

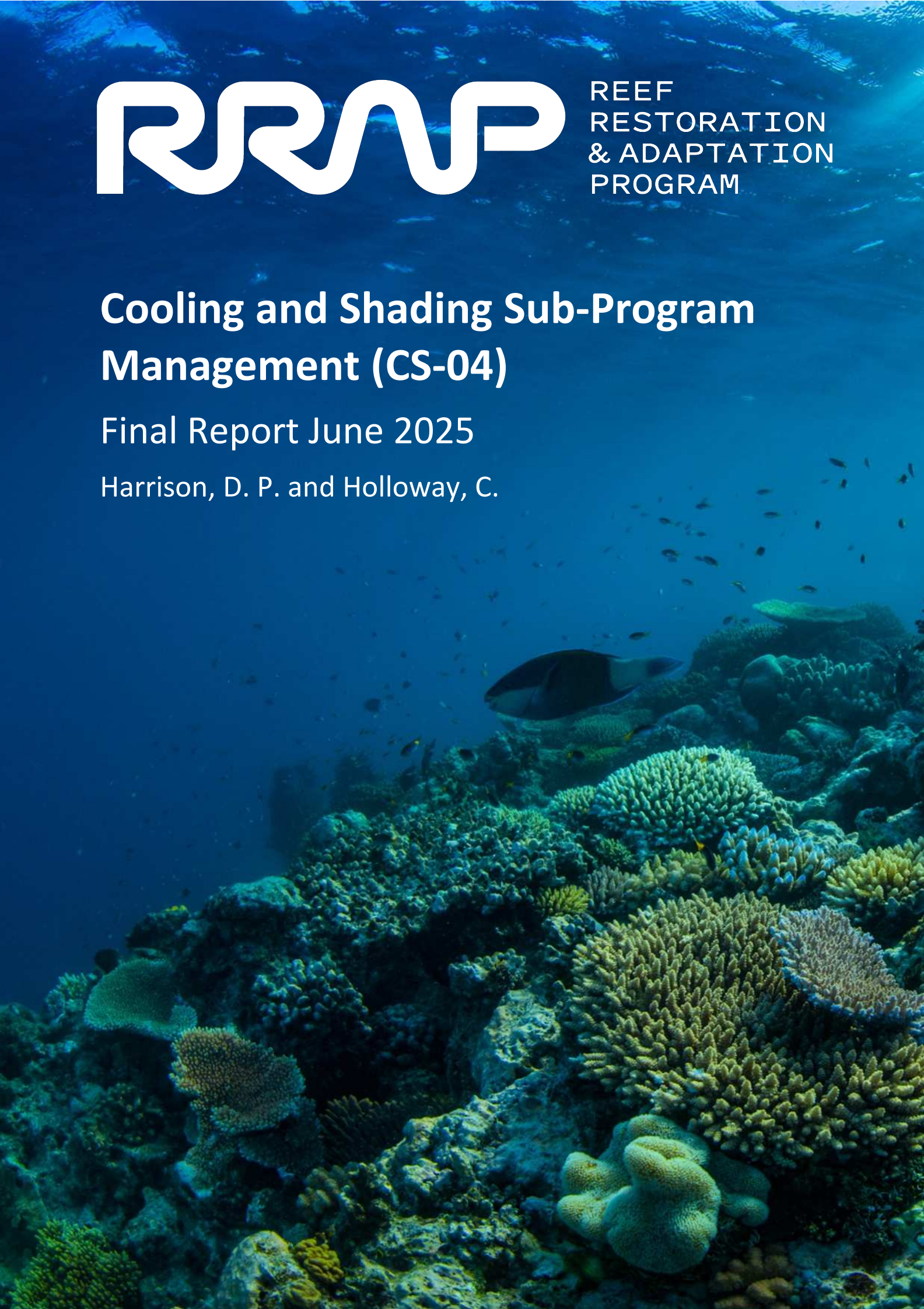


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RESTORATION  
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PROGRAM

# Cooling and Shading Sub-Program Management (CS-04)

Final Report June 2025

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## RRAP Cooling and Shading Sub-program Management (CS-04) Final Report June 2025

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Cover Page photo: Coral Reef, Credit: Gary Cranitch, Queensland Museum

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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:

<b>Location</b>	<b>Traditional Owner Group</b>
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 Cooling and Shading Sub-program Management Project (CS-04) has served as the central management and coordinating hub for the Cooling and Shading Sub-program of the Reef Restoration and Adaptation Program (RRAP). From 2020 to 2025, over the course of the first phase of RRAP this project provided sub-program leadership, administrative support and coordination, technical management, and logistical execution across a suite of multi-institutional and cross-disciplinary projects involving experimental, observational, and theoretical research aimed at researching, evaluating, developing and testing engineering intervention technologies with potential to reduce coral bleaching on the Great Barrier Reef (GBR).

Primary responsibilities included delivering the leadership, oversight, and operational infrastructure required to support the scientific, engineering, engagement, and regulatory activities of the RRAP Cooling and Shading Sub-program. Specifically, the Project delivered five interrelated functions: (1) sub-program-wide leadership, project management, and community engagement activities; (2) procurement and management of capital assets and technical services; (3) administration of engineering design, integration, and deployment; (4) execution of a complex, multi-year integrated field program and (5) coordinating reporting of the results within RRAP, through conference presentations, internal briefing notes and journal publications.

This management project was responsible for the planning, integration, and coordination of the four Cooling and Shading research projects. Previous projects RRAP Atmospheric and Meteorological Monitoring (CS-02) and RRAP Systems Engineering (CS-05) were rolled into other Cooling and Shading projects to streamline administration and reporting. The four remaining projects were:

- GBR Atmospheric Survey (CS-01)
- Environmental Modelling (CS-03)
- Cloud and Sky Brightening Development (CS-06)
- Fogging Development (CS-07)

The Cooling and Shading Sub-program Management Project (CS-04) leadership team played the central role in guiding the strategic direction of the sub-program. They refined its scientific and technical objectives, actively managed risks, and ensured alignment of activities both within the sub-program and with the broader goals of the RRAP initiative. The team fostered strong collaboration across participating institutions, subcontracted organisations, Traditional Owner groups and regulatory stakeholders, ensuring inclusive and coordinated engagement throughout.

Project roles and deliverables were regularly reviewed and adjusted in response to progress and emerging needs, allowing the sub-program to remain flexible and strategically responsive. A key responsibility of the leadership team was to integrate RRAP's cross-cutting operational requirements, such as communication, permitting, reporting, data management, and stakeholder engagement, into day-to-day activities. These functions were embedded to support compliance, continuity, and transparency. This integrated approach enabled the Project to maintain momentum despite significant external challenges, including COVID-19 lockdowns, delays in contracting and sub-contracting, and tropical cyclone disruptions.

A central output of the Project was the successful delivery of a five-year integrated field campaign, which included both major summer deployment campaigns and off-season (winter) engineering and instrumentation trials. The field program escalated in scale and complexity across the reporting period, with the largest and most ambitious multi-platform deployment ever undertaken by RRAP in early 2023. The campaign included two large research vessels, the procurement, instrumentation, and certification of the SCU meteorological-aerosol-microphysics-radiation research aircraft, temporary remote sensing stations established on the mainland and Heron Island as well as a full atmospheric aerosol characterisation laboratory installed on Heron Island. A further team operated several airborne remote sensing platforms from a temporary landing platform on One Tree Island. The 2023 field campaign refined our research team's

capabilities for future campaigns which ultimately culminated in the highly successful 2025 Cooling and Shading Sub-program field campaign.

Major summer field deployments occurred in:

- Year 1 (Dec 2021)
- Year 2 (Jan–Mar 2022)
- Year 3 (Nov 2022 and Feb–Mar 2023)
- Year 4 (Jan–Mar 2024)
- Year 5 (Feb–Mar 2025)

Each campaign featured operations across multiple platforms, including island-based research stations, marine research vessels, piloted and uncrewed aircraft systems, and floating fogging test arrays. Supporting logistics included coordination of vessel charters, research permits and regulatory compliance, inter-agency collaborations, and overseeing workplace health and safety (WHS) in real-time. Regulatory permits and certification were required from Great Barrier Reef Marine Park Authority (GBMPA), Queensland Parks and Wildlife Service (QPWS), and the Civil Aviation and Safety Authority (CASA). More than 60 tonnes of equipment were transported and re-deployed across the campaigns. In some cases, such as the 2023 cyclone event, the team was required to rapidly demobilise and reinstall more than 40 scientific instruments at short notice, an effort that ensured minimal disruption to the scientific objectives.

The field program also supported the delivery of a world-first large-scale marine cloud brightening (MCB) and fogging prototype systems and their deployment for outdoor real-world testing. A major fogging trial was conducted in year five, using a marine fogging system to test the creation of a persistent sea-surface fog over a targeted reef area. This trial was conducted under calm ("doldrum") conditions, designed to simulate the high-stress thermal environments in which corals are most vulnerable to bleaching. Concurrently, MCB systems were trialled aboard research vessels, supported by drone and satellite observations to detect and quantify cloud microphysical responses and changes in albedo.

The Project was responsible for planning and executing the procurement of major capital equipment and engineering services required across the entire sub-program. This included:

- Outfitting the Southern Cross University (SCU) research aircraft with a hyperspectral camera, meteorological, cloud microphysical and aerosol instrumentation, and mapping (light detection and ranging).
- Commissioning and upgrading a series of fogging and MCB nozzle systems, including marine-capable platforms with multi-directional control and satellite-detectable output rates.
- Procuring Unmanned Aerial Vehicles (UAVs) capable of carrying 10 kg payloads for up to four hours, with integration of meteorological, aerosol, cloud microphysical and remote sensing LiDAR payloads.
- Purchasing and maintaining laboratory instrumentation for droplet size measurement, spray characterisation, and nozzle system validation.
- Developing data logging, calibration, and synchronisation systems for multi-platform deployments in remote marine environments.

Many of these instruments and systems were bespoke or required significant modifications to operate in high-humidity, harsh marine environments. The project management team managed the engineering integration, installation, maintenance, calibration, and safe operation of this infrastructure across multiple sites.

This project also administered the design, fabrication, and testing of complex water atomising engineering systems, central to the intervention technologies being developed. This work included:

- Design and integration of nozzle arrays, compressors, and manifolds for MCB and fogging systems.
- Certification of modifications to the SCU research aircraft.

## **Testing and optimisation of droplet generation systems for both ground and vessel-based operations.**

- Development of floating array platforms to capture fogging plume dynamics under controlled conditions.

External consultants were engaged to support system design reviews, safety assessments, and sampling strategy development. Lessons from each campaign were used to refine and improve engineering systems, resulting in a rapid iteration cycle that delivered multiple generations of increasingly capable technology within the life of the project.

The Project maintained a strong and considered approach to engagement with Traditional Owners, community stakeholders, industry partners, and regulatory authorities. This included:

- Coordinating Free, Prior and Informed Consent (FPIC) processes for all field locations.
- Partnering with groups such as the Gidarjil Corporation to support meaningful participation in field campaigns.
- Negotiating support agreements with tourism operators to facilitate access and infrastructure support.
- Hosting internal workshops, presentations at national and international conferences, and co-authoring high-impact publications.
- Participating in community panels to provide scientific insights, discuss project progress, and gather local knowledge.

The project's internal management and WHS systems were recognised by Southern Cross University through a Vice Chancellor Award for Excellence in Safety, highlighting the team's proactive and professional approach to risk mitigation in a high-complexity research environment.

The foundation built by this Project provides a clear and strong platform for continuity and growth. The project has delivered on all core objectives, developing technical capability, demonstrating field feasibility, and building a functional framework for multidisciplinary collaboration. The integrated field campaigns are now complete, and a growing body of peer-reviewed publications is emerging. With clear opportunities for upscaling, the Cooling and Shading Sub-program is well-positioned to lead global research into atmospheric-cloud microphysical interventions for coral reef protection. This Project has not only delivered world-first field demonstrations of MCB and fogging on the GBR, it has created the operational, technical, and strategic infrastructure to support the next generation of climate resilience solutions for coral reefs globally.



*Figure 1: Marine cloud brightening sprayers in operation on the Great Barrier Reef, 2025.*

## 2 Background and Justification for the Research

The Reef Restoration and Adaptation Program (RRAP), launched in 2018, is one of the most ambitious coral reef science and intervention initiatives in the world. It is funded through a strategic partnership between the Australian Government's Reef Trust Partnership (RTP) and the Great Barrier Reef Foundation and brings together leading research organisations to deliver innovative solutions for the preservation of the Great Barrier Reef (GBR). Key partners include the Australian Institute of Marine Science, CSIRO, and a consortium of universities such as Southern Cross University, Queensland University of Technology, James Cook University, and the University of Queensland. Together, these institutions drive the research, development, and testing of interventions designed to protect and enhance the resilience of the GBR in the face of climate change.

In the face of accelerating ocean warming, mass bleaching events, and compounding stressors, RRAP's mandate is to move beyond conventional reef management and restoration into a new frontier of adaptive, scalable interventions. The program aims to deliver a "toolbox" of scientifically rigorous, socially acceptable, cost-effective, and ecologically viable interventions that can be deployed at relevant reef scales over the coming decade.

Within this overarching program, the Cooling and Shading (CS) Sub-program has emerged as a focal research axis. Its objective is to reduce thermal and irradiance stress on reef ecosystems during acute heating events by modulating the incident solar radiation reaching the water surface. Techniques under investigation include marine cloud brightening (MCB) spraying sea salt aerosol into the lower atmosphere to enhance cloud reflectivity and seawater fogging to directly shade reefs via microdroplet scattering.

These approaches are novel, technically complex, and operationally demanding. They require coordinated efforts across atmospheric physics, marine engineering, field logistics, permitting, safety certification, community and stakeholder engagement, data infrastructure, and risk governance. Over its course, the Cooling and Shading Sub-program has progressed from conceptual modelling to small-scale field trials, such as ship-based sea spray aerosol experiments and airborne measurements of cloud microphysical responses, laying essential groundwork for scaling.

Within this framework, the Cooling and Shading Sub-program Management Project (CS-04) serves as the central coordination and leadership project for the Cooling and Shading Sub-program, responsible for strategic oversight, internal and external reporting, integration of technical and administrative components, and delivery of a cohesive, multi-platform, multi-year field program. The Project plays a foundational role in enabling the successful design, implementation, and evolution of all Cooling and Shading activities through four interrelated core functions:

1. Leadership of the sub-program and coordination of research projects,
2. Procurement and integration of specialised instrumentation and engineering services,
3. Management of complex engineering systems, subcontracting, and compliance, and
4. Delivery and execution of an integrated, multi-year field campaign.

The Project leadership team is responsible for coordinating all Cooling and Shading research efforts, including the following projects: GBR Atmospheric Survey (CS-01), Environmental Modelling (CS-03), Cloud and Sky Brightening Development (CS-06), and Fogging Development (CS-07). This includes facilitating cross-project alignment, maintaining cohesion across technical activities, and integrating strategic planning with other RRAP Sub-programs.

Key responsibilities include:

- Defining and refining scientific aims, scope, and strategic direction;
- Setting and reviewing technical objectives, success criteria, and performance benchmarks;

- Monitoring sub-program progression against milestones and deliverables;
- Coordinating internal and external reporting to RRAP Program Management;
- External conferences and journal publications;
- Managing the sub-program budget and financial allocations;
- Overseeing sub-contracted organisations, partner institutions, and third-party consultants;
- Managing Traditional Owner engagement, stakeholder relationships, and permitting requirements in collaboration with the appropriate RRAP Sub-programs.

The Cooling and Shading Sub-program leadership also provides governance oversight for data quality, instrumentation deployment, and the provisioning of data to the RRAP Modelling and Decision Support (M&DS) Sub-program for simulation calibration and intervention feasibility assessments.

The Cooling and Shading Sub-program is guided by a highly capable multidisciplinary management team. Collectively, the leadership provides strong scientific direction, technical integration across projects, and comprehensive program oversight. This includes coordination of research activities, project management, budget tracking, subcontractor oversight, milestone reporting, and alignment of internal and external activities.

Administrative and technical support is delivered through Southern Cross University, encompassing media, communications, finance, legal, IT, and research services. Dedicated roles within the sub-program provide expertise in administration, financial oversight, engineering support, instrumentation, platform management, and research assistance ensuring that both scientific and operational requirements are met with precision.

In addition, the Cooling and Shading Sub-program Management Committee, active since 2016, provides an essential layer of independent scientific and engineering review. Comprising experienced engineers, physicists, and atmospheric and environmental scientists, this group meets regularly to review progress, assess new proposals, and provide strategic guidance. The committee has been instrumental in conceptualising the Marine Cloud Brightening approach for the Great Barrier Reef and in supporting the successful acquisition of program funding through government and competitive grant processes.

This project has served as the organisational and operational core of the Cooling and Shading Sub-program, providing leadership across research coordination, engineering development, regulatory compliance, Traditional Owner and stakeholder engagement, and field program execution. Operating across multiple years, partners, platforms, and geographic locations, the Project team enabled the successful demonstration of novel Cooling and Shading technologies designed to reduce coral bleaching on the Great Barrier Reef.

Beyond its technical and logistical accomplishments, the Project played a pivotal role in developing a ground-up approach to community engagement, cultural inclusion, and regulatory navigation. The project established enduring partnerships with Traditional Owner groups and engaged local communities and marine industries to ensure transparency, trust, and inclusion in all project phases. Through a robust and adaptive permitting process, the Project also maintained compliance with complex regulatory frameworks, including GBRMPA and CASA, while embedding workplace safety and environmental responsibility into every operational activity.

Together, these achievements have laid a strong foundation for the responsible scaling and integration of reef cooling interventions into future phases of RRAP. By coupling cutting-edge science and engineering with inclusive governance and engagement strategies, this Project has not only advanced the technical feasibility of Marine Cloud Brightening and fogging as potential reef interventions or climate mitigation strategies but also built the social and institutional capacity necessary to ensure their long-term legitimacy and success.



*Figure 2: Marine cloud brightening experimental operations in low wind conditions on the Great Barrier Reef.*

### 3 Research Objectives and Key Findings

A current list of project outputs are listed on the RRAP website: [gbrrestoration.org](http://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. Leadership of the Cooling and Shading Sub-program including project management and engagement activities, including management of sub-contracting research organisations. Coordinate the logistics, permitting, reporting and outreach activities, and provide overall Sub-program internal management activities.</p>	<p>The RRAP Cooling and Shading Sub-program Management Project (CS-04) has consistently provided effective leadership and coordination across the Cooling and Shading (CS) Sub-program, overseeing project management, reporting, Traditional Owner engagement, and sub-contractor delivery. The team maintained internal cohesion while managing multiple research partners, field deployments, and regulatory requirements across all five years of the first phase of RRAP.</p> <p>Effective governance and broad-based engagement have been central to the success of the Cooling and Shading Sub-program under RRAP. This Project was not only tasked with coordinating technical and operational research but also with building the social, cultural, and regulatory frameworks necessary to support such novel interventions. Given the emerging and potentially contentious nature of Marine Cloud Brightening and seawater fogging, trust, transparency, and legitimacy were just as important as technical capability. By embedding Traditional Owner participation, fostering partnerships with local communities and industry, and navigating complex regulatory environments, the Project established a model of collaborative governance that ensured both scientific progress and social license. This integration of technical delivery with engagement and oversight represents a critical innovation in the management of climate adaptation research.</p>



*Figure 3: Cheng Chen checking the nozzle tower of the marine cloud brightening sprayer during field tests in 2023 on the Great Barrier Reef.*

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**Community Engagement, Regulatory Navigation, and Governance**

A critical pillar of the Project has been the ground-up development of community engagement, regulatory compliance, and governance frameworks tailored to the novel and potentially controversial nature of cooling and shading interventions. Given the emerging status of Marine Cloud Brightening (MCB) and fogging technologies, these activities were not only scientific and technical in nature but also highly dependent on social license, trust, and transparent oversight.

**Traditional Owner Engagement and Codesign**

The Cooling and Shading Sub-program has proactively embedded Traditional Owner engagement across all phases of the project, from concept design and risk planning to field execution and long-term stewardship. The Project team supported Free, Prior and Informed Consent (FPIC) processes for every major deployment and facilitated direct involvement of Traditional Owner representatives in fieldwork, site selection, and local awareness activities.

Partnerships were developed with organisations such as the Gidarjil Development Corporation, with whom employment pathways, fieldwork participation, and cultural consultation activities were jointly delivered. Over the course of the program, this evolved into a more structured and scalable model of engagement that will support expanded work under RRAP into the future. In parallel, learnings from this process were shared with other RRAP Sub-programs to support a whole-of-program approach to Traditional Owner inclusion.

**Stakeholder and Industry Collaboration**

In conjunction with Traditional Owner engagement, the Project team developed strong relationships with local communities, marine industries, tourism operators, and scientific collaborators. Notably, a long-term partnership was established with Hamilton Island Resort, enabling collaborative use of marine and aviation infrastructure, support services for researchers, and enhanced field access. This relationship not only reduced operational barriers but demonstrated how industry partnerships can facilitate environmentally focused research.



*Figure 4: Stakeholder engagement at community panel meeting in Townsville, 2022.*

The project also ensured that public communication and outreach remained transparent and responsive. Internal seminars, national conference presentations, and international scientific contributions were balanced with tailored briefings to reef communities, policymakers, and stakeholder groups. This openness supported continued confidence in the program’s objectives and methods, particularly during high-profile deployment seasons.

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**Regulatory Approvals and Compliance**

The Cooling and Shading field research program was conducted under a highly regulated environment. This Project was responsible for obtaining and maintaining a suite of critical permissions, including:

- Marine research and intervention permits through the Great Barrier Reef Marine Park Authority (GBRMPA);
- Aviation safety and flight approvals from the Civil Aviation Safety Authority (CASA);
- State and institutional ethical and environmental approvals;
- Internal SCU compliance, WHS risk assessments, and operational safety documentation.

As the program progressed, the Project established processes for permit applications, compliance reporting, safety assessments, and incident tracking. These processes were continuously improved to support the increasing scale and complexity of interventions, from early lab-scale fog trials to full-vessel deployments and satellite-monitored MCB emissions.

A dedicated Workplace Health and Safety (WHS) system was developed and implemented, with daily reporting during campaigns and comprehensive documentation maintained across all operational platforms. These safety efforts were formally recognised through a Southern Cross University Vice Chancellor Award for WHS Excellence, reflecting the team's proactive and systems-based approach to risk management.

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*Figure 5: Laying the water delivery pipes for the fogging system prior to field experiments on the Great Barrier Reef, 2023.*

### **Governance and Oversight**

In support of good governance, the Project team provided consistent and detailed reporting to the RRAP Board and Steering Committee, as well as to internal oversight bodies at Southern Cross University. The Cooling and Shading Sub-program Management Committee played a key advisory role, offering regular technical review and strategic feedback. This Project supported RRAP's emerging governance frameworks by contributing to planning documents for future phases of RRAP, participating in working groups on intervention ethics and governance, and helping shape the program's long-term trajectory with lessons from operational experience.

Objective	Key Findings and/or Outcomes
	<p>Through this integrated engagement, regulation, and governance framework, this Project not only supported the technical delivery of the Cooling and Shading Sub-program but also ensured that its outcomes were legitimate, lawful, and socially informed, creating a strong foundation for the potential future deployment of these technologies on a larger scale.</p> <p>The work of the RRAP Cooling and Shading Sub-program management Project (CS-04) has demonstrated that good governance and genuine stakeholder engagement are indispensable to the responsible advancement of reef intervention science. Through regulatory compliance, proactive safety systems, and structured pathways for Traditional Owner involvement, the project delivered not only technical milestones but also legitimacy and accountability. Its partnerships with local industry and communities showed how research can be embedded within the social and economic fabric of the Great Barrier Reef region, while its transparent reporting and outreach reinforced public trust. Together, these achievements have positioned the RRAP Cooling and Shading Sub-program as a credible, ethically grounded, and operationally capable initiative. This foundation will be vital for scaling interventions, maintaining social license, and ensuring that research continues to be both scientifically rigorous and socially responsible.</p>
<p>2. Procure and manage large capital items, engineering and consulting services. Specialised instrumentation is needed to outfit the nozzle characterisation laboratory and wind tunnel facility and to supplement the existing instrumentation on the aircraft.</p>	<p>The Project team successfully oversaw the acquisition and deployment of capital equipment for Cooling and Shading research. This included:</p> <ul style="list-style-type: none"> <li>• Establishing and outfitting a dedicated nozzle test laboratory and wind tunnel facility.</li> <li>• Procuring and integrating instrumentation into the SCU research aircraft, including a hyperspectral camera, LiDAR, cloud microphysics probes, and aerosol sensors.</li> </ul>



*Figure 6: Birds eye view from the Southern Cross University research aircraft during marine cloud brightening field trials in the Great Barrier Reef.*

- Developing and commissioning two generations of nozzle and fogging system prototypes, including a world-first marine fogging system capable of 20× scale-up from initial tests.



*Figure 7: Marine fogging infrastructure set up on a research vessel during field trials in the Great Barrier Reef, 2023.*


- Commissioning atmospheric, metrological and cloud microphysical resources to support operations in the laboratory and field.
- Upgrading UAV platforms and designing custom payloads for aerosol sampling and atmospheric profiling.





*Figure 8: Landing an atmospheric profiling drone onboard a marine research vessel in the Great Barrier Reef, 2024.*

- Integrating data acquisition systems and calibration tools to support high-resolution aerosol and MCB measurement.

Procurement activities were aligned with evolving research needs and field conditions, with equipment sourced, modified, and tested under compressed timelines. The Project team demonstrated technical agility and foresight in acquiring capabilities that underpinned real-time monitoring and intervention testing.

Objective	Key Findings and/or Outcomes
	 <p data-bbox="568 770 1998 831"><i>Figure 9: View inside the Southern Cross University research aircraft underwing pod where the hyperspectral camera, optical particle counter, aerosol drying system and LiDAR are installed.</i></p>
<p data-bbox="125 858 539 1406">3. Administer and manage major engineering costs across the sub-program, including: design, procurement, and manufacture of hardware to create prototype cloud brightening or fogging systems and their ancillary components and systems; design, fabrication, and certification of additions and modifications to aircraft to enable the integration of scientific instrumentation and other hardware / software requirements; engagement of consultants to review and contribute to the science,</p>	<p data-bbox="568 850 2020 906">This Project provided technical and financial oversight for all engineering activities across the RRAP Cooling and Shading Sub-program. This included:</p> <ul data-bbox="618 954 2020 1118" style="list-style-type: none"> <li>• Designing, fabricating, and installing major hardware systems for MCB and fogging, including nozzle arrays, compressors, and control skids.</li> <li>• Engineering certification and integration of scientific instrumentation and sprayer systems onto aircraft and marine vessels.</li> <li>• Retrofitting a commercial aircraft to serve as a cloud microphysics platform.</li> <li>• Coordinating external consultants for engineering reviews, systems integration, instrumentation, and sampling strategies.</li> </ul> <p data-bbox="568 1161 2020 1254">The team delivered engineering milestones ahead of schedule and within tight budgets, managing system upgrades, WHS compliance, and international procurement. Key systems were commissioned, tested, and redeployed multiple times with enhancements after each campaign. Engineering outputs underpinned the transition from experimental feasibility to scaled deployment.</p>

Objective	Key Findings and/or Outcomes
<p>engineering, sampling, and instrumentation strategies.</p>	 <p><i>Figure 10: The fogging twins in operation during field trials near Eumilli Island (Fantome Island) in 2025. The twins are prototype direct drive diesel pump systems used to create a low hanging sea fog to shade corals during doldrum conditions.</i></p> <p>To enable field trials and technology validation, this Project oversees the procurement, calibration, and integration of a suite of specialised instrumentation across marine, airborne, island-based, and UAV platforms. These systems are used to quantify aerosol generation, transport, cloud microphysical changes, radiation fluxes, and meteorological conditions under both baseline and intervention scenarios.</p> <p>Key instrumentation includes:</p> <ul style="list-style-type: none"> <li>• Aerosol and Particle Counters: Scanning Electrical Mobility Spectrometer (SEMS), Aerodynamic Particle Systems (APS), Concentration Particle Counters (CPC) (miniature and fast-rate), Cloud Condensation Nuclei Counters (CCNC);</li> <li>• Cloud Microphysics Sensors: Cloud Droplet Probes (CDP), Combination Probes, Liquid and Total Water Meters;</li> <li>• Radiation and Energy Budget Tools: Pyranometers, Net Radiometers, IR Sensors;</li> <li>• Remote Sensing Platforms: Hyperspectral camera/LiDAR combinations;</li> <li>• Environmental Monitoring Equipment: Sonic Anemometers, Weather Stations, Dewpoint Hygrometers;</li> </ul>

Objective	Key Findings and/or Outcomes
	<ul style="list-style-type: none"> <li>• Airborne Systems: Inlet dryers, impactors, CVI aerosol inlets, GPS/IMUs, turbulence probes;</li> <li>• UAV Payloads: Aerosol pods, droplet sensors, and cloud probes for vertical profiling.</li> </ul> <p>These instruments are installed and operated across a fleet of modified research vessels, unmanned aerial vehicles (UAVs), manned aircraft, island research stations, and at-sea floating arrays. Instrumentation is subject to rigorous maintenance and calibration protocols to ensure data quality across campaigns.</p>  <p><i>Figure 11: The Southern Cross University research aircraft preparing for a day of atmospheric profiling over Heron Island in the lower Great Barrier Reef.</i></p>



*Figure 12: Cleaning the 640 nozzles during field trials, 2023.*

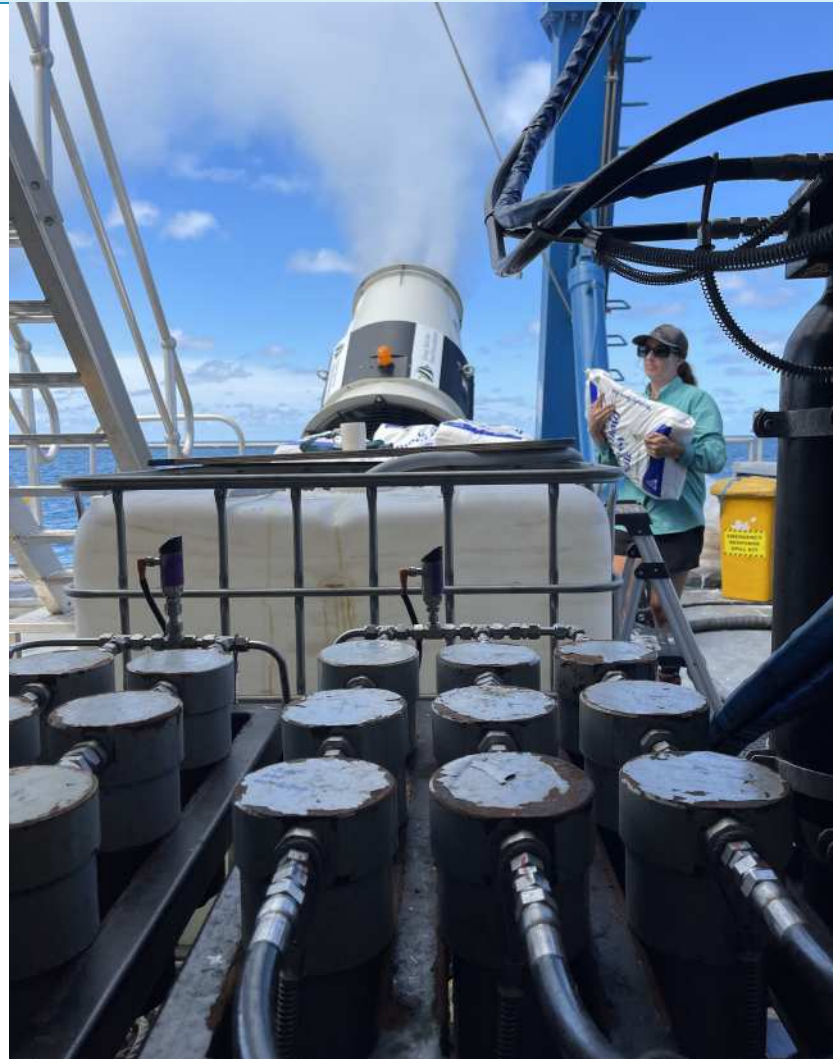
### **Engineering and Systems Development**

The Project centrally manages all major engineering expenditures and activities across the sub-program, encompassing:

- Design, fabrication, and certification of prototype MCB and fogging systems.
- Integration of hardware and software components for nozzle arrays, compressors, manifolds, and droplet dispersion systems.
- Modification and certification of piloted and uncrewed aircraft for instrument carriage and safe operation.
- Contracting and collaboration with expert engineering firms and consultants for safety reviews, sampling strategy design, and external validation.

**Objective**

**Key Findings and/or Outcomes**



*Figure 13: Operational view from the marine cloud brightening control container to the sprayers, 2025. In the foreground are the banks of three stage air filtration.*

Objective	Key Findings and/or Outcomes
<p>4. Deliver an integrated field program for all Cooling and Shading activities including all aspects of planning, collaboration, engagement, execution and communication. The four-year field program comprises 3 major field campaigns to occur in the summers of year 2 – 4, alongside land-based fieldwork for setting up, calibrating, and testing airborne measurement systems (both UAV and piloted), and testing of cooling and shading systems prior to their deployment at sea.</p>	<p>This Project has been responsible for the full design, planning, and execution of the Cooling and Shading field program. This includes all logistical coordination, personnel mobilisation, equipment transport, regulatory approvals, and on-site execution of experimental trials.</p> <p>The field program includes:</p> <ul style="list-style-type: none"> <li>• Annual summer on-reef engineering trials for fogging and MCB system validation;</li> <li>• Winter off reef testing of prototype hardware, nozzle arrays, and sampling instrumentation;</li> <li>• Five major field campaigns staged in: <ul style="list-style-type: none"> <li>➢ Year 1 (Dec 2021)</li> <li>➢ Year 2 (Jan - Mar 2022)</li> <li>➢ Year 3 (Nov 2022 and Mar 2023)</li> <li>➢ Year 4 (Jan - Mar 2024)</li> <li>➢ Year 5 (Feb - Mar 2025)</li> </ul> </li> </ul> <p>In Years 2, 3, 4 and 5, a comprehensive atmospheric-ocean survey was conducted to characterise the interaction between oceanic aerosols, clouds, and reef thermal environments. This involved:</p> <ul style="list-style-type: none"> <li>• Marine vessels with spray and sampling instrumentation.</li> <li>• Island-based atmospheric and irradiance sensors.</li> <li>• UAVs and piloted aircraft for vertical profiling and in-cloud measurements.</li> <li>• Satellite overpasses for remote sensing validation.</li> </ul> <p>In Year 4, this Project delivered the first full-scale field tests of the fogging concept by deploying marine fog systems to produce a persistent low-level sea fog over a coral reef during calm weather. These trials targeted periods of extreme thermal stress to assess the viability of fog as a reef protection method. The same season included cloud/sky brightening trials, where upscaled MCB systems aimed to modify low-level cloud microphysical properties and albedo.</p> <p>This Project supported these deployments through:</p> <ul style="list-style-type: none"> <li>• Field logistics planning and staff scheduling.</li> <li>• Air and marine charter management.</li> <li>• Resourcing and bookings.</li> <li>• Permitting and WHS compliance.</li> <li>• Aircraft and UAV calibration and flight testing.</li> <li>• Coordination with RRAP’s Integrated Logistics and Automation (ILA) Sub-program for systems analysis and operational efficiency.</li> </ul>

**Objective****Key Findings and/or Outcomes**

*Figure 14: All smiles after unloading research equipment from the marine vessel at the conclusion of the four-week 2025 field campaign.*

In summary, the Project successfully delivered an integrated, multi-platform field program encompassing several field campaigns with specific highlights:

- Advanced planning and multi-party coordination.
- Field trials using fogging and MCB systems with atmospheric and aerosol measurements across vessels, UAVs, and aircraft.
- Development and validation of plume mapping methods using floating arrays, drone-based sensors, and satellite overpasses.
- Response to cyclone events and adaptive planning to recover and reinstall equipment within days.
- Deployment of long-term monitoring infrastructure and real-time data sharing protocols.

In total, the team coordinated >60 tonnes of equipment (in each major field campaign), secured collaborations with key stakeholders (e.g., Traditional Owners and Hamilton Island Resort), and maintained WHS protocols across all deployments. Each campaign expanded the operational and scientific boundaries of field-based marine, atmospheric and cloud microphysical research.

## 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 RRAP Cooling and Shading Sub-program Management Project (CS-04) has proven to be of exceptional value as the central coordinating mechanism for the Cooling and Shading Sub-program under RRAP and subsequent project extensions. Its ability to unify technical, regulatory, engagement, and operational elements has been fundamental to the successful design, execution, and evaluation of novel and logistically complex climate intervention field and laboratory trials. As the program transitions into an anticipated second phase, it is strongly recommended that the Cooling and Shading Sub-program Management Project (CS-04) function not only be retained but also extended to safeguard continuity, ensure program coherence, and enable the scaling of innovation.

The Project team has provided oversight and connectivity across the RRAP Cooling and Shading Sub-program's projects (CS-01, CS-03, CS-06, and CS-07). This coordination has been critical in aligning scientific timelines, integrating instrumentation and logistics, and supporting inter-project communication and data interoperability. As RRAP moves into phases requiring more intensive modelling measurement feedback loops and larger scale implementation, this coordinating role will be even more important to ensure that atmospheric monitoring, modelling, technology development, and field deployment remain synchronised and mutually reinforcing.

Future campaigns are expected to involve wider geographic reach, increased system complexity, and greater integration of vessels, aircraft, drones, and remote sensing platforms. The program management team has already established the logistical expertise and operational frameworks necessary for large-scale, multi-platform deployments in remote reef environments. Its capabilities in permitting, risk management, charter negotiation, and platform instrumentation represent a rare and valuable skill set that should be preserved to avoid setbacks and costly duplication of learning.

Equally important has been the Projects pioneering work in community engagement, Traditional Owner partnerships, and social licence. The approach has gone beyond compliance to foster meaningful, employment pathways, and shared fieldwork ownership with Indigenous groups such as Gidarjil Corporation. Partnerships with industry stakeholders, including Hamilton Island Resort, have demonstrated the potential of productive public-private collaborations. Ongoing investment in this framework will be essential to ensure that future interventions proceed with transparency, legitimacy, and broad community support.

From an engineering perspective, this Project has overseen the iterative development of multiple generations of MCB and fogging systems, managed the integration of instrumentation across diverse platforms, and coordinated the certification and safety of both airborne and marine technologies. These achievements have been vital to experimental success and to building RRAP's international reputation in reef-scale MCB research. Sustaining the Projects engineering coordination capacity will be critical for the safe and efficient deployment of increasingly complex interventions in the future.

This Project has also led in ensuring data quality assurance, analysis coordination, and strategic reporting. This has established the RRAP Cooling and Shading Sub-program as a science-driven and high-impact initiative. With upcoming phases placing greater emphasis on peer-reviewed outputs, transparency, and global contributions, continuity of the CS-04 function will be essential for maintaining integrity, archiving, and consistent dissemination of program data and findings.

Finally, this Project has developed robust internal systems for governance, project tracking, WHS management, and compliance. These systems—covering risk assessments, standard operating procedures, procurement, and contractor engagement—have been refined over five years and are embedded into the daily operations of the Sub-program. Preserving these capabilities will be critical for mitigating regulatory and reputational risks as RRAP expands in scale, complexity, and visibility.

In conclusion, the Cooling and Shading Sub-program has emerged as a world-first, large-scale scientific initiative testing the potential of Marine Cloud Brightening and fogging technologies for coral reef protection. The continuation of this Project as the operational, strategic, and engagement backbone of this effort is not

only justified but essential. To ensure the success of RRAP's next phases, it is recommended that this Project be formally sustained and adequately resourced to act as the core delivery platform for integrated research, stakeholder engagement, and field deployment.

