale wind patterns. The results highlight the sensitivity of cloud properties in response to aerosol loading, coastal topography and local wind regimes. These findings suggests that aerosol injection could influence cloud properties in regions where aerosol significantly impact cloud microphysics, and topography impacts and wind regime background should be considered when selecting timing and areas for cloud brightening interventions.

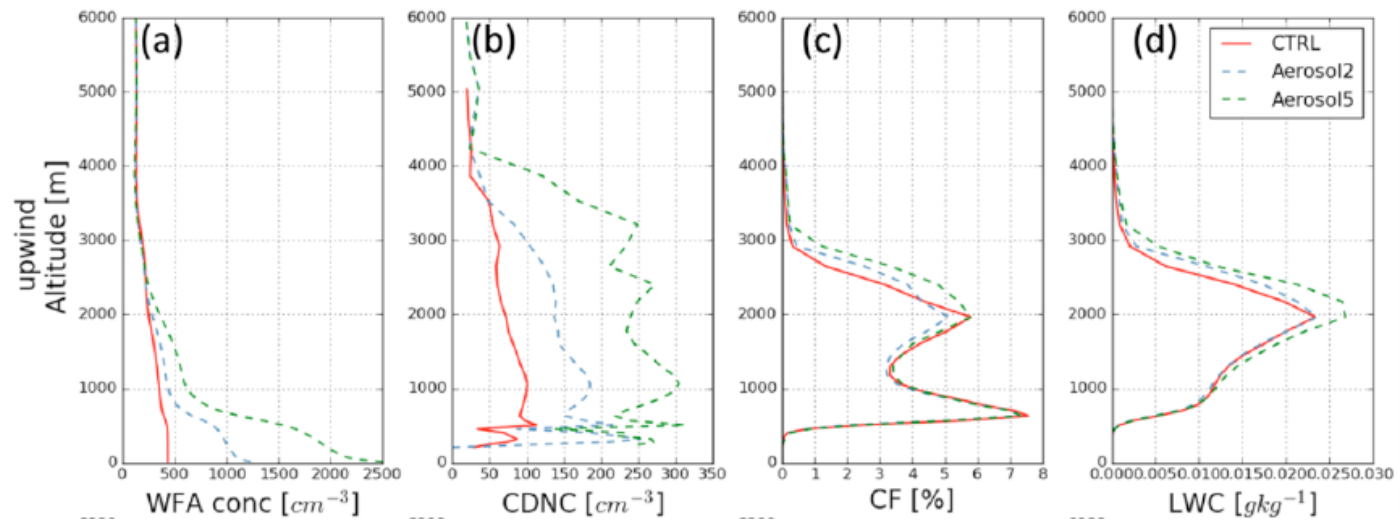


Figure 6: Vertical profiles of domain-averaged (a) water-friendly aerosol number concentration, (b) in-cloud Cloud Droplet Number Concentration (CDNC), (c) cloud fraction, and (d) liquid water content over the upwind sub-domain from Control (CTRL) (in red), and two sensitivity experiments (in blue and green).

The detailed results of this work are published in (Zhao et al. 2024), while the outcomes of more recent simulations can be found in (Zhao et al. 2025).

4.	<p>Utilise nested model domains and resolutions to bridge the spatial scale between the regional coupled eReefs-Atmospheric modelling and the LES scale simulations.</p> <p>WRF Scenario Testing at intermediate spatial scales</p> <p>Sensitivity studies of MCB scenarios in WRF, using a fixed-CCN number addition to the model, have been conducted to investigate the response of cloud-aerosol interaction to varying aerosol loadings with different spatial distributions and aerosol levels over the GBR. The initial results showing that both sensitivity experiments exhibit a substantial increase in surface aerosol number concentrations over the Cairns region compared to the CTRL simulation. Increases of up to 450 cm^{-3} in aerosol number concentration are observed, particularly evident over the source stations, confirming the effectiveness of the emission perturbations imposed in the experimental setups. In the EXP20 experiment, where source points are closely spaced (20 km apart),</p>
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the downwind aerosol enhancements are spatially diffuse but broadly distributed, indicating a widespread influence. Overall, the closer spacing of the source points contributes to a more significant overall enhancement in surface aerosol number concentration across the domain.

Additionally, a widespread dispersion of aerosols beyond the target domain (Cairns region), extending both downwind and upwind area is shown from both sensitivity MCB scenario experiments.

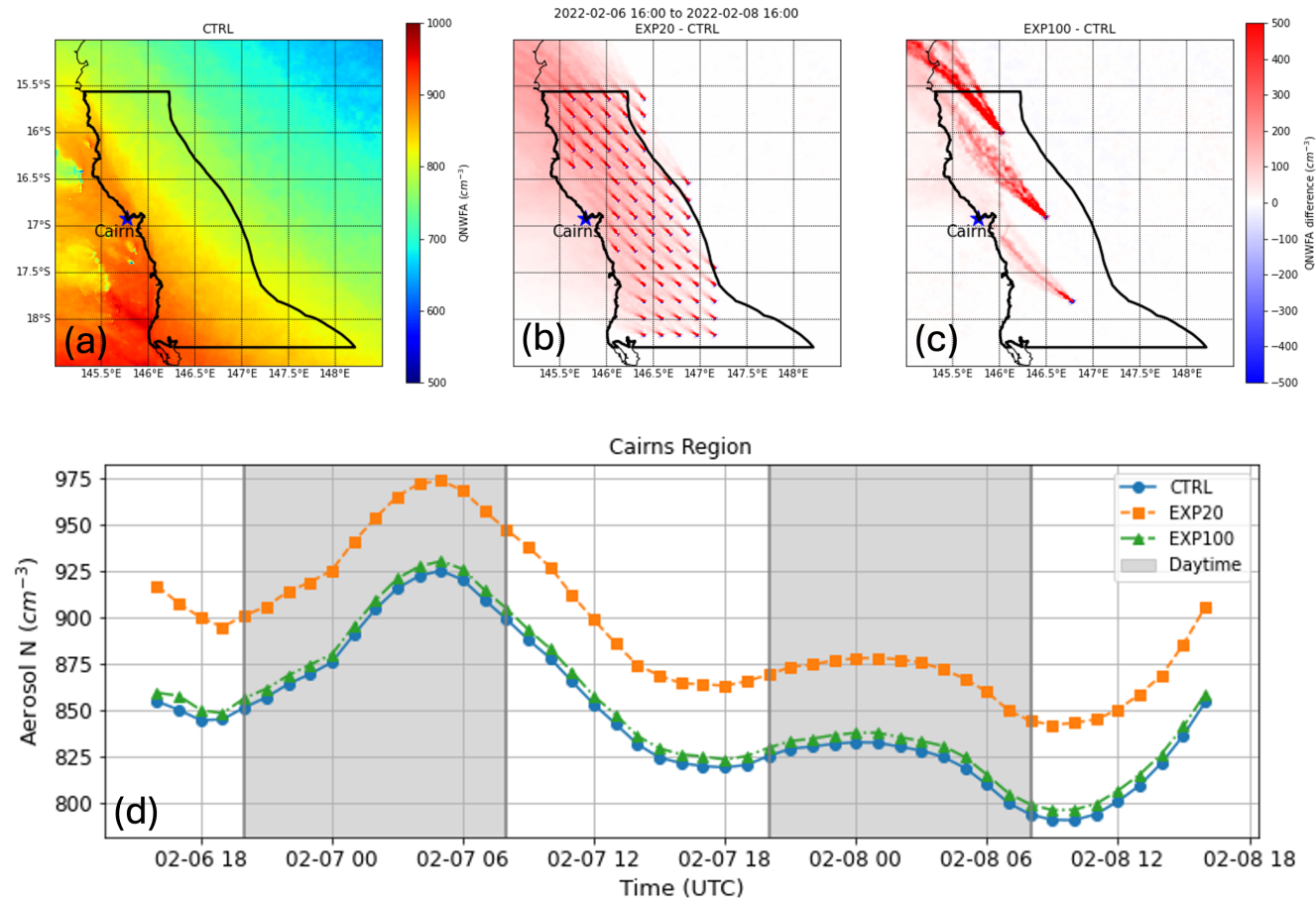


Figure 7: (a) Surface aerosol number concentration distribution from CTRL over the time period 1600UTC on 06 Feb to 1600UTC on 08 Feb. (b) Difference in surface aerosol number concentration between EXP20 and CTRL. (c) same as (b), but

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	<i>for difference between EXP100 and CTRL. (d) Time series of area-averaged surface aerosol number concentration over Cairns Region throughout the simulation time.</i>

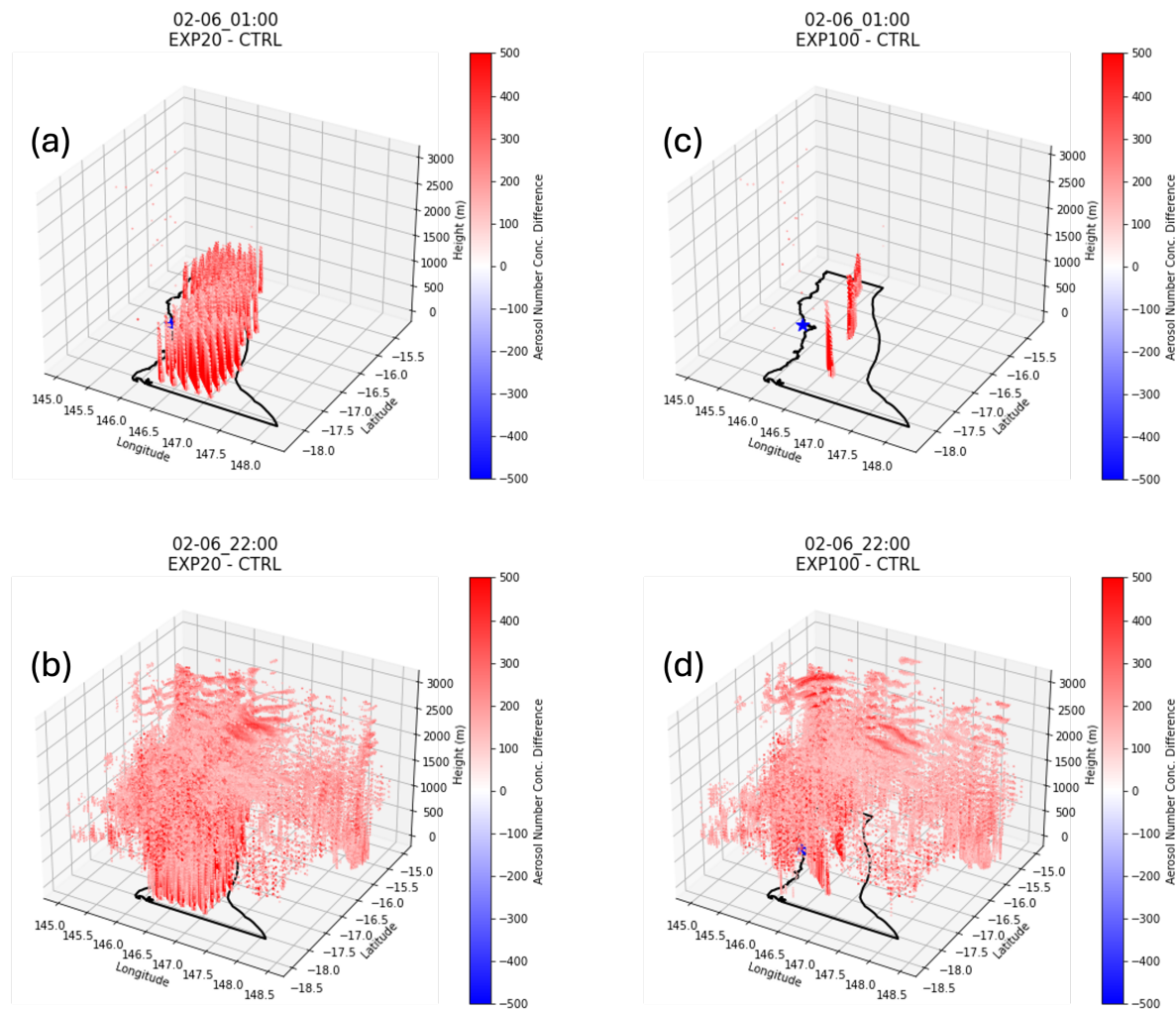


Figure 8: Example 3D distribution of difference in aerosol number concentration between EXP20 and CTRL at the first simulation hour from WRF experiment. (b) same as (a), but for the simulation time of 22 hours from the starting time. (c-d), same as (a-b), but showing difference between EXP100 and CTRL.

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WRF-Chem Scenario Testing

A series of deployment scenarios were tested in WRF-Chem to assess the impact of deployment siting under typical trade wind conditions.

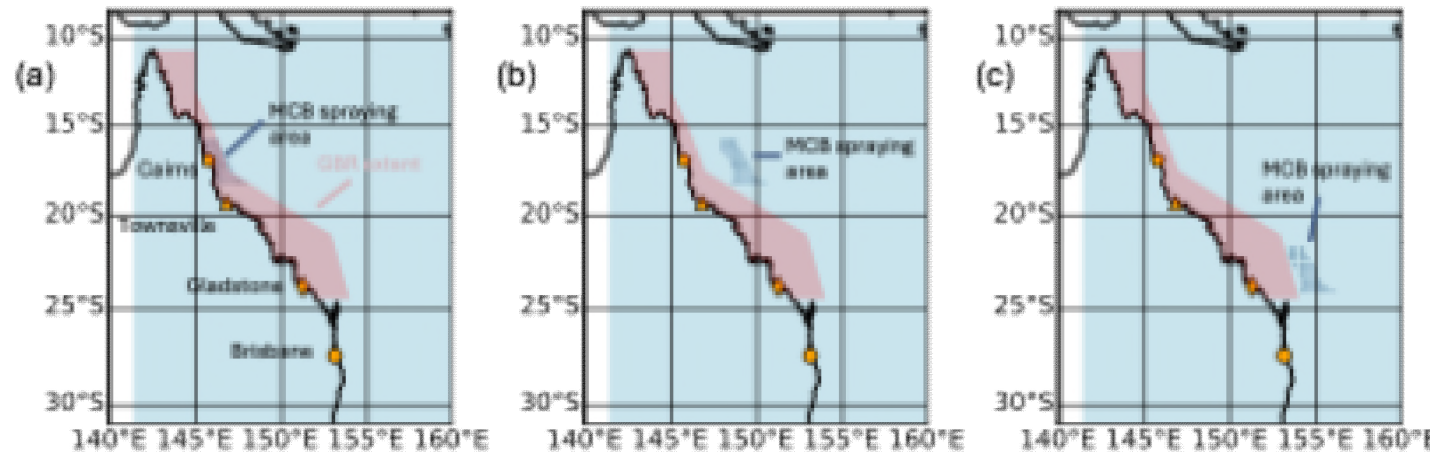


Figure 9: Figure showing the flexibility of WRF-Chem to move MCB spraying location around the GBR. The pink shaded region shows the GBR Marine Park boundary. The blue dots show sprayer locations in WRF-Chem 9x9 km resolution MCB experiments, shifted, for example, (a) inside the GBR boundary near Cairns, (b) outside the GBR boundary near Cairns and (c) outside the GBR near Gladstone.

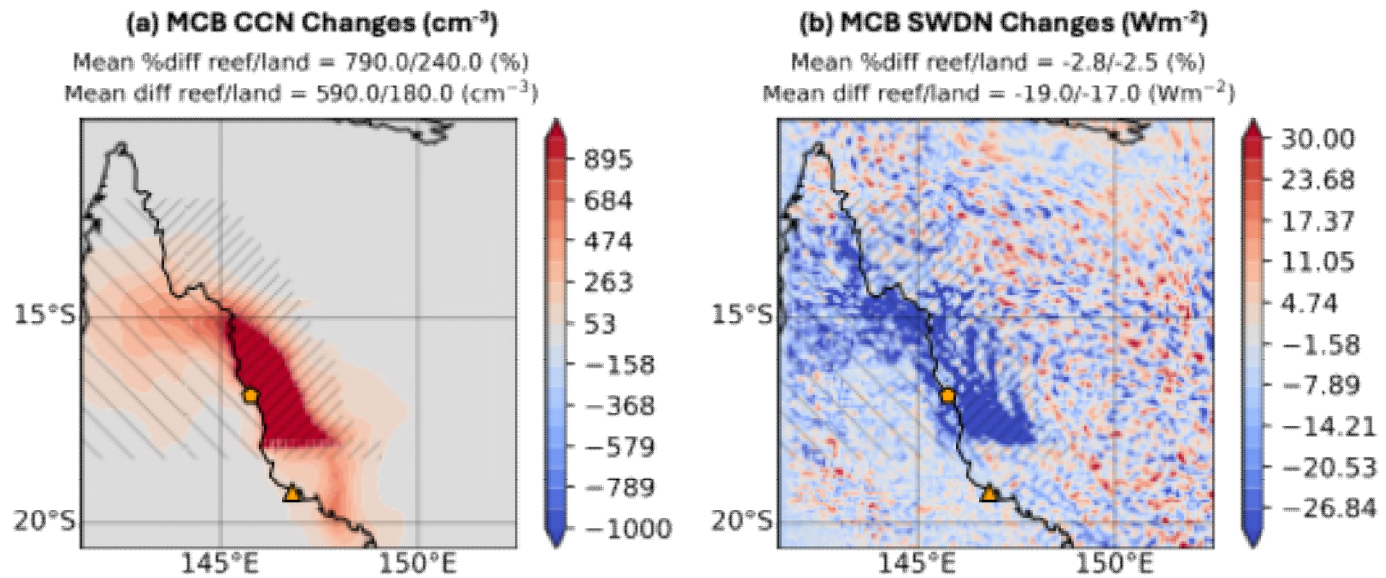


Figure 10: Results of MCB test in WRF-Chem in which 99 sprayers off the coast of Cairns spray with area flux of $0.1985 \mu\text{gm}^{-2}$. The spraying region is that shown in Figure 9 (a) above. Maps show the difference in (a) surface layer CCN and (b) surface downwards shortwave radiation, averaged over 10 days of simulation from 18-27 February 2022. This plot demonstrates MCB working over the GBR. It also indicates teleconnections and downstream impacts by showing significant CCN migration and associated shortwave radiation effects over Cape York, not just confined to the GBR near the spraying region. Percentage and absolute changes in each value are listed in the top of each panel, where 'reef' is the region indicated by forward slash stippling and 'land' is the area of Cape York marked with back slash stippling.

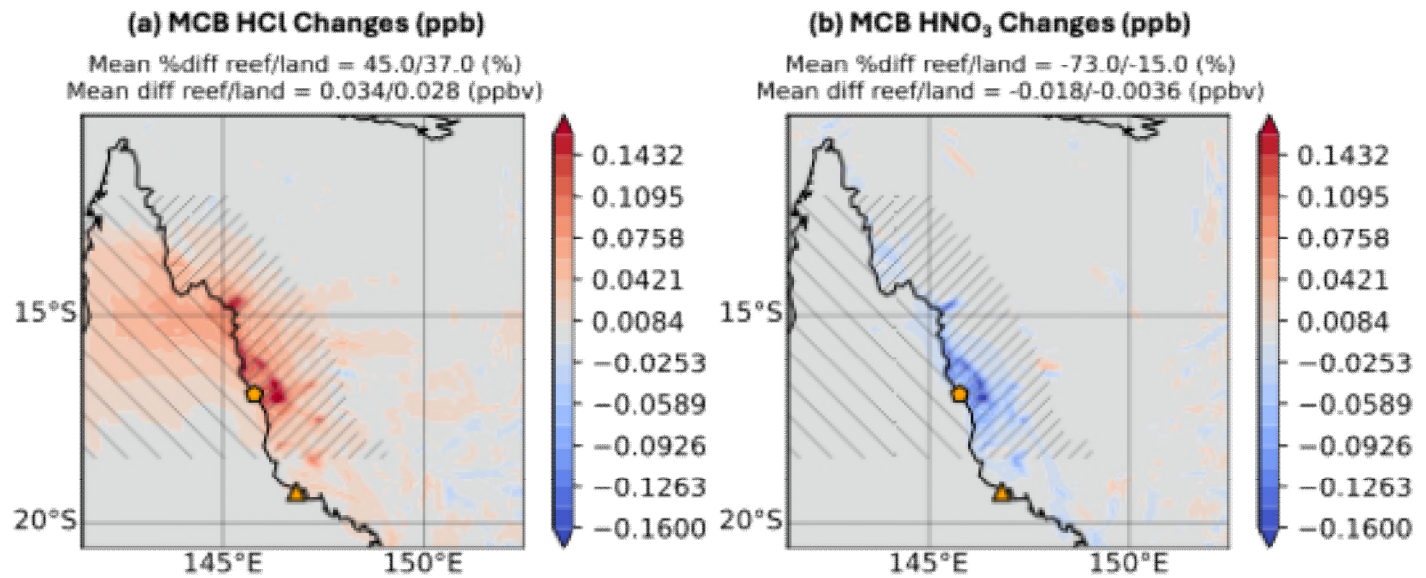
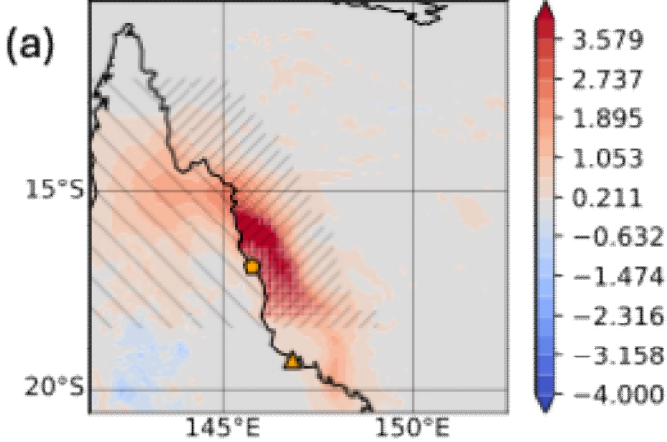
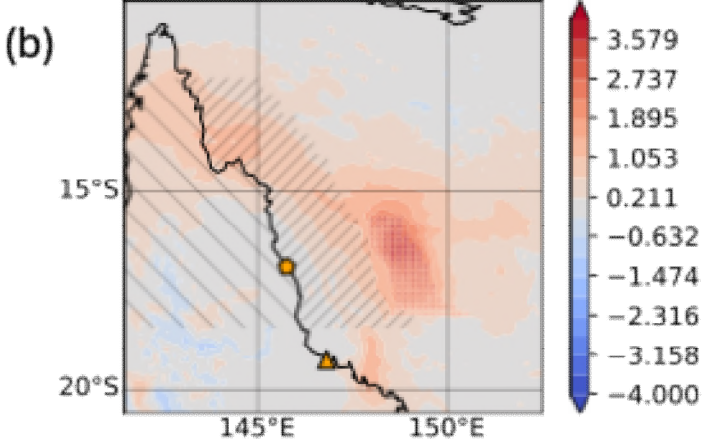


Figure 11: Results of MCB testing in WRF-Chem (same simulation details and plot detail as Figure 10), for mixing ratios of hydrochloric acid (HCl) and nitric acid (HNO₃). Downstream impacts to be explored further are demonstrated here, specifically, the mean increases in HCl over Cape York (37 %) and over the GBR (45 %). This is accompanied by a 73 % decrease in HNO₃ over the GBR and 15 % decrease over Cape York.

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	<div style="display: flex; justify-content: space-around;"> <div style="text-align: center;"> <p>(a) MCB PM_{2.5} Changes (µg·m⁻³) Inside GBR spraying</p> <p>Mean %diff reef/land = 25.0/12.0 (%) Mean diff reef/land = 1.3/0.61 (µg·m⁻³)</p>  </div> <div style="text-align: center;"> <p>(a) MCB PM_{2.5} Changes (µg·m⁻³) Outside GBR spraying</p> <p>Mean %diff reef/land = 12.0/5.2 (%) Mean diff reef/land = 0.63/0.27 (µg·m⁻³)</p>  </div> </div> <p><i>Figure 12: Results of MCB testing in WRF-Chem (same simulation details and plot detail as Figure 10, for particulate matter less than 2.5 micrometre (µm) diameter. (a) is when MCB spraying is inside the GBR (scenario in Figure K(a)), (b) is spraying outside the GBR (Figure K(b)). PM_{2.5} is a criteria air pollutant and population exposure along coasts should ideally be minimised. Here we show that PM_{2.5} changes across Cape York average a 12 % increase if the spraying is within the GBR, reduced to 5 % for spraying outside the GBR.</i></p>
<p>5. Development of a regional atmospheric model configuration, using improved aerosol and cloud microphysics schemes, of the Reef region, coupled to eReefs, providing an integrative tool for assessment of efficacy and regional scale downstream</p>	<p>Atmospheric model - ACCESS-GBR</p> <p>The atmosphere-only configuration for the GBR is called ACCESS-GBR and is based on the Unified Model Regional Nesting Suite. The regional domain is nested inside a full global domain which has a horizontal grid-spacing of approximately 65 km. The nested domain covers north-eastern Australia (NE AUS; Fig. 1) and has a horizontal grid-spacing of 0.04° (~4 km), with 90 vertical levels (17 below 1 km).</p>

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impacts on cloud and precipitation processes.

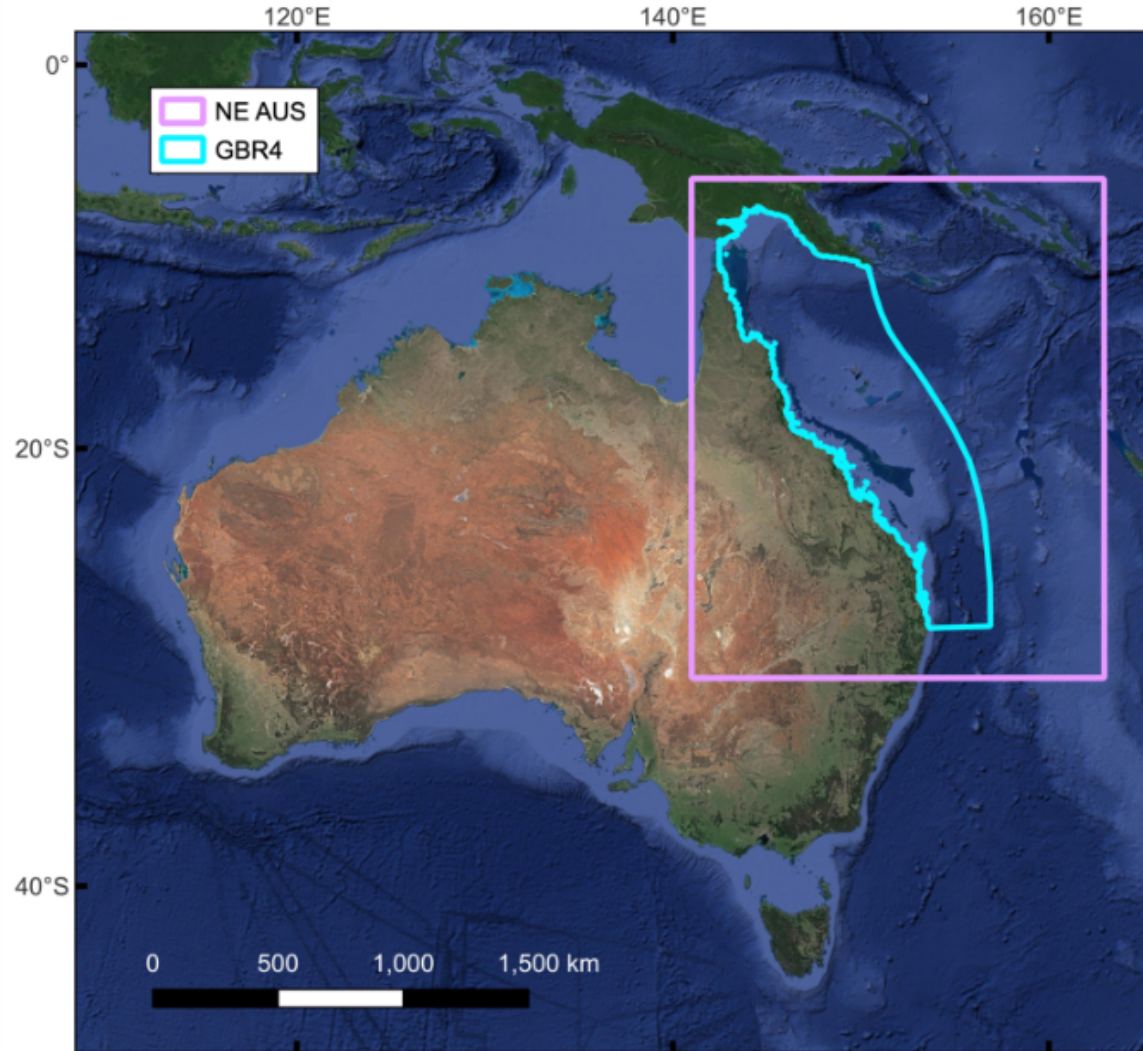


Figure 13: Map of Australia showing the atmospheric NE AUS domain (0.04 degree horizontal resolution) and ocean GBR4 domain (~4 km horizontal resolution on a curvilinear grid).

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	<p>Synoptic meteorology in the global model is ‘nudged’ to ERA5 (European Centre for Medium-Range Weather Forecasts Reanalysis version 5) (Hersbach et al. 2020). Constraining the meteorology allows for better attribution of perturbations (e.g. sea salt aerosol injections) and for comparison between simulated and measured variables.</p> <p>The NE AUS domain is re-initialised daily, depending on the experiment requirements. However, the meteorology is always constrained at the domain boundaries from the global model. Further detail on the atmospheric model domains is provided in Table 3.</p> <p><i>Table 3: ACCESS-EMS-GBR model domains.</i></p> <table border="1" data-bbox="557 571 1839 839"> <thead> <tr> <th></th> <th>Global atmosphere</th> <th>NE AUS atmosphere</th> <th>GBR4 ocean</th> </tr> </thead> <tbody> <tr> <td>Domain</td> <td>–</td> <td>6-31°S, 141-163°E</td> <td>7-28.5°S, 142-157°E</td> </tr> <tr> <td>Horizontal resolution</td> <td>N216 (~65 km)</td> <td>0.04° (~4km)</td> <td>~4 km</td> </tr> <tr> <td>Vertical levels</td> <td>70 (0 – 80 km)</td> <td>90 (0 – 40 km)</td> <td>48 (surface – 4 km)</td> </tr> <tr> <td>Initial conditions</td> <td>–</td> <td>Derived from global model</td> <td>Derived from eReefs hindcast</td> </tr> <tr> <td>Boundary conditions</td> <td>–</td> <td>Derived from global model</td> <td>Bluelink Reanalysis v 2020</td> </tr> </tbody> </table> <p>Improved aerosol and cloud schemes</p> <p>A major milestone in the setup of ACCESS-GBR was the addition and evaluation of coupled aerosol and cloud schemes. Aerosol mass, number concentration and interactions with cloud droplets are now simulated, allowing aerosol direct and indirect radiative effects to be simulated and the response of aerosol and cloud to sea salt injections to be better captured.</p> <p>ACCESS-GBR uses the GLObal Model of Aerosol Processes modal configuration (GLOMAP-mode) aerosol scheme (Mann et al. 2010; Mann et al. 2012). GLOMAP-mode represents aerosol number concentration, mass and composition in five log-normal size modes (soluble nucleation, Aitken, accumulation and coarse modes, and insoluble Aitken mode). Aerosol species included in GLOMAP-mode are sulfate, organic carbon (both from primary and secondary sources), sea salt and black carbon.</p> <p>Processes that influence aerosol number, mass and composition are explicitly represented in GLOMAP-mode, from emission of aerosol precursors (e.g. dimethylsulfide) to deposition.</p> <p>GLOMAP-mode is now coupled to the Cloud AeroSol Interacting Microphysics (CASIM) cloud microphysics scheme (Shipway and Hill 2012) in ACCESS-GBR. CASIM is a double-moment scheme that simulates cloud droplet number concentration and mass across five hydrometer classes (liquid, rain, ice, snow and graupel), using aerosol properties simulated by GLOMAP-mode.</p>		Global atmosphere	NE AUS atmosphere	GBR4 ocean	Domain	–	6-31°S, 141-163°E	7-28.5°S, 142-157°E	Horizontal resolution	N216 (~65 km)	0.04° (~4km)	~4 km	Vertical levels	70 (0 – 80 km)	90 (0 – 40 km)	48 (surface – 4 km)	Initial conditions	–	Derived from global model	Derived from eReefs hindcast	Boundary conditions	–	Derived from global model	Bluelink Reanalysis v 2020
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Boundary conditions	–	Derived from global model	Bluelink Reanalysis v 2020																						

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	<p>Although CASIM is more sophisticated than the previous cloud scheme, it is more computationally demanding. Therefore, the previous generation cloud scheme is preferentially used in the global driving model, with CASIM representing cloud microphysics in the higher-resolution regional domains.</p> <p>The structural representation of aerosol in GLOMAP-mode was improved with an upgrade to allow addition of sea salt into the Aitken mode. The benefits are two-fold: 1) to better simulate observed marine aerosol size distributions, and 2) to allow simulation of MCB aerosol injections, which substantially occur in the Aitken mode size range.</p> <p>Implementation of sea salt injections</p> <p>In order to represent the additional source of aerosol to simulate MCB, new code and input files (and associated ancillary tools) were introduced to the regional model. The flexible approach adopted allows specification of relevant parameters (see Table 4). These parameters will change as nozzle and sprayer technology develops, and will be updated in the model accordingly.</p> <p><i>Table 4: Initial parameters used to define the offline sea salt emissions.</i></p> <table border="1" data-bbox="555 746 1966 1125"> <thead> <tr> <th>Parameter</th> <th>Value</th> </tr> </thead> <tbody> <tr> <td>Sea salt mass flux</td> <td>20 $\mu\text{g m}^{-2} \text{s}^{-1}$</td> </tr> <tr> <td>Mode mean dry diameter</td> <td>37.2 nm</td> </tr> <tr> <td>Mode geometric standard deviation</td> <td>2.1</td> </tr> <tr> <td>Mode emission fraction</td> <td>100% to soluble accumulation mode (future implementation will distribute between Aitken and accumulation modes)</td> </tr> <tr> <td>Organic fraction</td> <td>0</td> </tr> <tr> <td>Timing</td> <td>Constant</td> </tr> <tr> <td>Locations</td> <td>Davies Reef (18.8°S, 147.6°E) Heron Island (23.4°S, 151.9°E)</td> </tr> </tbody> </table> <p>These values were derived from recent field tests and will be updated in response to changes in the sprayer technology. Further, each parameter can be modified to conduct a sensitivity test to identify the ideal sea spray injection mass, size, timing and location for achieving a cooling effect over the reef.</p> <p>The sea spray emissions are specified as a mass flux at each location, scaled to the gridbox area to ensure a consistent flux is applied to the global and NE AUS domains. A mass flux of 20 $\mu\text{g m}^{-2} \text{s}^{-1}$ is equivalent to emitting $\sim 0.32 \text{ kg s}^{-1}$ from each gridbox (or 27 tonnes per day), integrated over a $0.04^\circ \times 0.04^\circ$ ($\sim 16 \text{ km}^2$) area in the NE AUS domain and $0.56^\circ \times 0.83^\circ$ area in the global model.</p> <p>eReefs: EMS configuration for the GBR</p>	Parameter	Value	Sea salt mass flux	20 $\mu\text{g m}^{-2} \text{s}^{-1}$	Mode mean dry diameter	37.2 nm	Mode geometric standard deviation	2.1	Mode emission fraction	100% to soluble accumulation mode (future implementation will distribute between Aitken and accumulation modes)	Organic fraction	0	Timing	Constant	Locations	Davies Reef (18.8°S, 147.6°E) Heron Island (23.4°S, 151.9°E)
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The ocean component of ACCESS-EMS-GBR is the EMS model of the GBR, developed as part of the ‘eReefs’ project. The uncoupled EMS configuration for the GBR is called ‘eReefs’, and is summarised in Baird et al. 2020. The eReefs model includes hydrodynamic and biogeochemistry (BGC) components, as summarized in Figure 14.

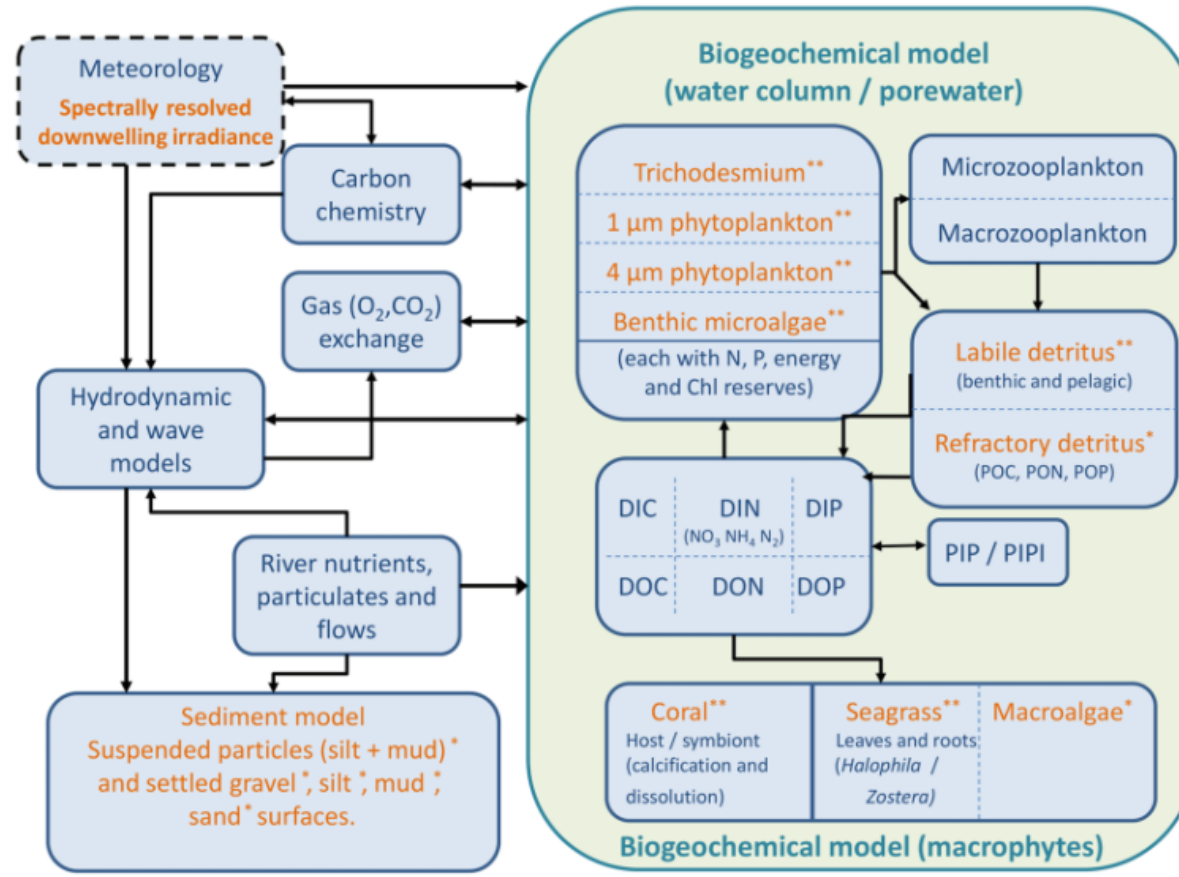


Figure 14: Overview of the components and processes included in eReefs (Baird et al. 2020).

Ocean domain

The ocean domain covers the continental shelf of north-eastern Australia (Fig. 1, approximately 7.5-28.5°S, 142.5-157.5°E) and has a horizontal resolution of approximately 4 km (called ‘GBR4’) on a curvilinear grid. The GBR4 domain has 48 vertical levels, with 1 m resolution above 2 m depth, increasing to 220 m at 4 km depth.

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	<p>Improved representation of radiative transfer</p> <p>The EMS optical model calculates radiative fluxes using surface radiation, temperature and humidity provided by atmospheric forcing files. To improve radiative transfer through the water column, the HydroLight optical model and associated RADTRAN-X simple atmospheric model have been added to the EMS code base.</p> <p>RADTRAN-X passes total cloud fraction, aerosol type, solar angle, humidity, winds, temperature and other variables to HydroLight, which then simulates the resulting direct and diffuse radiation fluxes across several spectral bands. Although more computationally expensive, these changes enable radiative fluxes to be calculated with more accuracy, allowing more detailed simulation of the impacts of the sea salt injections.</p> <p>Addition of dimethyl sulfide production</p> <p>A new process to represent dimethyl sulfide (DMS) production in EMS has been included. DMS is produced by corals, algae and other marine organisms and is an important source of natural sulfur to the atmosphere.</p> <p>DMS is produced in response to physiological stress via enzymatic cleavage of dimethyl sulfoniopropionate (DMSP) and is thought to play an important role in the coral oxidative stress response (Deschaseaux et al. 2014). DMS and DMSP are released from phytoplankton, in coral mucous and from expelled zooxanthellae. In EMS, DMS is represented in terms of milligrams (mg) of carbon m^{-3} and is formed via the degradation of particulate organic matter (including phytoplankton), scaled by the Redfield and Atkinson ratios of carbon, nitrogen and phosphorus. Further work is planned to improve the representation of DMS sources in EMS, by including additional processes such as DMS production by corals.</p> <p>Model Coupling</p> <p>In order to explicitly resolve the impact and effect of MCB on coral in the GBR, the ACCESS-GBR and EMS/eReefs models have been coupled through the exchange of respective atmospheric and ocean forcings, resulting in ACCESS-EMS-GBR. A compartmentalised approach is used, where the models run sequentially and exchange forcings each day.</p> <p>ACCESS-GBR uses the Cylc framework (Oliver et al. 2019) to schedule model tasks and handle dependencies. The scripts required to run eReefs and create the model forcings have been incorporated into the ACCESS-GBR Cylc workflow. A 'run_eReefs' option has been included so that ACCESS-GBR may be run as an atmosphere-only simulation or as the ACCESS-EMS-GBR coupled model.</p> <p>ACCESS-GBR will run for one day, the output will be processed (e.g. regridding, file formatting) and passed to eReefs to run for the same day. On completion of the eReefs simulation, the surface ocean output will be processed to create forcings for ACCESS-GBR to run for the next day.</p> <p>The compartmentalised coupling approach was chosen as it best met the needs of the project while balancing developmental and computational costs. Further, this approach allows the models to be independently updated and modified as needed, with minimal changes to the code.</p> <p>Coupling parameters</p>

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The fields that are currently coupled in ACCESS-EMS-GBR are shown in Figure 15. Only essential variables have been coupled, however additional variables can be coupled depending on experimental needs.

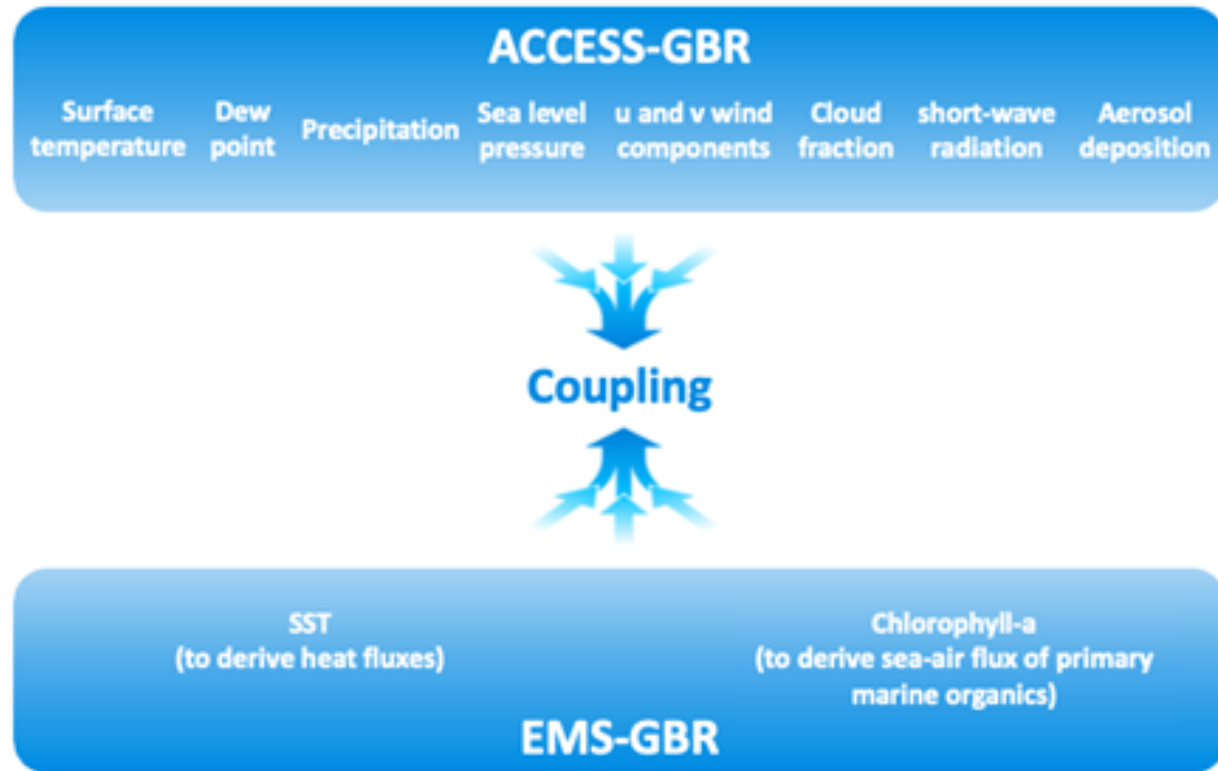


Figure 15: Coupling parameters used in ACCESS-EMS-GBR.

Ocean Forcings

Ocean forcings required by ACCESS-GBR are provided by ancillary files, which have particular grid, variable and formatting requirements. The default sea surface temperature (SST) ancillary used in ACCESS is derived from the Met Office Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) monthly climatological dataset (Rayner et al. 2003). For consistency with the eReefs ocean boundary conditions and to minimise inconsistencies in heat fluxes across the NE AUS and GBR4 domains, ACCESS-GBR

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instead uses a daily mean SST ancillary derived from the BRAN2020 dataset (Bluelink ReANalysis 2020, CSIRO's high-resolution ocean reanalysis dataset).

When run in coupled mode, the GBR4 daily mean SST output is merged with the daily mean BRAN2020 values after each day of ocean simulation.

Updating SST allows feedbacks in surface heat and radiation fluxes between the atmospheric and ocean models to be captured within the GBR. The new ancillary data better captures the influence of surface currents throughout the model domain (Figure 16).

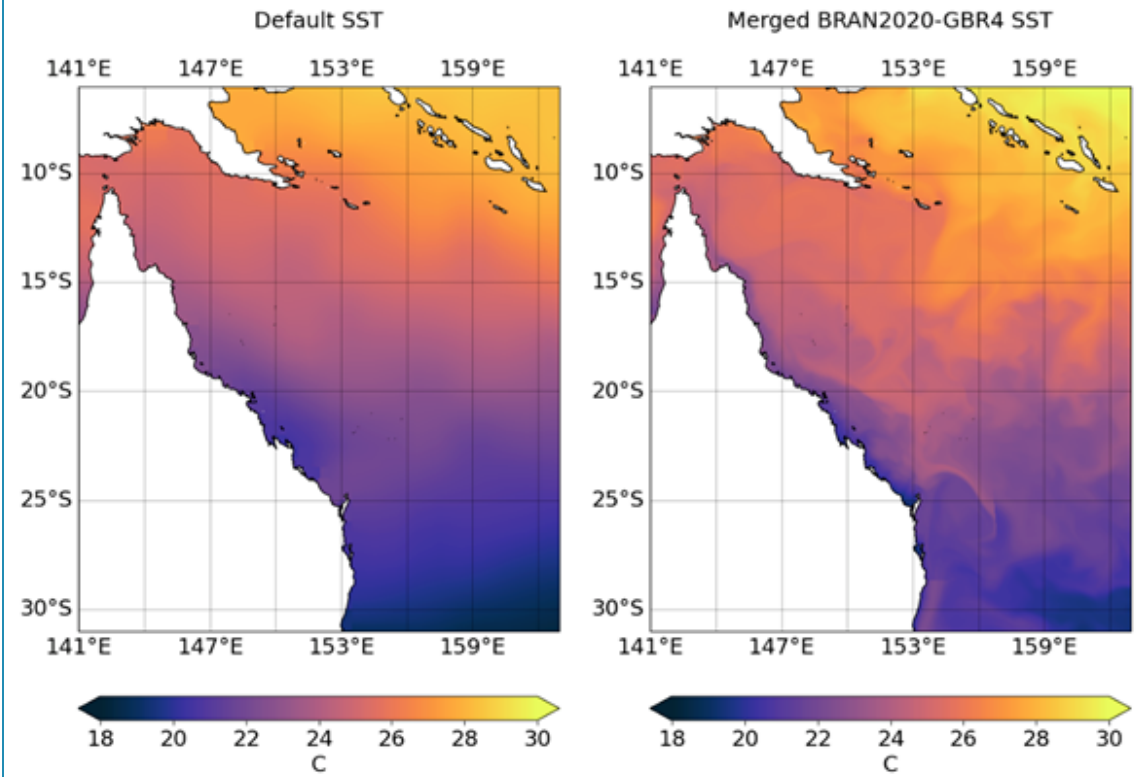


Figure 16: Example SST ancillary data used to force the NE AUS domain from the (left) default climatological ancillary and (right) new merged BRAN2020-GBR4 ancillary file.

Objective	Key Findings and/or Outcomes
	<p>Atmospheric Forcings</p> <p>The uncoupled eReefs configuration is forced with BARRA2 (Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia) (Su et al. 2019; Su et al. 2022) hourly mean atmospheric fields at 12 km resolution. Atmospheric forcings required by eReefs are surface temperature, relative humidity, precipitation, sea level pressure, cloud fraction and horizontal wind u and v components.</p> <p>In ACCESS-EMS-GBR, additional atmospheric forcings of surface downwelling Shortwave Radiation (SWR) and aerosol deposition of dust and black carbon have also been included. The amount of SWR reaching the surface has an effect on ecological processes, including in corals. Similarly, dust, black carbon and other particles in the water column can influence light attenuation. These extra atmospheric forcings have been included due to their relevance in simulating the impacts of MCB.</p> <p>Comparison of sea spray injection impacts in ACCESS-GBR</p> <p>Quantitative measures have been defined to compare and assess the aerosol injection efficacy over specific domains. For use in this work, a new metric has been defined: $CCN \text{ sensitivity} = \Delta CCN / \Delta SSflux$</p> <p>Where the numerator is the simulated difference (perturbation - control) in the quantity of interest, and the denominator is the mass flux of sea salt injected ($20 \text{ mg m}^{-2} \text{ s}^{-1}$ in this case). Thus, the metric gives an indication of the impact per unit mass of sea salt injected.</p> <p>Careful consideration needs to be given when using the metrics. For example, when using the SWR sensitivity metric, dRadiation should be an area mean over the targeted reef (as that's where the radiation changes are relevant). Here, the sensitivity metrics are calculated from the difference of the means for a 0.1° area ($\sim 100 \text{ km}^2$, to capture the effects of advected sea salt) centred on the injection locations.</p> <p>Results from an aerosol injection simulation</p> <p>Figure 17 shows the CCN number concentration averaged in time and over the lowest 20 model levels (0-1457 m) for the perturbed simulation and the change due to the sea salt injections.</p>

Objective

Key Findings and/or Outcomes

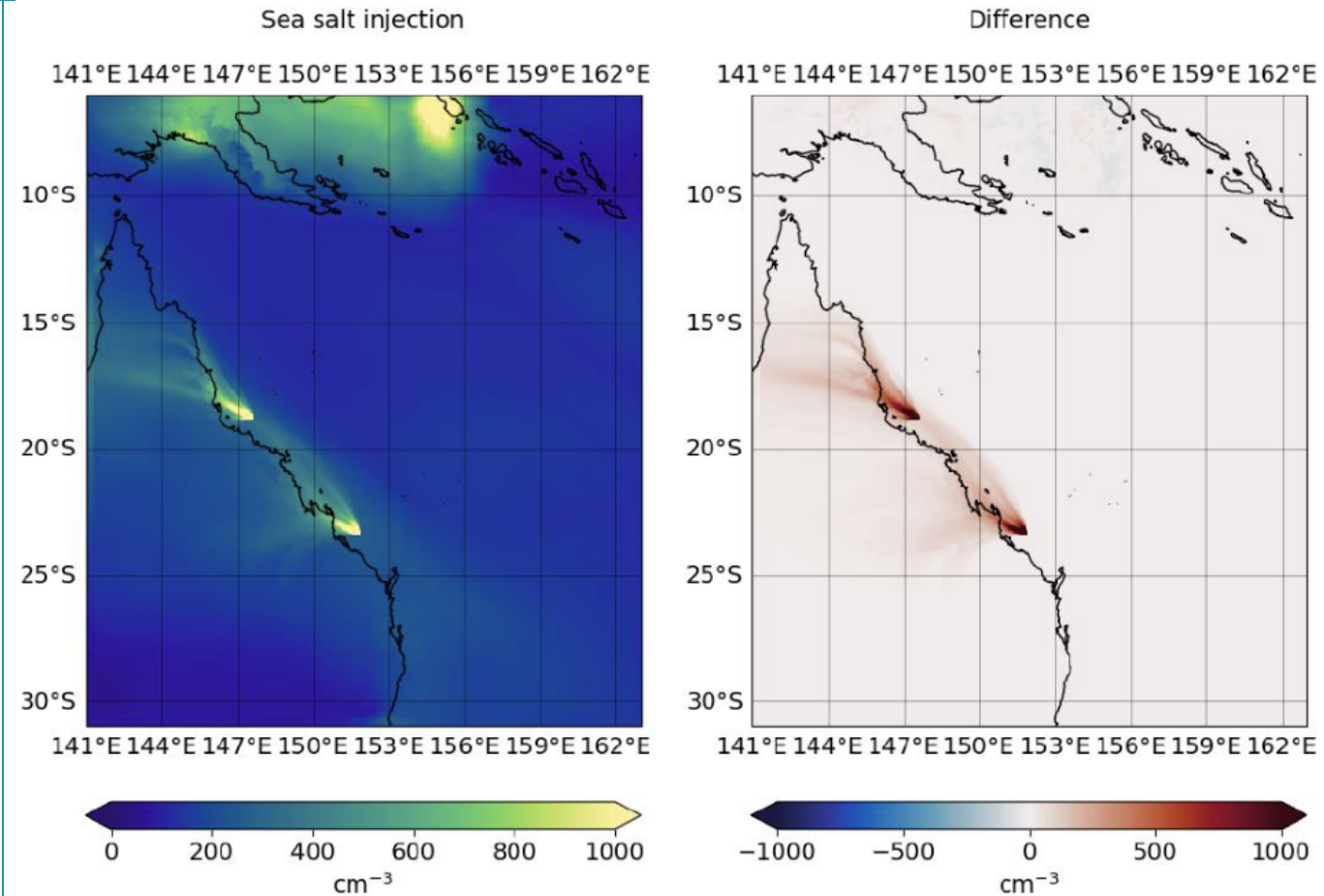


Figure 17: CCN (diameter > 70 nm) number concentration in the NE AUS domain for the (left) sea salt injection simulation and (right) the difference due to the extra sea salt emissions (perturbation - control).

In response to very large aerosol injections, two distinct plumes of CCN are clear, originating at Davies Reef and Heron Island. The emitted sea salt plume (not shown) was advected north in south-easterly trade winds, with emissions from Heron Island likely contributing to the increase in CCN observed downwind over Davies Reef and beyond. The CCN plume resulting from the sea salt injections is relatively well mixed within the boundary layer (Figure 18).

Objective	Key Findings and/or Outcomes
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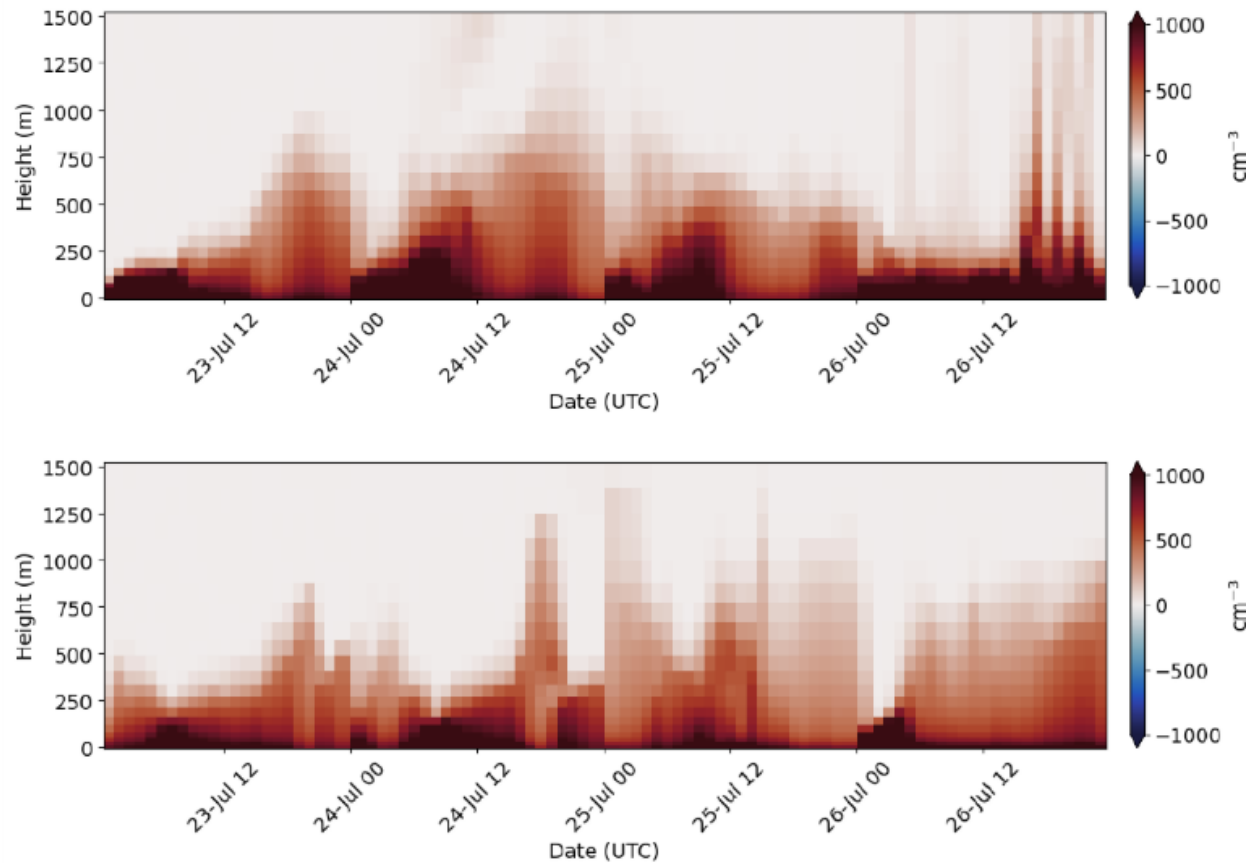


Figure 18: Vertical profile time-series of the change in CCN (perturbed – control) averaged over a 1° area centred on the (top) Davies Reef and (bottom) Heron Island injection locations.

In this scenario, the mean sensitivity of CCN to the sea salt injections is +263 cm⁻³/mg m⁻² s⁻¹ of sea salt at Davies Reef and +241 cm⁻³/mg m⁻² s⁻¹ of sea salt at Heron Island. The slightly lower sensitivity over Davies Reef could be a result of higher background aerosol concentration, in part due to advection of sea salt aerosol from the southern GBR. These results are intended as a demonstration only, to highlight the metrics that will be used to directly compare the impacts of different injection scenarios, and to prove the overall modelling concept. It is expected that different injection perturbations will reveal different CCN sensitivities. It

Objective	Key Findings and/or Outcomes
	<p>is also clear that assessment of different injection locations will need to be undertaken in separate simulations to genuinely disentangle contributions from each site.</p> <p>Model Capability</p> <p>A key achievement has been the development of the coupled ACCESS-EMS-GBR model, which will be a useful tool to assess the effectiveness and potential unintended impacts of the MCB intervention at regional to local scales. The atmospheric model includes coupled aerosol and cloud microphysics schemes and a mechanism to represent sea salt injections, that together can simulate the direct and indirect effects associated with MCB. When coupled to EMS, the subsequent influence on temperature, light and bleaching risk in the coral reef can also be investigated.</p> <p>ACCESS-EMS-GBR was initially intended to study the regional impacts of the MCB intervention at a scale of 10's km over north-eastern Australia. However, the regional atmospheric model has been setup to simulate a convection-permitting domain, with a much higher horizontal resolution (0.04°) than what was initially thought possible. Further, there is potential for a second, higher-resolution domain (up to ~100 m) to be nested within NE AUS, which would enable overlap and comparison with other RRAP Environmental Modelling Project (CS-03) high-resolution modelling activities.</p> <p>There is also potential to include a higher-resolution ocean domain, with a horizontal resolution of approximately 1 km on a curvilinear grid ('GBR1'). The GBR1 domain would better capture the coral reef matrix and variability in temperature, light and depth throughout the GBR.</p> <p>We note that in reality, sea salt injections will occur during summer over several days to weeks. The results presented below are intended to demonstrate the methods available to assess the impacts and efficacy of various sea salt injection scenarios. The experiment ran during Winter 2019 due to an initial lack (now rectified) of available data on the National Computational Infrastructure (NCI) to initialise and 'nudge' the atmospheric model for other time periods. These datasets have since been extended to enable simulations beyond July 2019. The most recent simulations cover the 2022 and 2023 field campaigns and are the case studies used in an ACCESS-EMS-GBR description paper (in prep).</p> <p>Summary of outcomes for the ACCESS-EMS-GBR coupled ocean - atmospheric model</p> <ul style="list-style-type: none"> • The United Kingdom Chemistry and Aerosol (UKCA) code has been updated to allow sea salt to be emitted into the soluble Aitken mode, representing a significant improvement in the representation of sea spray aerosol emissions (both natural and injected). The changes have enabled the sea salt injections to be more realistically distributed over a range of size modes, with important implications for aerosol and cloud responses. • Primary marine organics are an important component of sea spray aerosol, with implications for CCN activation. The aerosol scheme simulates primary marine organic emissions using prescribed chlorophyll-a concentration as a proxy for organic

Objective	Key Findings and/or Outcomes
	<p>matter. The monthly mean chlorophyll-a climatology used by default in the atmospheric model has been updated with a daily reanalysis to better represent daily variability in organic emissions over the GBR.</p> <ul style="list-style-type: none"> • Dimethyl sulfide (DMS) is another important source of non-sea salt sulfate aerosol over the GBR. The climatology of seawater DMS concentration used by the aerosol scheme to simulate sea-air flux has been updated to the Hulswar et al. (2022) climatology, better representing DMS emissions in the GBR. <p>Following these improvements, 10 GBR-wide sea salt injection scenarios were simulated, representing small to maximum feasible injections, with the following key outcomes:</p> <ul style="list-style-type: none"> • Modelled sensitivity of aerosol and cloud droplet number concentration increased with emitted sea salt mass and smaller mean particle sizes (in the 40 – 130 nm dry diameter range). The findings have provided valuable insight that will help to optimise and guide nozzle technology development and possible future deployments. • Emitting 1567.35 tonnes day⁻¹ of sea salt, with a mean diameter close to the CCN activation size could enhance aerosol direct and indirect effects over the GBR during the 2022 summer. AOD (an approximation of the aerosol direct effect) and calculated cloud albedo increased by a respective 49.5% and 9.4%, reducing mean summer surface downwelling SWR by 2.5% (-5 W m⁻², 24-hour mean). Simulated changes were largely contained to the GBR and coastal regions of north-eastern Australia. • A preliminary risk assessment demonstrated that the simulated aerosol injections had no discernible effect on average daily nor total precipitation during the 2022 summer, even in response to a maximum deployment scenario that is beyond what is feasible. <p>While the impacts of additional scenarios and during different time-periods need to be investigated, the results to date are encouraging and suggest that regional marine cloud brightening can be achieved without widespread impacts on aerosol and clouds beyond north-eastern Australia, and with negligible impacts on precipitation.</p>
6. Scenario testing within a regional model configuration to examine continental scale unintended impacts and atmospheric teleconnections.	<p>Background</p> <p>This report presents the results of a modelling study undertaken to assess the risk of precipitation change due to sea spray aerosol injections for marine cloud brightening in the Great Barrier Reef (GBR). Marine cloud brightening has been proposed as a possible intervention to reduce light and temperature over the GBR during summer to prevent or lessen the severity of coral bleaching.</p> <p>Any aerosol perturbation can affect cloud microphysical properties and therefore possibly precipitation. Regional marine cloud brightening aims to increase the number concentration of cloud condensation nuclei (CCN) and cloud droplets (Nd), thereby enhancing low-level cloud albedo (Twomey, 1974) but potentially affecting local and downwind precipitation (Rosenfeld et al. 2008; Hernandez-Jaramillo et al. 2025).</p>

Objective	Key Findings and/or Outcomes
	<p>The scale of sea spray aerosol injections considered for RRAP are several orders of magnitude smaller than the background range of sea spray emissions from the adjacent Coral Sea and Pacific Ocean and are not expected to impact precipitation. However, the risks associated with sea spray aerosol injections over the GBR will be assessed to provide confidence around the expected impacts.</p> <p>Here, the risk of modifying precipitation is assessed in terms of the magnitude, extent and significance of changes in daily and total precipitation quantities. A series of sea spray injection scenarios were simulated using a regional configuration of the Australian Community Climate and Earth System Simulator (ACCESS) for the GBR region (ACCESS-GBR) described above.</p> <p>The findings help to identify the optimal sea spray injection (mass flux, particle size and injection area) that can achieve regional marine cloud brightening without unintended impacts on local or regional precipitation. Future work will incorporate additional sea spray injection scenarios, including a smaller injection area and during different climate regimes (e.g. ENSO phases).</p> <p>Key findings</p> <p>The changes in modelled precipitation in response to moderate to high sea spray aerosol injections were negligible in comparison to the background variability in precipitation over north-eastern Australia and the GBR (Figure 19). The changes were small and not linear across the different injected mass flux and particle size assumptions, indicating that changes were likely dominated by noise due to small differences in meteorology rather than the aerosol perturbations.</p>

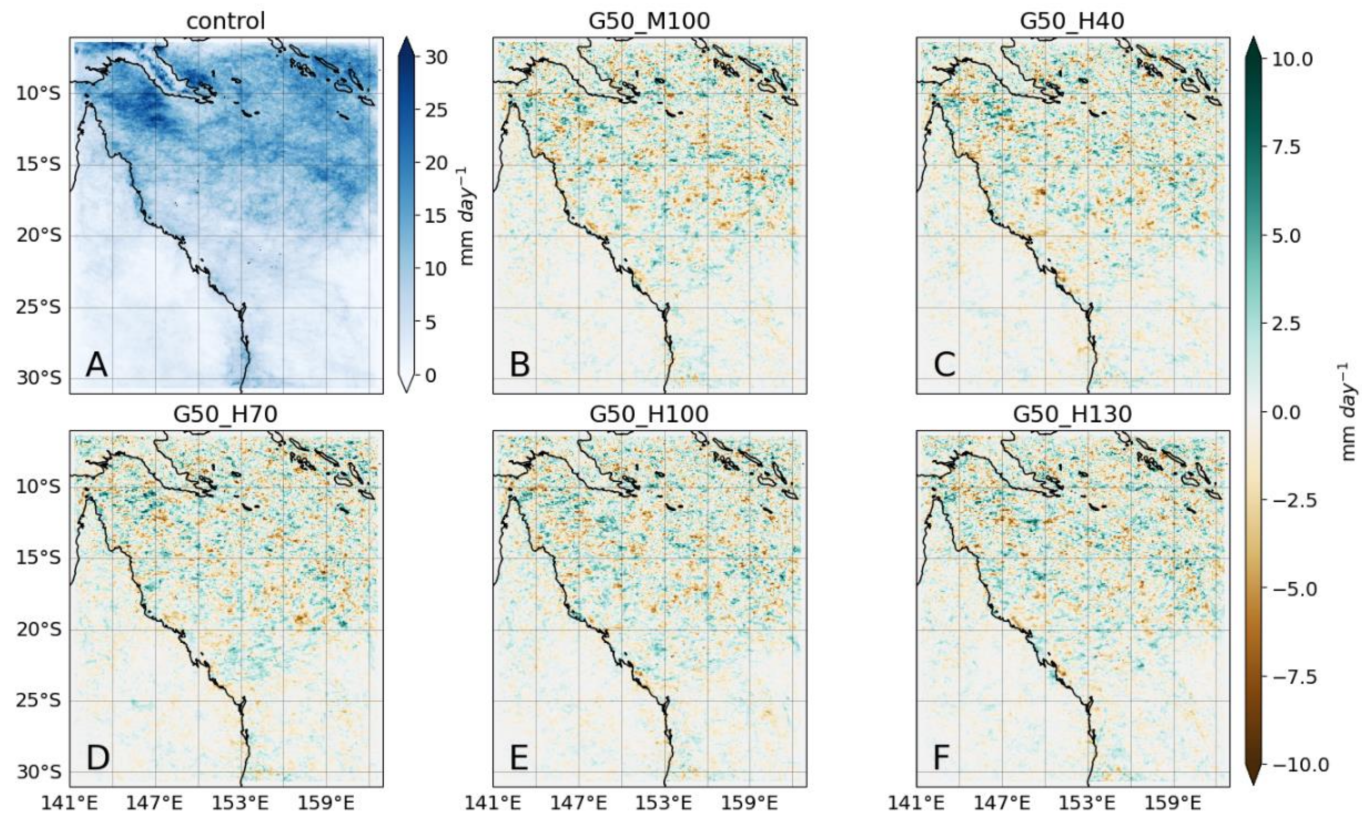


Figure 19: (A) Mean daily accumulated precipitation and change due to the (B) G50_M100, (C) G50_H40, (D) G50_H70, (E) G50_H100 and (F) G50_H130 sea spray injection scenarios.

While small, the G50_H40 sea spray injection had the largest impact on simulated mean and total precipitation during the 2022 summer, with respective changes of $-0.31 \text{ mm day}^{-1}$ and -36.49 mm in total. The findings suggest that a very large sea spray aerosol injection has an effect that is substantially smaller than the natural variability in summer rainfall over coastal regions of north-eastern Australia.

Further work is needed to examine the impacts of other sea spray injection scenarios and time periods, and to increase confidence and robustness on impacts to precipitation. Nonetheless, the findings to date suggest that regional marine cloud brightening can be achieved by emitting a moderate to high mass flux, without a risk of significant impacts to precipitation.

Objective	Key Findings and/or Outcomes
<p>7. Improve radiative transfer modelling within eReefs to capture the 3-dimensional atmospheric and underwater light field. In addition, improve light mediated thermal bleaching sub-routines to assess efficacy of cooling and shading interventions. Additionally, DMS production will be considered to improve feedback to atmosphere.</p>	<p>Improved representation of heating of shallow waters, including improved representation of wind-driven surface albedo and habitat-influenced bottom albedo.</p> <p>The following improvements have been made and checked into the CSIRO Environmental Modelling Suite (EMS) code repository (EMS is the underlying model for eReefs) and made available to all eReefs / RRAP projects:</p> <ol style="list-style-type: none"> 1. EMS now includes a more comprehensive dataset of benthic types. The code has been improved to allow more flexible specification of optical properties from major optical libraries of coral reef habitats. 2. Model formulation of downwelling radiation at the seabed has been improved to represent absorption, transmission and reflection of light by the benthos. 3. Radiative transfer model has been implemented to allow consideration of both downwelling and upwelling light in model calculations. <p>Implement spectrally-resolved solar radiation forcing through use of standard atmospheric radiative transfer schemes used in oceanography.</p> <p>The EMS optical model has been re-coded to better be able to accommodate the ACCESS atmospheric model. Details of this coupling are in the accompanying Briefing Report “CSIRO - Internal briefing paper for regional atmospheric model”. The radiative transfer model RADTRANX has also been included in the EMS code base. It is not clear yet what role ACCESS or RADTRANX will play in the simulations.</p> <p>Represent aerosol-producing organically-driven fluxes of dimethyl sulphide (DMS).</p> <p>A new process has been introduced into EMS that represents the generation of dimethyl sulfide through organic matter degradation, and its exchange with the atmosphere. The atmospheric exchange is based on (Jackson et al. 2021). The changing in-water concentration of DMS, and its rate of exchange, are shown in Figure 20.</p>

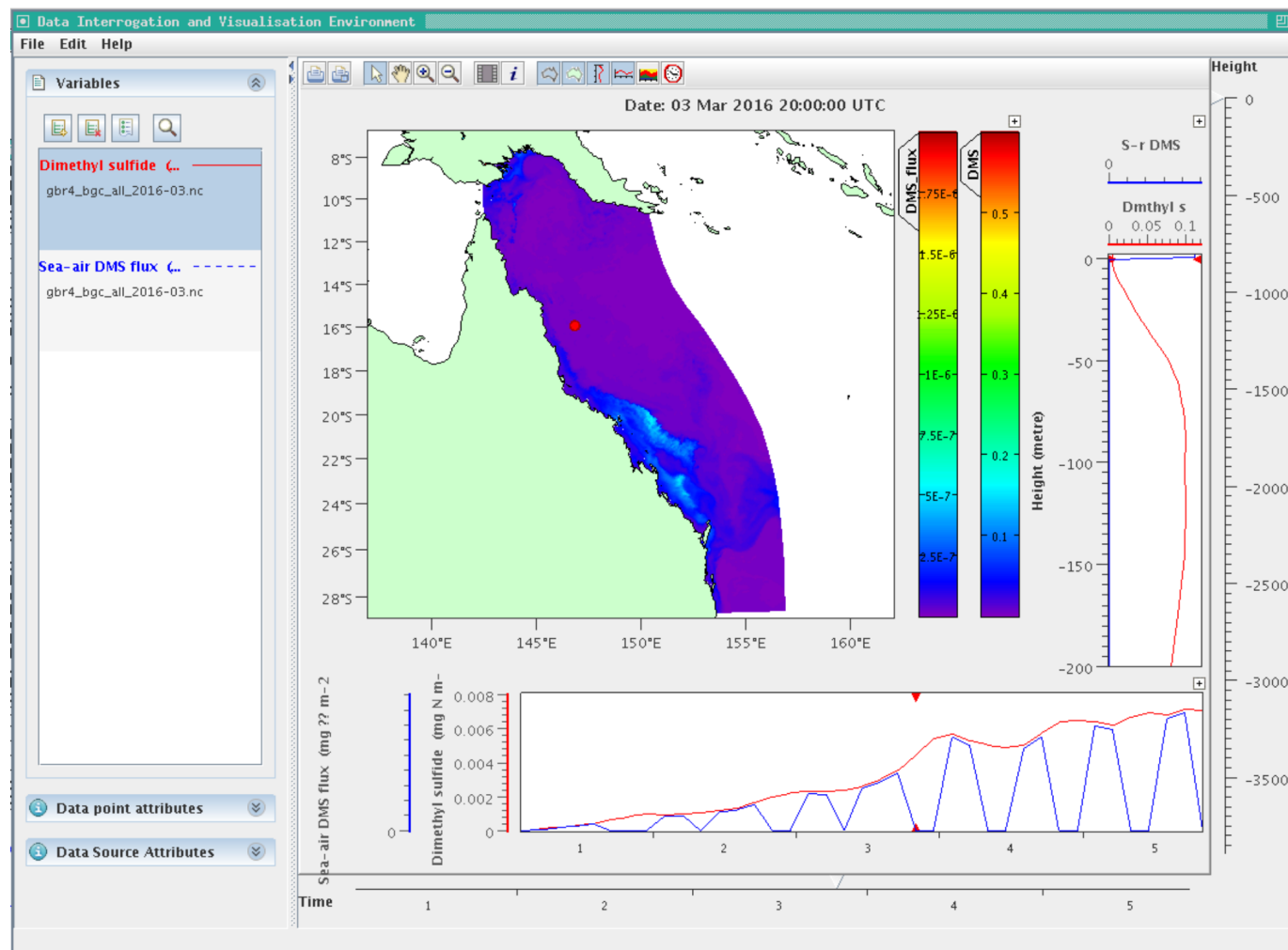


Figure 20: Model outputs of the new DMS sub-model in eReefs.

The map in Figure 20 shows surface DMS concentration, with a maxima in regions of high suspended organic matter, such as created by coral reefs. The vertical profile in the right panel and the timeseries in the bottom panel, show data from the red dot in the map. The time series show the flux (blue) is generally proportional to the near surface concentration (red). The zero value for flux occurs when the model removes DMS from lower model layers (i.e. 1-3 m deep) because tidal movements have reduced the thickness of the top layer. Units of mass are normalised to nitrogen for calibration.

Objective	Key Findings and/or Outcomes
	<p>Other improvements in the eReefs optical model relevant to RRAP.</p> <ol style="list-style-type: none"> 1. Optical model data inputs and metadata have been improved to align with the transparency and reproducibility goals of the RRAP Modelling and Decision Support Sub-program (M&DS). A description of these improvements is included in the EMS documentation (https://research.csiro.au/cem/software/ems/ems-documentation/). 2. Improved process representation, including: <ol style="list-style-type: none"> a) Spectrally-resolved refraction at sea surface. b) Better spectral-resolution to include ultraviolet (UV) and infrared (IR).
<p>8. Scenario testing of the in-water efficacy of cooling and shading methods in reducing coral bleaching stress and mortality.</p>	<p>Description of the approach</p> <p>A regional scale hydrodynamic and biogeochemical modelling system was used to investigate the potential effects of MCB implementation over the GBR. A range of scenarios were investigated which varied the assumed MCB implementation effectiveness (i.e. cloud change percentage) and the spatial extent of the implementation over three previous mass bleaching events. These scenarios hoped to answer the questions; can MCB reduce the SST on the GBR significantly? And what is the minimum viable area that MCB can be effective?</p> <p>The CSIRO eReefs implementation of sparse hydrodynamic ocean code (SHOC) is a suite of tools which includes a hydrodynamic and offline biogeochemical model. This system uses the atmospheric inputs from the Bureau of Meteorology's ACCESS-R (APS-2) model and utilises BRAN2020 global ocean model as the open boundary forcing. Along with riverine discharge rates from the Queensland Government monitoring system. This system was run with 4km grid spacing (GBR4) to examine a wide range of possible implementation scenarios of MCB.</p> <p>For perturbation scenarios the input atmospheric forcing files were modified to simulate an increase in the albedo of low clouds. Because SHOC does not differentiate between high and low clouds, and only considers cloud cover rather than albedo, an increase in the amount of total cloud was applied which was proportional to an increase in the fraction of low cloud present. This perturbation was applied to all low clouds within the designated perturbation region, for the entirety of the simulation, i.e. starting on 1st December and running until 30th April. To account for the ocean-atmosphere temperature feedback in this solely hydrodynamic modelling system an iterative approach was adopted. Each scenario was run six times, with the spatially and temporally resolved change in SST from the previous run being used to offset the atmospheric temperature forcing applied to the subsequent run.</p> <p>Specific scenarios included three spatial extents, Whole GBR, midsize region (~20% of the GBR) and Cairns region (~10% of the GBR). One control scenario in which the amount of low cloud was not altered, and two perturbation scenarios A02 and A03, 0.2 and 0.3 albedo increase respectively was simulated for each spatial scenario over three previous mass bleaching events, 2016, 2017 and 2020 events.</p> <p>Major outcomes</p>

Objective	Key Findings and/or Outcomes
	<p>Across all spatial, temporal and assumed MCB cloud efficacy a significant drop in SST was observed for reefs within the perturbed region. As shown in Figure 21, reef average temperatures were lower by between 0.25 and 1°C than the control simulation when MCB was applied over the whole reef at our lower assumed effectiveness of A02. Reducing the amount of area MCB was applied to resulted in a 6.3% decrease in the amount of avoided warming. And reducing the area by 90% resulted in a 33.2% decrease in the efficacy for the reefs within the perturbed area. There is some fringe benefits to reefs beyond the latitudinal extent of perturbation as shown in Figure 21, however the SST decrease is generally quite confined to the perturbation region. This provides some evidence that, despite previous assumptions, MCB could be an effective mitigation technology even at relatively small areas of the GBR scale. This opens pathways for implementation as MCB could be slowly ‘ramped up’ or trialled over smaller regions of the reef, at vastly reduced cost and environmental risk whilst maintaining significant benefit.</p>

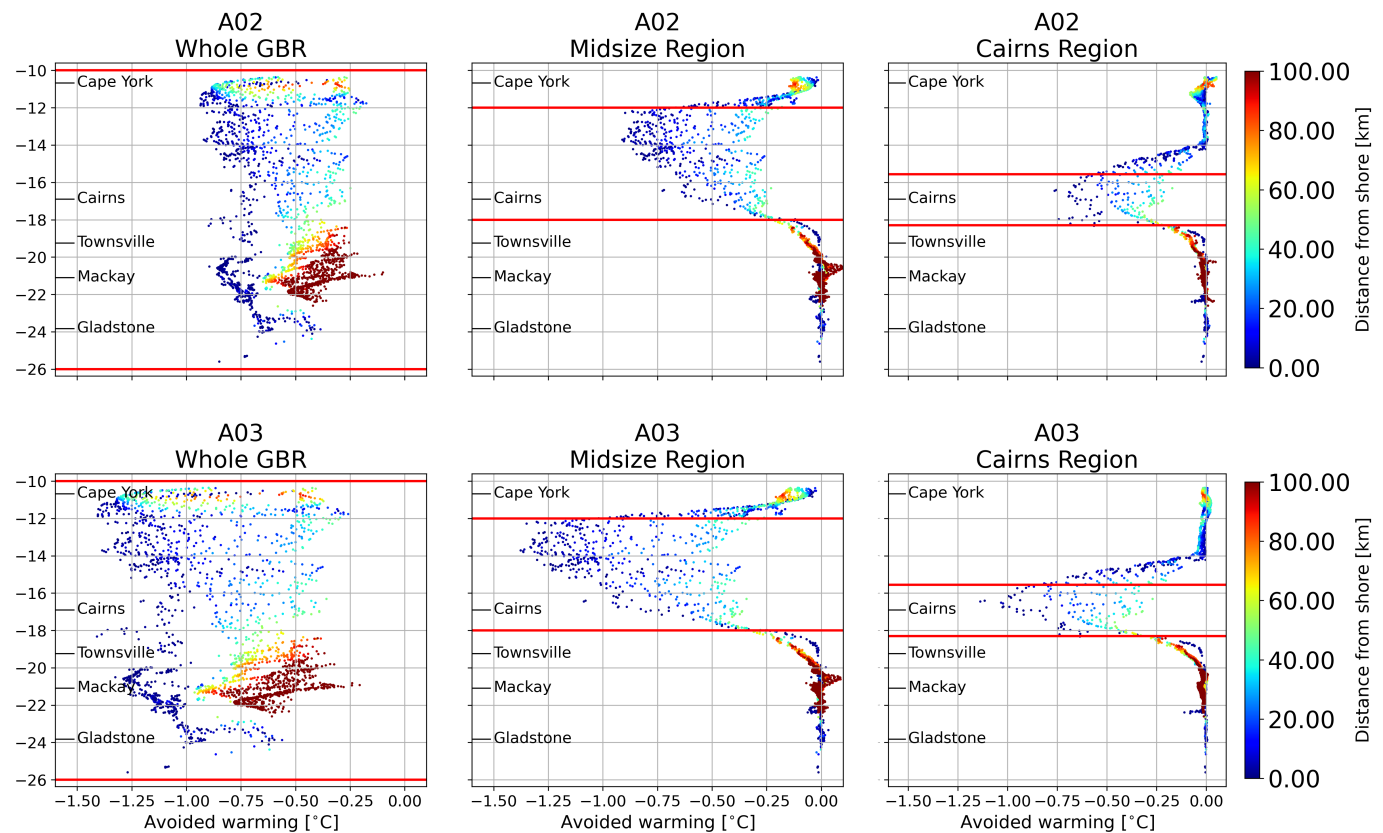


Figure 21: Average SST change from February to May shown at ~2000 individual reefs for the 2016-17 bleaching event. Reefs are coloured by their distance from shore to a maximum of 100km. Red lines indicate latitudinal extent of MCB perturbation (Harrison et al. in-prep).

The efficacy of MCB in reducing coral bleaching stress and mortality can be more closely examined using the Degree Heating Week (DHW) metric. Figure 22 shows maximum DHW experienced during each bleaching event, averaged across reefs within each region of the GBR. The National Oceanic and Atmospheric Administration (NOAA) defines greater than 4 DHW as a risk of reef-wide bleaching, and above 8 DHW as risk of Reef wide bleaching with mortality of heat sensitive corals. Across all years examined the A02 scenario reduced the DHW stress below the 8 DHW threshold across all regions of the GBR, and in the A03 scenario all regions across all years experienced no more than 4 DHW. This shows that over these previous bleaching events MCB application could have greatly reduced if not removed the bleaching stress experienced by corals on the GBR.

Objective	Key Findings and/or Outcomes
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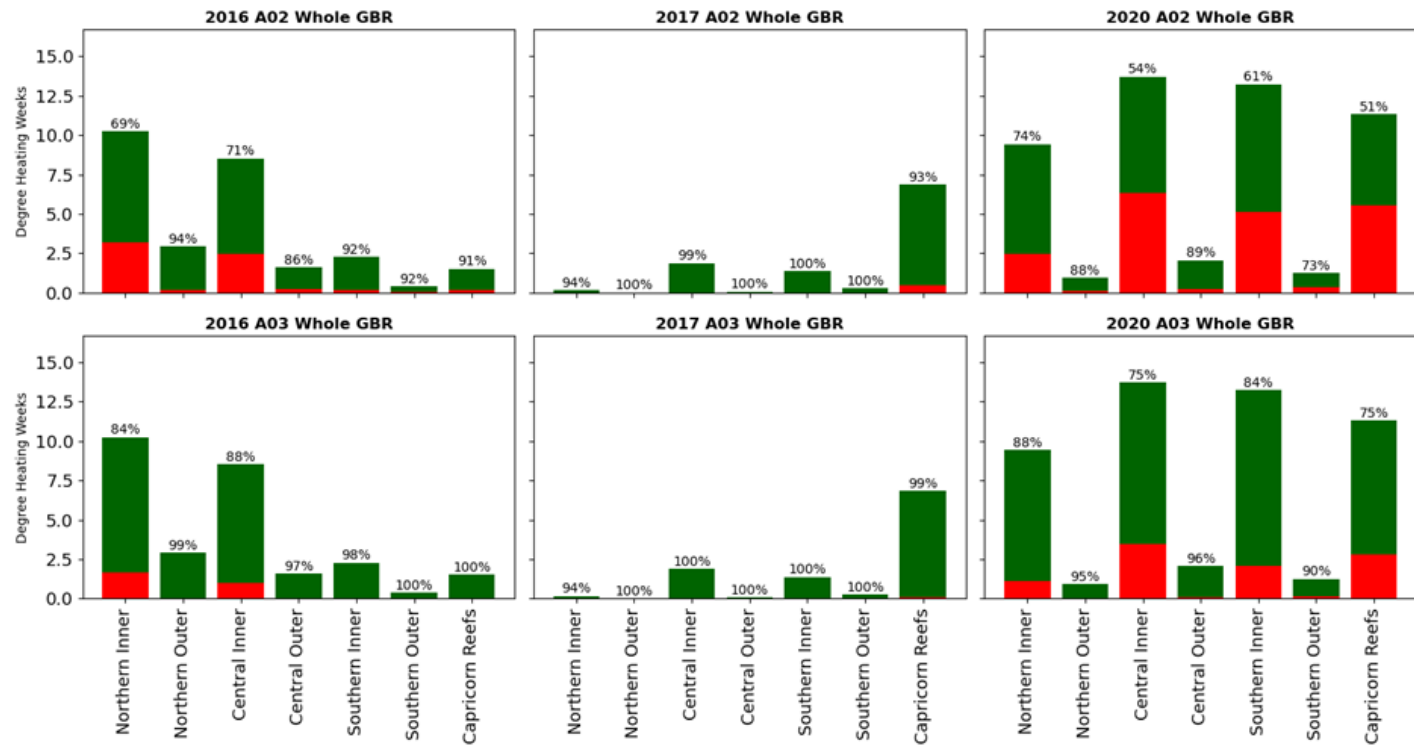


Figure 22: Maximum Degree Heating Weeks experienced by individual reefs aggregated by region of the GBR. Green shows avoided DHW with the percentage at the top of each bar. Red shows the remaining DHW.

Adjustments to key research objectives

Table 5: 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

Considerable progress has been made in the modelling work in the RRAP Environmental Modelling Project (CS-03). With new model capabilities now available and tested (now referred to collectively as the RRAP Cooling and Shading (C&S) modelling suite), the modelling tools can be used to probe a wider set of questions in support of the cooling and shading activities. The future research recommendations below are grouped into threads. Each thread involves a combination of the different modelling tools and metrics so far developed.

Thread 1 - Efficacy of deployment-scale injections

With the C&S modelling suite, and the associated techniques and metrics, the efficacy of proposed deployment scenarios can be simulated as injection parameters become known and feasible scales become clear. Importantly, the efficacy can be quantified and compared in a range of different ways. For example, the effect of an aerosol injection can be assessed in terms of the number of additional cloud droplets, the change in shortwave radiation, or the change in degree heating weeks experienced by the coral reef.

The latter 'whole system' efficacy is a particularly important open topic. Simulations to date have proven the MCB concept over the GBR, and the next tranche of simulations should focus on quantifying the benefit to the reef of a particular scenario, or range of scenarios, to enable decision and policy-making.

Thread 2 - Optimisation across scales

The modelling suite can be used in support of the nozzle engineering activities to inform the optimal emitted size from several viewpoints: efficacy, energy use, and economics. This is an iterative process, where engineering advances in the lab lead to revised parameters to be simulated, the results of which can suggest directions for nozzle and scenario development.

In consideration of deployment, the modelling suite can assess the full range of parameters associated with aerosol injection e.g. size width of injected aerosol mode, optimal size of emitted aerosol, timing of injection, spacing between injection sites, spatial location of injection, size of injection site, planning for downtime during synoptic events etc. The results of which can be used to optimise the scenario to achieve the most efficient or effective solution.

Thread 3 - Quantification and assessment of risk

Existing simulations and previous work have suggested a negligible impact of the additional aerosol on precipitation, particularly in the context of natural variability. Given the likely scrutiny associated with the intervention, increasing the robustness of this result is important, particularly while simulating plausible deployment scenarios.

Thus, a substantial research effort in consideration of impacts on precipitation from MCB is desirable, quantifying the changes under a range of conditions, e.g. different El Nino / La Nina phases, and using metrics that quantify both the impact on the mean change, as well as any changes to natural extremes.

This thread of work should proceed in close co-operation with the RRAP Independent Risk Review Group (IRRG).

Beyond precipitation, additional possible impacts include changes to gas-phase chemistry and salt deposition on land. The results of this work are critical for future decision and policy-making.

Thread 4 - Efficacy under future scenarios

Consideration thus far has only been given to present-day conditions. When considering the health of the reef for future generations, future climatic conditions need to be accounted for, and this can only be achieved through modelling.

Our modelling suite can be modified to simulate future warmed scenarios, e.g. at 2050, 2070 etc. The need for and efficacy of interventions can be tested in a similar manner to the simulations conducted for present day conditions. The simulation scope could also include efficacy of other RRAP interventions.

Thread 5 - Application to other reef environments

The atmospheric models developed so far are all relocatable with minimal effort. The EMS model is relocatable but requires developmental effort to ensure the input parameters are correct. Thus, the possibility exists to explore the application of MCB in other reef areas that are threatened by climate change-induced bleaching.

Thread 6 - Increasing model fidelity and resolution

Both scientific understanding and computing resource availability are increasing, presenting opportunities for improving modelling capability. Increased scientific understanding can be incorporated into models to better resolve processes and increase fidelity. Additional compute power can be deployed to run more simulations to create an ensemble, or to increase the resolution of a simulation (increasing spatial detail).

Incorporating advances in our understanding of gas-phase chemistry, aerosol-cloud interactions, and biogeochemical responses, are all valuable paths to pursue in future research.

To exploit the latter, all modelling tools in the suite can be run at higher resolutions, or over larger domains. A possibility also exists to deploy extra computing resources to resolve the atmospheric vertical structure with more detail, and in conjunction with increased horizontal resolution, open the door to simulation of fogging.

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