T14: ENVIRONMENTAL MODELLING OF LARGE-SCALE SOLAR RADIATION MANAGEMENT

A report provided to the Australian Government by the Reef Restoration and Adaptation Program

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October 2019

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This report should be cited as:

Harrison DP, Baird M, Harrison L, Utembe S, Schofield R, Escobar Correa R, Mongin M, Rizwi F (2019) Reef Restoration and Adaptation Program: Environmental Modelling of Large Scale Solar Radiation Management. A report provided to the Australian Government by the Reef Restoration and Adaptation Program (83pp)

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Acknowledgement

This work was undertaken for the Reef Restoration and Adaptation Program, a collaboration of leading experts, to create a suite of innovative measures to help preserve and restore the Great Barrier Reef. Funded by the Australian Government, partners include: the Australian Institute of Marine Science, CSIRO, the Great Barrier Reef Marine Park Authority, the Great Barrier Reef Foundation, The University of Queensland, Queensland University of Technology and James Cook University, augmented by expertise from associated universities (University of Sydney, Southern Cross University, Melbourne University, Griffith University, University of Western Australia), engineering firms (Aurecon, WorleyParsons, Subcon) and international organisations (Mote Marine, NOAA, SECORE, The Nature Conservancy).

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1. PREAMBLE

The Great Barrier Reef

Visible from outer space, the Great Barrier Reef is the world's largest living structure and one of the seven natural wonders of the world, with more than 600 coral species and 1600 types of fish. The Reef is of deep cultural value and an important part of Australia's national identity. It underpins industries such as tourism and fishing, contributing more than $6B a year to the economy and supporting an estimated 64,000 jobs.

Why does the Reef need help?

Despite being one of the best-managed coral reef ecosystems in the world, there is broad scientific consensus that the long-term survival of the Great Barrier Reef is under threat from climate change. This includes increasing sea temperatures leading to coral bleaching, ocean acidification and increasingly frequent and severe weather events. In addition to strong global action to reduce carbon emissions and continued management of local pressures, bold action is needed. Important decisions need to be made about priorities and acceptable risk. Resulting actions must be understood and co-designed by Traditional Owners, Reef stakeholders and the broader community.

What is the Reef Restoration and Adaptation Program?

The Reef Restoration and Adaptation Program (RRAP) is a collaboration of Australia's leading experts aiming to create a suite of innovative and targeted measures to help preserve and restore the Great Barrier Reef. These interventions must have strong potential for positive impact, be socially and culturally acceptable, ecologically sound, ethical and financially responsible. They would be implemented if, when and where it is decided action is needed and only after rigorous assessment and testing.

RRAP is the largest, most comprehensive program of its type in the world; a collaboration of leading experts in reef ecology, water and land management, engineering, innovation and social sciences, drawing on the full breadth of Australian expertise and that from around the world. It aims to strike a balance between minimising risk and maximising opportunity to save Reef species and values.

RRAP is working with Traditional Owners and groups with a stake in the Reef as well as the general public to discuss why these actions are needed and to better understand how these groups see the risks and benefits of proposed interventions. This will help inform planning and prioritisation to ensure the proposed actions meet community expectations.

Coral bleaching is a global issue. The resulting reef restoration technology could be shared for use in other coral reefs worldwide, helping to build Australia's international reputation for innovation.

The $6M RRAP Concept Feasibility Study identified and prioritised research and development to begin from 2019. The Australian Government allocated a further $100M for reef restoration and adaptation science as part of the $443.3M Reef Trust Partnership, through the Great Barrier Reef Foundation, announced in the 2018 Budget. This funding, over five years, will build on the work of the concept feasibility study. RRAP is being progressed by a partnership that includes the Australian Institute of Marine Science, CSIRO, the Great Barrier Reef Foundation, James Cook University, The University of Queensland, Queensland University of Technology, the Great Barrier Reef Marine Park Authority as well as researchers and experts from other organisations.

2. EXECUTIVE SUMMARY

Within the cooling and shading category of reef restoration and adaptation interventions, the subcategory of solar radiation management options compose a suite of interventions that reduce stress on corals by decreasing the flux of incoming solar energy (shortwave radiation). Of these techniques, several may be sufficiently scalable to operate regionally and impact ocean mixed layer temperatures and thus reduce bleaching stress on corals by both cooling and shading them. Cooling and shading techniques, if applied at such regional scales, could potentially mitigate the impacts of rising ocean temperatures due to climate change. Cooling and shading technologies with the potential for regional-scale application include: marine cloud brightening, fogging, misting, and ocean whitening.

The preliminary modelling presented in this report addresses several key feasibility questions pertinent to regional-scale application of solar radiation management techniques. These questions along with the type of modelling used to address each are:

- What is the relationship between an imposed reduction in incoming shortwave solar radiation and cooling of Great Barrier Reef seawater surface temperatures? – Hydrodynamic.

- How is this relationship affected by scale of intervention, and does the response vary if the shading is applied consistently (i.e. evenly and all the time) or intermittently (e.g. by the modification of low-cloud albedo)? – Hydrodynamic.

- What is the magnitude of associated reduction in stress metrics related to bleaching resulting from cooling *and* shading? – Hydrodynamic and biogeochemical.

- To inform atmospheric interventions, what is the source and direction of prevailing winds over The Reef during summer when bleaching is most likely to occur? – Atmospheric Lagrangian particle tracking

- Are low-level clouds over the Reef likely to be susceptible to albedo increase by marine cloud brightening during the summer bleaching season? – Atmospheric, meteorological and microphysical.

All models were run in a hindcast mode, to consider the impact of simulated interventions over either the 2015/2016 or 2016/2017 bleaching events, or both.

For the scenarios in which solar radiation management is assumed to occur from land to the edge of the continental shelf, there is a gradient in cooling effectiveness with decreasing cooling of sea surface temperatures with increasing distance from the coastline. Conversely, there is no latitudinal gradient in cooling for scenarios representing either intermittent (cloud albedo) or consistent (direct shading) solar forcing. Intermittent and consistent shading scenarios had very similar reef scale cooling impacts, and elicited generally similar responses at individual reefs modelled in high resolution, however at some reefs the difference could be significant. For a mid-shelf location near Cairns the relationship between shortwave radiation forcing and sea surface temperature reduction could be approximated as linear over the range 0 to -35 W m^{-2}, with a cooling of around 0.225°C per 10 W m^{-2} reduction. We consider this a good preliminary guide, as it is apparent that extending the region of forcing some way beyond the edge of the continental shelf will subject most reefs to this level of cooling or better. Enlarging the region of applied forcing to the entire model domain led to approximately 40 percent more cooling mid shelf. Reducing the area to a region from approximately Townsville to Cooktown, and to the edge of the shelf, decreased the cooling by around 20 percent. The result for intermittent cloud albedo forcing varied significantly between the two bleaching events due to more low cloud cover during the 2016/2017 event than the 2015/2016 event, as only low-level cloud was assumed to be modified by intervention.

More so than the change in sea surface temperature, the reduction in both temperature stress (i.e. degree heating weeks) and bleaching stress (as estimated by build-up of reactive oxygen species in the coral symbionts) was highly heterogenous. One reason is that there was large variation in how much stress reefs were subjected to in the base case without intervention, both by location and between years. Reef location is another important factor, with reefs near to the boundary of applied forcing generally experiencing less stress reduction than those further within the region. This is especially apparent if the reef is in the path of water flowing from outside to inside the region of applied solar radiation management. Thus, the spatial heterogeneity can be explained conceptually as largely a function of the residence time of the surface waters within the footprint of intervention and the spatial distribution of heat stress accumulation in the control case. The between year variation is related to both the efficacy of intervention, subject to the control case atmospheric conditions and the underlying oceanographic and climate conditions, i.e. the temporal and spatial profile of stress to which corals were subjected by the control climate without intervention.

In general terms, an average reduction in incoming solar shortwave radiation of around 6.8 percent (relative to clear sky) applied to the shelf break, resulted in an average reduction in bleaching stress of ~50 percent in 2015/2016 and ~65 percent in 2016/2017, though these results are based on a small sample size of 14 reefs with considerable variation between reefs (as discussed above).

Atmospheric Lagrangian particle tracking indicated the prevailing wind direction over the reef during summertime conditions is from the south-east. While the southern three quarters of the Reef is supplied air from the south-east, the northernmost quarter of the reef is often supplied air from a counter rotating cell bringing air form the north to north-east. There was little variability within the summer months or between the two years considered; future work should develop a climatology by considering a longer period. Backtracking the airmass over the reef to its source five days earlier showed that the vast majority is advected from, and over, remote ocean regions. It is therefore expected to have relatively low existing background concentrations of cloud condensation nuclei. A low background cloud condensation nuclei concentration is advantageous for achieving maximum efficacy from marine cloud brightening.

Atmospheric meteorological and cloud microphysical modelling of marine cloud brightening was conducted for 10 days of typical synoptic conditions in December 2016. During this period, low-level marine clouds were the dominant cloud type. The time period, and resolution which was cloud permitting (rather than cloud resolving), were limited by the compromise between sufficient spatial domain, computational time, and resources available. This model setup was considered appropriate for this preliminary investigation, which sought to gain a sense of the potential for albedo increase (or lack thereof) over the Reef. Cloud albedo responded positively to scenarios of enhanced sea-salt flux imposed at the ocean surface. Maximum domain and time averaged cloud albedo increase was estimated as 0.16 for an imposed flux of 0.5 $\mu g\ m^{-2}\ s^{-1}$ of sea-salt nuclei in the size bin of 156 to 312 nm. However, the response started to become saturated at lower fluxes around 0.2 $\mu g\ m^{-2}\ s^{-1}$. Experiments considering increased sea-salt flux of other size classes suggest that the albedo might be increased further if a broader size distribution of sea spray were generated, in contrast to previous studies. Spacing spraying stations up to 20km apart, the furthest spacing considered, was found not to lessen the albedo change.

Combining the atmospheric and ocean modelling results allows consideration of the magnitude of potential forcing. If the cloud albedo increase observed in the atmospheric modelling was applied to all low-level cloud cover during the summer period, the average shortwave solar forcing would be approximately -12 W m^{-2} in 2015/2016. This is well within the envelope of median empirically observed radiative forcing for CCN – cloud albedo relationships representative of those over the Reef. As far as we are aware, this modelling study is the first to model cloud brightening in other than the marine stratocumulus cloud decks for which it has generally been suggested.

While preliminary in all areas, the results of our modelling studies are encouraging with regard to the potential of regional-scale solar radiation management to lower sea surface temperatures and shade corals sufficiently to mitigate a significant portion of bleaching stress. We have not attempted to realistically simulate the detailed physical application of any intervention as the engineering concepts are not yet sufficiently well-developed in this context. Rather we have sought to examine the underlying physical and biological relationships of the potential response. We note that the uncertainty is high with regards to the potential efficacy of the interventions considered here. Addressing this knowledge gap along with potential for unintended impacts, societal and regulatory implications, logistics, engineering, and the long-term impact on the reef ecosystem should be a priority for future work in stage two of the Reef Restoration and Adaptation Program.

3. INTRODUCTION, BACKGROUND AND OBJECTIVES

Solar radiation management options are a sub-category within the *Cooling and Shading* class of interventions considered during the concept feasibility study of the Reef Restoration and Adaptation Program (RRAP). These interventions and delivery mechanisms aim to reduce or prevent damage to coral reef ecosystems by lessening the intensity of thermal bleaching events which occur during marine heat waves, such as those that occurred on the Great Barrier Reef during 1998, 2002, 2016, and 2017 (De'ath et al. 2012; Hughes et al. 2017). This class of intervention aims to relieve stress on corals and other heat- or light-sensitive organisms by lowering the amount of solar energy, i.e. photons, entering the system by blocking a portion of the incoming solar radiation (see **T3: Intervention Technical Summary**).

Corals bleach due to excessive water temperature in the presence of light energy (Skirving et al. 2018); if the amount of light energy reaching corals during periods of increased water temperature is reduced, the overall stress on the symbiotic relationship is lessened. Applied on a reef or sub-reef scale, 'shading' to reduce light energy from the sun over short periods when conditions are most conducive to bleaching is therefore expected to reduce bleaching severity and mortality. Interventions in this class include: shade cloths, surface films, microbubbles, and localised misting or fogging. If 'shading' is conducted over larger regional areas encompassing many reefs for longer periods of weeks to months, then sea surface temperatures could conceivably be lowered, reducing both heat and light stress to corals and other reef associated organisms. These interventions may be capable of providing significant mitigation of bleaching over large areas encompassing hundreds to thousands of individual reefs. Large-scale application of cooling and shading techniques through solar radiation management is the focus of the modelling studies presented in this report. Interventions capable of regional-scale shading and cooling include: marine cloud brightening, large-scale fogging, large-scale misting, and potentially large-scale application of microbubbles/ocean whitening. A combination of these interventions applied over multiple scales simultaneously could also lead to regional-scale alteration of sea surface temperatures.

For brevity, a brief description of each intervention/delivery mechanism is given below, sufficient to provide background for the modelling reported herein. Further technical descriptions are provided in **T3: Intervention Technical Summary**.

3.1 Cooling and shading interventions with potential for regional-scale

3.1.1 Marine Cloud Brightening

Marine cloud brightening is the process of supplying additional aerosols to regions where lack of cloud condensation nuclei limits the droplet density within low-lying marine clouds (Latham 1990; Latham et al. 2012). Proponents of the technology advocate supplying aerosols in the form of nano-sized salt crystals generated by spraying micron-sized seawater droplets into the atmospheric boundary layer and allowing them to evaporate (Salter et al., 2008). However suitable cloud condensation nuclei could be formed of other materials, such as sulphur derived particulates, and distributed by other means such as by aircraft. Of the numerous nano-sized sea-salt aerosols introduced to the marine boundary layer, those that are entrained into clouds serve as cloud drop condensation nuclei (CCN), i.e. initiating the formation of cloud droplets. Additional CCN affect the droplet distribution within the cloud by increasing the number of droplets while decreasing the mean droplet size. The resultant effect is larger overall surface area of the droplets. Since light scattering occurs from the surface of the droplets, the result is ‘brighter’ clouds which have higher albedo, thus reflecting a greater portion of incoming shortwave solar radiation back into space (Twomey 1974).

Critically the radiative forcing benefit from marine cloud brightening results from three discrete effects; one direct (scattering and absorption from the introduced particles themselves) and two indirect (from their interactions with cloud). The direct effect is the reflection of incident radiation away from the Earth’s surface by the seawater droplets (or resulting salt aerosol particles) themselves. The magnitude of this effect may be equal to or larger than the effect from actual cloud brightening (Ahlm et al. 2017), especially when clouds are scarce or naturally consisting of large cloud droplet number concentrations. Operating marine cloud brightening in the absence of suitable clouds, or in atmospheric conditions unfavourable to cloud albedo enhancement will still induce a solar radiative forcing effect due to the direct effect, which will be near linear with the number of injected aerosols. Targeting the marine cloud brightening direct effect, for example in regions without suitable clouds for albedo enhancement has sometimes been referred to as ‘marine sky brightening’ (Ahlm et al. 2017).

The first indirect effect (the Twomey effect) results from the changed droplet size distribution within the cloud, assuming constant liquid water content. Elevated CCN concentrations reduce the mean droplet size with the result that albedo is increased and the cloud is ‘brighter’ (as viewed from space) (Twomey 1974). Much of the marine cloud brightening research to date has concentrated on this first indirect effect, as it is better understood and more reliably modelled then the second indirect effect. It is also sufficiently large in magnitude that globally the potential change in cloud albedo resulting from just the Twomey effect is estimated as being sufficient to offset anthropogenic forcing of ~4 W m^{-2} (Latham 1990).

The second indirect effect is actually a combination of effects that result from changes to macro-physical properties of the cloud caused by the additional aerosols. These effects include changes to the liquid water path of incoming solar radiation through the cloud, suppression of precipitation, and increased cloud longevity (Albrecht 1989). The second indirect effects may also be as important or more so than the Twomey effect (Wood and Ackerman 2013). Recent research has indicated that the second indirect effects of aerosols dominate coverage and water content of oceanic low-level clouds (Rosenfeld et al. 2019).

Until recently, marine cloud brightening has primarily been considered on a global scale as a geoengineering response to offset rising planetary temperatures due to climate change. Latham et al. (2013) suggested that the application of marine cloud brightening sub globally, to regions with the most extensive decks of low-level marine stratocumulus clouds could reduce the heat stress on coral reefs by lowering global ocean surface temperatures. More localised applications of cloud brightening have begun to be considered as a mitigation measure to reduce regional impacts of climate change, such as to weaken hurricanes or protect heat sensitive ecosystems (Latham et al. 2014). Harrison (2018) suggested that applying marine cloud brightening, or sky brightening, directly over coral reefs during marine heatwaves may mitigate bleaching by both locally reducing sea surface temperatures and by reducing incoming incident solar radiation (‘shading’) through the aerosol direct and indirect effects. While warmer water temperatures are closely correlated with coral bleaching, the actual mechanisms of bleaching are complicated and are believed to relate to an inability of temperature-stressed corals to process incoming solar energy (Lesser 1997). Hence, reducing the incoming solar radiation could be expected to also mitigate bleaching mortality, beyond that solely due to lowered temperature exposure, thus benefiting corals through a dual mechanism of cooling and shading when solar radiation management is applied over a sufficiently large area.

3.1.2 Fogging

Producing a low hanging ‘sea fog’ of seawater droplets is another proposed intervention. Producing sea water droplets around two orders of magnitude larger than for marine cloud brightening would be roughly equivalent to the properties of a heavy sea fog. Although the process of pumping seawater and spraying it into the marine boundary layer is almost identical to that of marine cloud brightening, the target atmospheric effects, lifecycle of the produced droplets, and probable scale are quite different.

Droplets of order 10μm would tend to hang low in the marine boundary layer, unlike nano-sized droplets produced for cloud brightening. They would experience a much shorter lifetime before predominately falling back into the ocean. Equivalent to the direct effect of marine cloud brightening and misting, the droplets produced by fogging would reduce the incoming shortwave solar radiation, providing shading. Commercial fogging systems are commonly used in industrial processes to provide either cooling (by evaporation) or dust suppression. The evaporation of these relatively large seawater droplets near to the sea surface would lead to evaporative cooling of the air mass in which they were suspended, potentially providing cooling by both shading and by sensible heat flux into the ocean surface waters. Some of this potential cooling maybe offset by a reduction in latent heat flux from the ocean due to the increased humidity of air above the ocean surface. As with misting, fogging could conceivably be applied at the scale of individual reef or collection of reefs. Proponents also argue it may also be possible to operate fogging over a larger regional area (Sev Clarke, *pers. comm.)*, the engineering feasibility of large-scale fogging was not been considered during the RRAP Concept Feasibility Study.

The modelling presented herein only considers the impact of reduced incoming shortwave solar radiation and therefore does not consider the potential feedbacks to the ocean-atmospheric heat budget of the evaporation and evaporative cooling aspects of large-scale fogging. An investigation of these feedbacks is essential to estimate the cooling efficacy of large-scale fogging. Such work is planned to occur, along with a desktop study into the feasibility of fogging at larger than local scales, during the RRAP R&D Program.

3.1.3 Misting

Within RRAP, misting refers to distributing particles into the atmosphere over the Reef to reduce incoming solar radiation by vaporisation of a biogenic oil to form a mist of reflective 'smoke-like' particles. Modern misting machines produce particles centred around 500nm which is close to optimal for light scattering per unit volume. The solar forcing is analogous to the cloud brightening direct effect or 'marine sky brightening'. The primary differences are that seawater is not used to produce the atmospheric particles and that the aerosol direct effect is targeted, rather than both the aerosol direct effect and indirect interactions with clouds. Nevertheless, aerosol indirect effects on cloud formation and microphysics will still inadvertently occur, and if misting is conducted over a large area, the impacts on clouds may be very similar to that of cloud brightening. Indeed the misting technique has been used previously to study the interactions between aerosols and low level clouds (Russell et al. 2013). Dependent on the size distribution, concentrations, and chemical composition of the atmospheric particles produced, the net effect on cloud albedo could be either positive or negative. Whether this enhances or detracts from the direct forcing effect must be considered in the engineering design and evaluation.

Generators to produce white smoke from the vaporisation of oil are available for a variety of applications ranging from the movie special effects industry through to military applications where they are operated by defence forces around the world to obscure the field of battle. The most commonly employed method is to use the hot exhaust gases of a pulsejet turbine engine to vaporise the oil, with the military grade of technology being the most suitable for producing large quantities of 'mist'. Application over the Reef would require identification of a biogenic biodegradable misting oil which could be shown to have no or minimal negative impacts on the marine environment.

Misting could conceivably be operated on a local scale such as that of an individual reef or collection of reefs. Operated in this manner the primary effect would be shading to reduce the light component of stress on corals. There may also be some transient localised cooling of shallow waters within reef lagoons, similar to surface films. Alternatively, it may be possible to operate misting on a regional scale, similar to cloud brightening, by employing a large number of generators distributed throughout the region and relying on atmospheric mixing and advection to distribute the generated particles. In this scenario of large-scale misting, the radiative forcing effect would be similar to that of cloud brightening and would act to both lower sea surface temperatures and reduce light stress on corals. The potential benefits of large-scale sky brightening are considered in the eReefs hydrodynamic and biogeochemical modelling portion of this study. The impact on coral bleaching of small-scale misting is not considered here, however the potential mechanism and effectiveness is analogous to the modelling of surface films, where various levels of light reduction without surface seawater cooling were considered on the scale of an individual reef (see [T13: Ultra-Thin Surface Films]).

3.1.4 Ocean whitening

Ocean whitening refers to the process of increasing the albedo of the ocean surface or upper water column. Microbubbles of air suspended in the surface ocean reflect incoming sunlight in a very similar way to droplets of water suspended in air (e.g. clouds or fog), albeit with less efficiency, due to the absorption of backscattered light in ocean waters (Seitz 2011). Generation of large quantities of microbubbles in the surface ocean has been suggested for use in global-scale geoengineering (Seitz 2011; Forster et al. 2014), but could also be applied at a local or regional scale (Seitz 2011). Microbubbles can be generated by a variety of methods with varying requirements for energy, however it is not clear to what extent these methods could practically be scaled up (William et al. 2008). Seitz (2011) suggests that sufficient bubbles for effective solar radiation management can be produced by hydrosols in the upper few metres of the ocean and are expected to persist from hours to days. Both the lifetime and reflectance of the microbubbles are expected to increase with the concentration of surfactants in the seawater.

It is conceivable, subject to further investigation, that microbubbles could be applied at an individual reef scale, for shading, or operated more continuously at a regional scale for both shading and cooling. If proven to be feasible, microbubble generation could be operated as an alternative, or to supplement, atmospheric interventions described above. The potential applicability of ocean whitening was not been comprehensively assessed during the RRAP Concept Feasibility Study, particularly with respect to possible implications on reef biology, thus a desktop study is planned prior to any research and development activity.

Nevertheless, in terms of the hydrodynamic modelling presented here, ocean whitening applied on a large scale is broadly analogous to atmospheric solar radiation management, noting the modelling assumes that the change in solar forcing occurs above/at the surface of the ocean. The implications of additional absorption/scattering within the water column was not considered.

3.2 Benefits modelling approach

The primary purpose of modelling during the RRAP Concept Feasibility Study was to evaluate the potential for benefits to the ecological state and functioning of the Great Barrier Reef. A secondary goal was to provide a preliminary high-level understanding of the engineering feasibility of proposed interventions. This early-stage modelling did not seek to quantify risk of unintended impacts, nor to represent an accurate scenario of implementation. This was deemed infeasible given the lack of engineering development for most interventions. Rather, given the high level of uncertainty, particularly around engineering feasibility and implementation, efficiencies, and efficacy, we sought to investigate the envelope representing the range of potential responses and thus ‘bracket’ the parameter space for each broad class of intervention. This investigative approach was designed to ascertain whether interventions or combinations of interventions were feasible, elucidate the critical parameters, and ascertain the efficacy an intervention would need to achieve to deliver a significant benefit. As such, these modelling studies largely constitute sensitivity studies of the system rather than attempts to realistically model the implementation of any single intervention. The interventions, even within the sub category of solar radiation management technologies, encompass a variety of approaches leveraging different aspects of physical and biological earth systems to deliver the desired benefit. Preliminary assessment of these interventions within RRAP has thus required a collection of computational models including cloud microphysical, plume dispersion, and Lagrangian particle tracking atmospheric models, hydrodynamic and biogeochemical ocean models, and ecological models representing coral communities.

Many of the solar radiation management interventions evaluated are analogous in their impact on the target physical or biological system. For example, there are various methods which target the reduction of some fraction of light energy directly over a reef, or region of reefs for a period of time during which bleaching stress conditions exist. As such, the modelling conducted during the RRAP Concept Feasibility Study was undertaken in such a way as to be agnostic to the particular intervention or approach wherever this is appropriate. Of the work presented within this report, the ocean modelling (hydrodynamic and biogeochemical) considers scenarios where the shortwave solar radiation forcing is applied intermittently (as a presumed change in low-level cloud albedo) and consistently (as an assumed change to atmospheric albedo); the latter in particular is agnostic to intervention type. The cloud microphysical modelling is applicable only to cloud brightening, while the atmospheric Lagrangian particle tracking is applicable to all atmospheric intervention types.

3.3 Structure of this report and acknowledgements

To simplify presentation, this report's body has been structured as an overview of the environmental modelling of regional-scale solar radiation management benefits conducted during concept feasibility of the Reef Restoration and Adaptation Program. Further detailed technical description of the atmospheric modelling has been attached as appendix A.

Co-funding for the technical work reported herein and in the appendices was provided by various partners, acknowledged in Table 1.

Table 1: List of co-funding organisations by activity area.

Activity	Additional funding provided by
Atmospheric modelling	• Queensland & Australian Federal Governments, Advance Queensland, boosting coral abundance on the Great Barrier Reef challenge, awarded to the Sydney Institute of Marine Science.
Hydrodynamic and biogeochemical ocean modelling	• Myer Foundation, 2017 Innovation Fellowship, awarded to D. Harrison • Queensland & Australian Federal Governments, Advance Queensland, boosting coral abundance on the Great Barrier Reef challenge, awarded to the Sydney Institute of Marine Science • University of Sydney/Omni Tanker Pty Ltd, Commercial Development and Industry Partners grant, awarded to D. Harrison.
Hysplit Lagrangian particle tracking	• Queensland & Australian Federal Governments, Advance Queensland, boosting coral abundance on the Great Barrier Reef challenge, awarded to the Sydney Institute of Marine Science.

This research was undertaken with the assistance of resources from the National Computational Infrastructure (NCI Australia), an NCRIS enabled capability supported by the Australian Government.

The authors acknowledge the Sydney Informatics Hub and access to, and use of, the high performance computing facility, Artemis, at the University of Sydney.

The authors acknowledge the use of the high performance computing facility, Spartan, at the University of Melbourne (Lafayette et al. 2016).

4. OCEAN MODELLING

4.1 Background and objectives

Solar radiation management interventions aim to introduce a change in the amount of solar radiation either reaching the ocean surface (atmospheric interventions) or penetrating beyond the ocean surface to depth (surface shading interventions). Interventions which could be implemented at regional, up to Great Barrier Reef-wide scale, over continuous or semi-continuous periods, may sufficiently alter the ocean heat budget to lower ocean water temperatures in the surface mixed layer. Atmospheric interventions such as marine cloud brightening, fogging, and misting particularly lend themselves to wide spatial scales of deployment due to the relatively high rates of atmospheric wind advection and turbulence which will disperse the introduced material rapidly over large areas. Nevertheless, surface-based solar radiation management techniques, such as microbubbles or other forms of ocean whitening, if deployed on a large enough scale, may also alter the ocean heat budget sufficiently to change mixed layer temperatures. A hydrodynamic model as implemented in the eReefs Project (Herzfeld et al. 2010), allows for quantification of the relationship between reduced incoming shortwave solar radiation and any corresponding reduction in ocean temperatures over the model domain.

This class of intervention may also benefit corals by reducing the light energy during periods of high bleaching stress. The biogeochemical portion of the coupled eReefs model includes a detailed representation of the underwater light field as well as a mechanistic coral bleaching model (Baird et al. 2018). Using the biogeochemical model, it is possible to evaluate the combined benefits which may occur as a reduction in both sea surface temperatures and light intensity as experienced by corals.

There are critical knowledge gaps in potential efficacy of the interventions proposed both in terms of the magnitude of solar forcing which could be achieved, as well as the temporal and spatial extent of coverage that could be maintained during an implementation. Given these constraints, the purpose of this modelling study is to elucidate the underlying critical relationships, quantify the effectiveness which would be required to achieve beneficial results, and to provide a first assessment as to whether this requirement might reasonably be achievable.

The primary aims of the ocean modelling were to:

- Derive the relationship between reduction in regional shortwave radiation forcing and corresponding reduction in sea surface temperatures
- Develop insight into how the relationship is affected by scale of implementation and interannual variability of ocean temperature and atmospheric conditions

- Determine an envelope of potential reduction in reef surface water temperatures by regional-scale cooling and shading.
- Evaluate the potential impact on coral bleaching stress of regional-scale cooling and shading, as estimated by the build-up of reactive oxygen species in coral symbionts (a process described in section 4.2.4).

We examined scenarios representing various levels of assumed cloud brightening efficacy, and a range of assumed albedo increases representative of large-scale shading in general (i.e. marine sky brightening/large-scale ocean whitening). There is no allowance for inefficiencies in the engineering application of the intervention in this set of scenarios, i.e. they are assumed to work over 100 percent of the region and over the full temporal period for which they are applied. As such, the results represent an upper bound of effectiveness for each individual scenario simulated and should be considered in this context.

4.2 Model description

4.2.1 eReefs model description

As part of the eReefs project, CSIRO used the Environmental Modelling Suite (https://github.com/csiro-coasts/EMS/) to simulate the hydrodynamics, biogeochemistry, and coral/water column ecology for the Great Barrier Reef region on a 3D curvilinear ocean grid (latitude, longitude, and depth).

The eReefs-coupled marine model is run in a hind cast configuration using measured and modelled input data for catchment riverine discharge, atmospheric conditions, and ocean boundary constraints. The model was designed to be run continuously in near real time to provide an ongoing estimate of ocean state. The model can also be re-run over previous time periods with input parameters altered, facilitating evaluation of various hypothetical scenarios, which is how it has been used in this study. As such, the evaluation has been undertaken using the eReefs modelling suite to consider how interventions may have been able to reduce stress on corals through re-simulation of past bleaching events. The degree to which bleaching stress might be potentially reduced by cooling and shading interventions is evaluated for previous major bleaching events in terms of water temperature reduction and reduction in reactive oxygen species (ROS) build-up in corals. The findings from the physical and biological modelling are then implemented in the ecological models CoCoNet and ReefMod as an indicative range of reduced DHW (degree heating week) stress equivalent to assess the potential benefit of the proposed interventions on future reef condition over multi decadal time scales. The outcomes of this ecological forecast modelling are presented in **T6: Modelling Methods and Findings**.

The eReefs Project (https://ereefs.org.au) includes an implementation of the CSIRO-developed sparse hydrodynamic ocean code (SHOC). SHOC is a general purpose model (Herzfeld 2006) based on the paper of Blumberg and Herring (1987). Hydrodynamics are solved by a three-dimensional finite-difference model, based on the primitive equations. The eReefs implementation of SHOC includes 4km domains (hereafter GBR4, within which is nested a smaller 1km domain (hereafter GBR1), which includes The Reef itself and extends to the edge of the continental shelf. Nesting to finer scales, such as an individual reef is achieved using the relocatable fine-scale coastal ocean model (RECOM). RECOMs are user-defined grids nested within either GBR4 or GBR1 which are populated with initial conditions and boundary forcing from the larger eReefs domain. In this study, RECOM grid resolution is approximately 250m. The model domains are shown below in Figure 1.

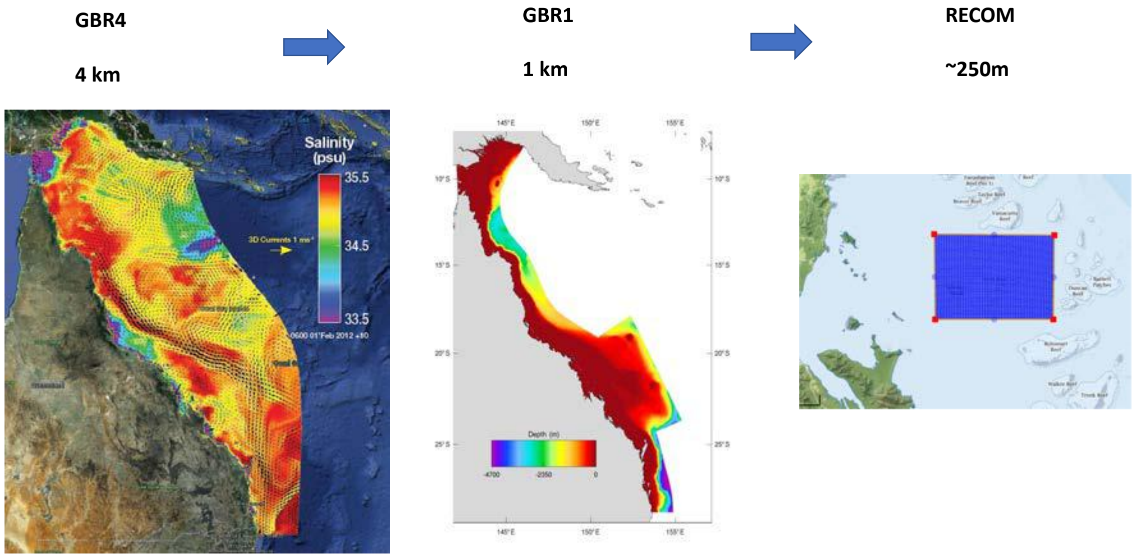


Figure 1: eReefs model domains for (a) GBR4, (b) GBR1, and an individual reef. Distance values represent approximate resolution.

For the interface from hydrodynamic to biogeochemical modelling, a transport model is used to store ocean velocity fields and mixing variables offline. These three-dimensional fields are then used as inputs to the biogeochemical model. Within the biogeochemical model, the 3D fields are used to advect and diffuse the sediment transport and biogeochemical state variables for biogeochemical modelling including the bleaching sub-model. The biogeochemical model uses an unconditionally stable semi-Lagrangian advection scheme, providing for a larger time-step and associated improvement in computational efficiency. The biogeochemical model is largely described in Wild-Allen et al. (2009), while carbon chemistry is described in Mongin et al. (2016), and the bleaching sub model described in Baird et al. (2018). A comprehensive, up to date description including a full model equation set is currently under review and posted online for public comment, available at: https://www.geosci-model-dev-discuss.net/gmd-2019-115/gmd-2019-115.pdf, accessed 9 October 2019. A schematic of the major components of the biogeochemical-ecology-sediment transport configuration is shown in Figure 2.

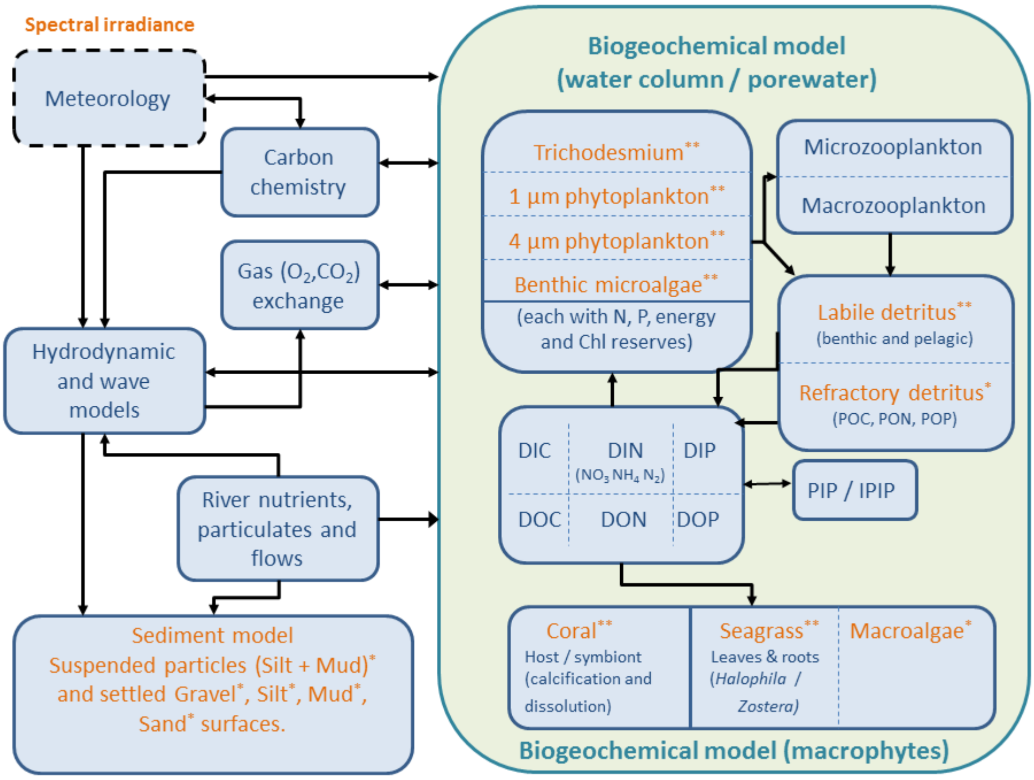


Figure 2: Schematic of the components of the biogeochemical model as implemented in eReefs (Baird et al. 2018).

4.2.2 Model forcing

Atmospheric forcing of the hydrodynamic and biogeochemical models is provided by one-way coupling to the Australian Bureau of Meteorology ACCESS-R version APS2 atmospheric model which provides input parameters (Figure 3). This meteorological model is run on an approximately 12km grid with three-hourly output used for forcing eReefs. More information about the ACCESS-R atmospheric model is available at: http://www.bom.gov.au/australia/charts/about/about_access.shtml.

Ocean boundary conditions are derived from the Australian Bureau of Meteorology OceanMAPs version 3 near real time product. For further details: http://www.bom.gov.au/oceanography/forecasts/technical_specification.v2.pdf

River flow data is measured gauge data, provided by the Queensland Government Department of Natural Resources, Mines, and Energy.

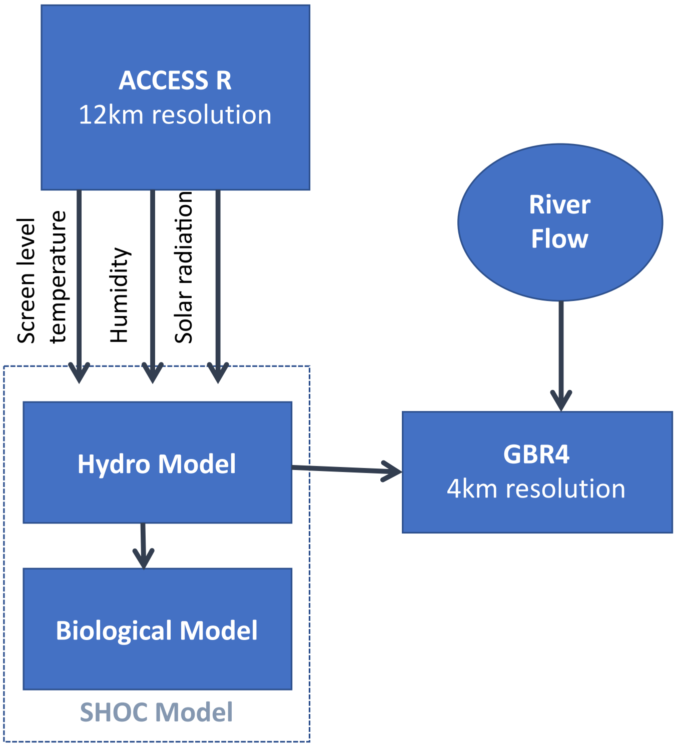


Figure 3: Schematic of atmospheric forcing data flow within eReefs.

4.2.3 Ocean heat flux scheme

The heat flux formulation uses an advanced bulk parameterisation for sensible and latent heat fluxes, enhanced longwave formulation and the shortwave component is calculated at each timestep. The heat flux formulation is accommodated using meteorological parameter input from the ACCESS-R atmospheric model described above. The net heat flux is computed as the sum of the components, then applied as the surface boundary condition in the vertical diffusion equation. Heat is input and mixed through the water column simultaneously using this approach due to the implicit nature of the vertical diffusion equation, hence avoiding undesirable skin effects when layers are thin. The components of the heat flux scheme are described in detail in the SHOC Science Manual (Herzfeld et al. 2010). The components of the heat flux scheme and modifications made to accommodate the current study are described in detail below in section 0.

4.2.4 Bleaching sub model

To capture the process of build-up of reactive oxygen species (ROS), the eReefs coupled hydrodynamic – biogeochemical model explicitly represents absolute coral host biomass, as well as zooxanthellae biomass, intracellular pigment concentration, nutrient status, and the state of reaction centres and the xanthophyll cycle (Baird et al. 2018). Photophysiological processes represented include photoadaptation, xanthophyll cycle dynamics, and reaction centre state transitions.

In the eReefs bleaching model, ROS build-up depends on light because ROS are generated by unused photons and temperature, as warmer temperatures inhibit the enzyme RuBisCO (Ribulose-1,5-bisphosphate carboxylase/oxygenase) whose activity is required for the productive use of solar radiation for photosynthesis, leaving more unused (or excess) photons. A full description of the bleaching parameterisation has been documented and assessed at a Great Barrier Reef-wide scale in Baird et al. (2018).

When light intensity is reduced, initially less photons will be absorbed by the pigments. With a smaller flux, less excess photons will be present after those used for RuBisCO-mediated carbon fixation. The smaller fraction of excess photons results in less state transitions of the reaction centres (from Q_{ox} to Q_{red} to Q_{in}) and less production of ROS.

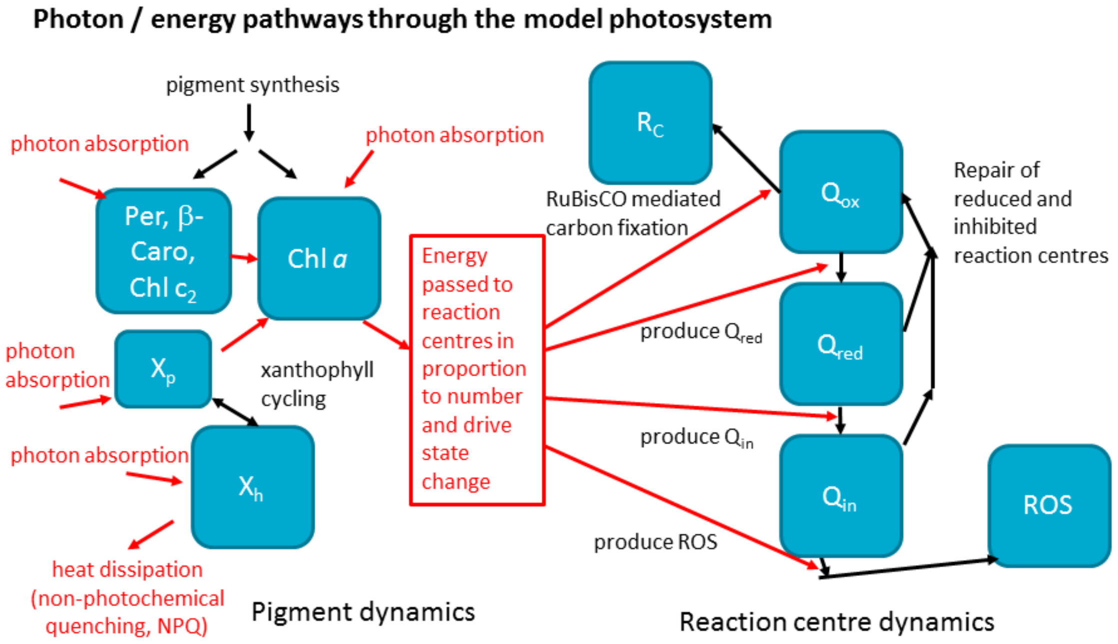


Figure 4: Schematic of the eReefs bleaching model. Note the temperature dependence of bleaching occurs because the process of RuBisCO-mediated carbon fixation is inhibited at temperatures above the summer maximum.

If seabed temperatures are above the summer climatology maximum, then the RuBisCO-mediated carbon fixation is inhibited, leading to more excess photons. However, if the seabed temperature is reduced, then more photons are used in carbon fixation, resulting in, like reduced PAR, a smaller number of excess photons resulting in less state transitions of the reaction centres (from Q_{ox} to Q_{red} to Q_{in}) and less production of reactive oxygen. Thus, the emergent feature of the bleaching model is that symbionts don't build up lethal reactive oxygen concentrations in low light at high temperature (because there are no excess photons) or in bright sun at moderate temperatures (because the combination of photoadaptation, carbon fixation and reactive oxygen detoxification prevents toxic concentrations). But at high temperatures, carbon fixation is inhibited, and with high light, the photoadaptation and detoxification processes cannot prevent reactive oxygen build-up, and after a period of time this leads to bleaching.

The effect of temperature on RuBisCO-mediated carbon fixation is not accurately known. In order for the bleaching model to have a similar response to thermal stress, as do field observations to degree heating metrics, it is assumed:

$$a_{Qox}^{*} = (1 - \exp(-(2 - \Delta T)))/(1 - \exp(-2))$$

where ΔT is the temperature anomaly and is calculated as the difference between the model seabed temperature and the spatially and temporally-varying climatological temperature at that depth (Ridgway and Dunn 2003). The form of the above equation was based on a general line of reasoning that bleaching stress begins at a temperature anomaly of 1°C (the NOAA bleaching index uses 1°C above climatology that would reduce a_{Qox}^{*} to 0.73), and that for a sustained period (two summer months) 2°C (equivalent to 16 degree heating weeks) causes maximal stress

(a_{Qox}*= 0). If the climatological temperature is below 26°C, then ΔT is given by the model seabed temperature minus 26°C. The constant 2°C represents the temperature anomaly above which activity of oxidised reaction centres is zero. For $\Delta T < 0°C$, $a_{Qox}* = 1$, and all oxidised reaction centres are active, and $\Delta T > 2°C$, $a_{Qox}* = 0$, and all oxidised reaction centres are inactive. Both the constant 2°C, and the use of a seasonally-varying seabed climatological temperature which is based on all available, but nonetheless limited number of *in situ* observations and interpolated onto a course 0.5° grid, are key uncertainties worth consideration in future work. One of the important implications of using this formulation is that the effect of temperature on bleaching saturates at 2°C above the climatology.

Reactive oxygen species per symbiont as a measure of stress

Coral symbionts naturally contain reactive oxygen species (ROS) such as hydrogen peroxide (Suggett et al. 2008), but ROS becomes toxic at high concentrations. Due to the difficulty in measuring ROS concentration (it is often measured as a fluorescent signal rather than a mass per unit volume), there is no precise value for toxicity in the literature. There may also be different levels of toxicity for the different symbiont species (*Durusinium* vs. *Symbiodinium*) as well as for different coral hosts.

In the model we have a parameter for the lowest toxic level of reactive oxygen species, $ROS_{threshold} = 0.0005$ mg O cell^{-1} (Baird et al., 2018; this number is relative since the ROS measurements they are based on are relative). This was a value that was exceeded in the 1km eReefs model at sites that began bleaching in 2017. Interestingly, even under extreme bleaching conditions, the model ROS per cell rarely exceeded 0.001mg O cell^{-1}. While 0.0005mg O cell^{-1} is imprecise, it is noteworthy that laboratory experiments show that reactive oxygen concentrations only appear toxic at more than half their maximum values (Suggett et al. 2008).

In the eReefs bleaching model we consider zooxanthellae expulsion as a function of how much greater the reactive oxygen concentration is above the threshold (i.e. mortality = $a[\max(0, ROS - ROS_{threshold})]^b$, where *a* is a rate coefficient, *b* is a power exponent). However, due to the uncertainty of the values of *a* and *b* (*b* is 1 in this study), we consider a more robust measure of the model-predicted threat of bleaching to be the reactive oxygen species concentration, rather than the rate of expulsion predicted by the model.

For further detail on the implications of shading with the formulation of this sub model within eReefs a detailed discussion is provided in **T13: Ultra-Thin Surface Films**.

4.3 Methods

4.3.1 Radiation forcing inputs

Atmospheric inputs are provided to eReefs using the output from the ACCESS-R regional atmospheric forecasting model operated by the Australian Bureau of Meteorology. In its standard configuration, eReefs calculates the clear sky incoming shortwave radiation flux based on Julian day of year and solar zenith angle, the incoming shortwave radiation (SWR) is then corrected for cloud albedo by:

$S_{gc} = S_g, 0 \leq C < 0.25.$

$S_{gc} = S_g(1 - 0.62C + 0.0019h_n)$,0.25 ≤ C ≤ 1.

where C is the cloud cover fraction and h_n is the noon solar elevation.

This simple parameterisation of cloudiness does not differentiate between altitude of cloud cover, nor its albedo. All cloud is assumed to have an albedo of around 0.62, and total cloud cover of less than 0.25 is ignored.

To implement scenarios representative of marine cloud brightening (MCB), it is necessary to separate low cloud fraction from total cloud fraction for the shortwave radiation flux, as its low-level cloud which would be targeted by cloud brightening due to its generally net negative radiative forcing. The SHOC source code was altered to read low-cloud fraction as a separate input variable. The limit of one for fractional cloud cover was increased to allow the fractional cloud cover to be increased up to the equivalent of a maximum cloud albedo of 0.9.

Nominal low-level cloud albedo increases were then applied as increases to cloud fraction per horizontal cell by:

$C_{mcb} = C + A_{increase}/0.62 * C_{low}$

where C_{mcb} is the input cloud fraction for SWR calculation, C is the total cloud fraction, $A_{increase}$ is the albedo increase to be applied to low level cloud, and C_{low} is the low-level cloud fraction.

The shortwave radiation term is further adjusted for the surface albedo which includes a term for cloud cover, this cloud cover term uses the increased cloud albedo, but capped at a total fraction of one, i.e. albedo of 0.62. The calculation of longwave radiative flux includes a term for total cloud cover to adjust the clear sky longwave radiation, which we assume to be unaltered by the increase of low-level cloud albedo.

Although the cloud brightening direct effect (shading by additional salt particles and droplets in the atmosphere) and the misting direct effect are not actually an adjustment to cloud albedo, the simplicity of the scheme adopted in eReefs and the modifications outlined in this section allow us to also represent the direct aerosol effect by adjusting C_{mcb}. However, in order to represent an absolute change in atmospheric shortwave radiation as albedo the scaling equation adjusts to:

$C_{mcb} = C + A_{increase}/0.62$

Changes to the eReefs hydrodynamic source code necessitated new runs of baseline conditions using the updated source code, model parametrisations and settings, and modified input fields containing the additional atmospheric information such as low cloud fraction. Significantly, to allow temperature perturbations induced by changes to the solar radiation to fully propagate through the model, it was necessary to turn off temperature and salt ‘relaxation’ in the model configuration. The ‘relaxation’ is a form of data assimilation wherein the model predicted values are interpolated towards observed values at the boundaries. Disabling temperature relaxation is expected to impact the calibration of the model and reduce the similarity between model and observed ocean temperatures in the unperturbed control case.

Some improvements were also made to the eReefs model. The first was invoking the scaling equations (Herzfeld et al. 2010, equations 9.1.26) to reconcile the difference in ACCESS-R reference height (2m) with that of eReefs (10m). The second was correcting the assignment of input air temperature which was previously read from ACCESS-R as sea surface temperature. As many of the heat flux formulations in eReefs incorporate the difference between air and sea surface temperatures, this correction could also be expected to have a non-negligible impact on the existing model calibration. Thus, new control runs which differ from the near real time estimation were performed and all scenarios evaluated against these.

4.3.2 Ocean atmosphere feedbacks

Successful cooling of the ocean surface layers which may be achieved via large-scale solar radiation management will introduce feedbacks in the ocean-atmosphere heat flux components. The lowering of average sea surface temperature over a large region can be expected to correspondingly lower the surface air temperature with an associated impact on sensible and latent heat fluxes between the ocean and atmosphere. Cooler ocean surface temperatures will reduce the rate of evaporation and the emission of longwave radiation. Each of these feedbacks could be expected to have implications on atmospheric dynamics and potentially alter patterns of cloud formation, potentially leading to either further positive or negative feedback. These ocean-atmosphere interactions and their quantification cannot be fully considered using eReefs until it is fully online coupled with an atmospheric model.

In this study, attention was given to approximating first order physical feedbacks which directly impact the estimation of the eReefs heat flux components. Both the sensible and latent heat flux formulations in eReefs are sensitive to the air temperature over the ocean. Therefore, to improve the accuracy of the result, it was necessary to approximate the change in screen height (2m) air temperature due to ocean cooling. This approximation increases in importance with increasing shortwave radiative forcing and with increasing spatial extent of implementation. The change in screen level air temperature (T_a) due to a change in sea surface temperature over the domain of the eReefs can be estimated using a linear model derived from the correlation between Bureau of Meteorology ACCESS-R atmospheric model air temperature and sea surface temperature (SST) as predicted by eReefs. This relationship suggests a reasonable approximation of 0.72°C reduction in reference height air temperature for each 1°C drop in sea surface temperature. This correction is implemented by adjusting reference height air temperature and dew point temperature in the model forcing files along with a process of iteratively running each model scenario to converge on a solution where the average sea surface temperature variation due to a scenario across the region of applied solar forcing is approximately equal to the scaling applied. While not perfect, this solution is adequate for this preliminary assessment of the potential impacts on ocean hydrodynamics. Future refinement of feedback terms will require a coupled ocean-atmosphere model, the work to develop such a model is planned to occur during the RRAP research and development program.

4.3.3 Biogeochemical and bleaching simulations

Corals are a fixture of the sea floor. As such, the amount of heat and light they experience are a strong function of depth. Accurate representation of bathymetry within eReefs is critical in obtaining a reasonable assessment of the thermal bleaching stress and how it responds to heat and light fields propagated throughout the water column. The 4km grid used for the regional-scale hydrodynamic scenario simulations is much too coarse to represent the bathymetric detail required for the evaluation of the combined heat and light field. To overcome this problem, the RECOM tool within eReefs was used to create grids of around 250m resolution for a number of individual reefs. These grids were nested within the larger 4km domain for both hydrodynamic and biogeochemical model runs.

The changes to eReefs described in Section 4.3.1 impacted the existing hydrodynamic calibration, leading to cooler water temperatures in the control runs. The biogeochemical and bleaching models use thresholds in numerous calculations requiring precise absolute water temperatures rather than temperature differences. To accurately represent the changed temperature and light fields in the biogeochemical and bleaching modelling, control runs were conducted using the production version of eReefs, without the modifications described in Section 4.3.1. Changes to the light and temperature fields were then applied from the hydrodynamic model to the offline transport files for each scenario prior to running the biogeochemical-ecology-bleaching sub-model.

4.3.4 Scenarios

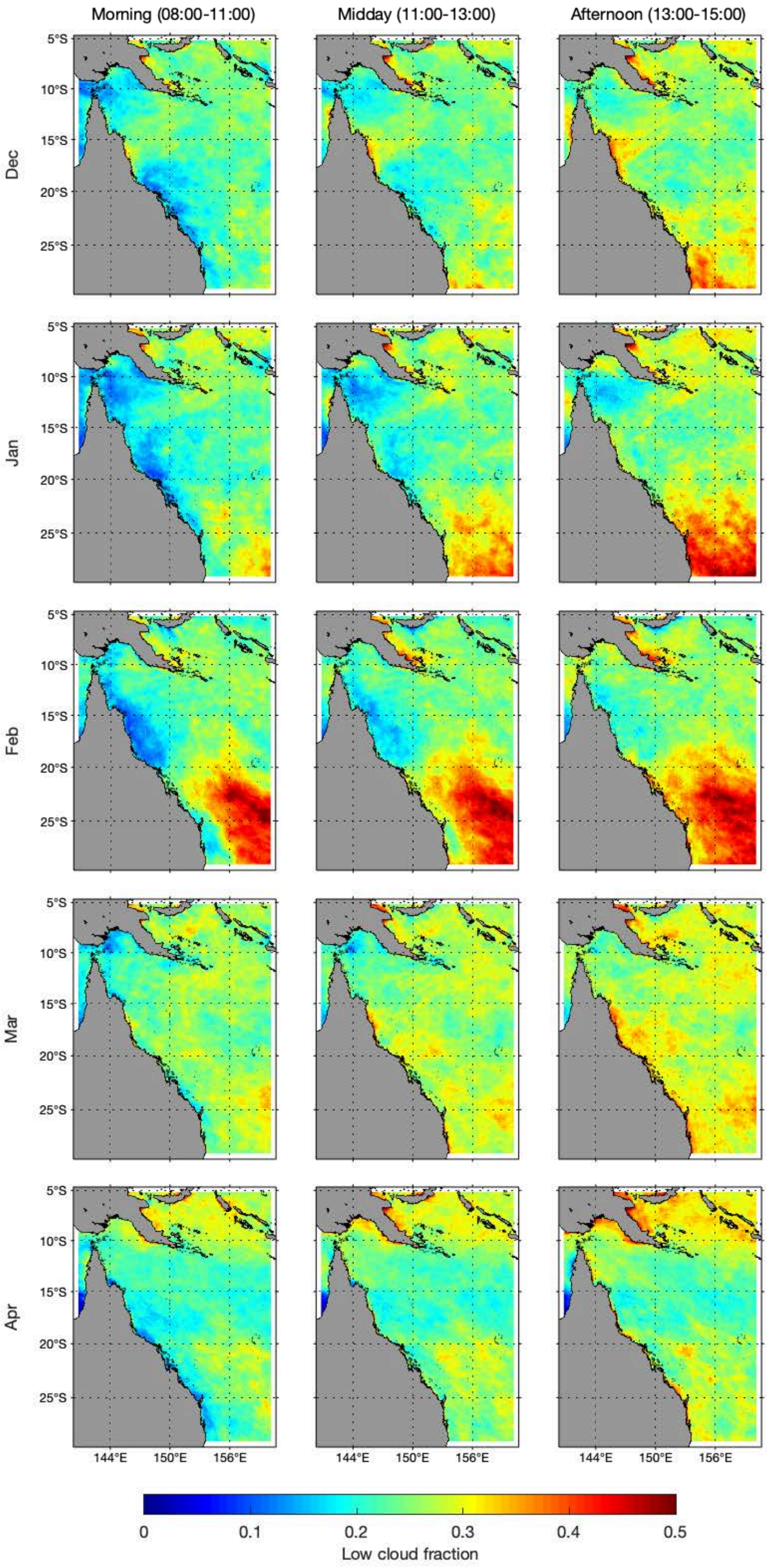
Control Scenarios

The eReefs model runs record stretches from 2011 to present. Control scenarios were run for December-April 2015/16 and 2016/17. This covers the two most recent severe bleaching events on the Great Barrier Reef. Two parameters which are likely to have an impact on the result vary significantly between these two periods. The first, cloud cover was significantly lower during 2015/16, likely related to the strong El Niño conditions present during this Austral summer. Low cloud fraction is shown for the two summer periods in Figure 5. The second major difference between these two periods is the profile of heat stress build-up over the season, this is illustrated in the model results for the 2015/16 and 2016/17 control scenarios (section 4.5.2). It is evident from Figure 5 that on a monthly averaged basis low cloud fraction over the reef during summertime increases throughout the daytime with lowest cloud fraction in the morning and maximum in the afternoon.

Forcing scenarios

The first set of scenarios was designed to investigate an intermittent change to solar forcing, associated with cloud modification such as the first and second indirect effect of marine cloud brightening (Twomey 1974; Albrecht 1989). In these scenarios, the albedo of low-level clouds occurring between the shoreline and 200m depth contour and 10°S to 24°S was increased by 0.1, 0.2, and 0.3, designated A0.1, A0.2, & A0.3 respectively. This is most analogous to the first indirect effect of cloud brightening, the Twomey effect (Twomey 1974). Cloud macrophysical properties including formation, size, longevity, and track over the region are unchanged. For interpretation however, these scenarios could be considered reasonably representative of total net albedo change from both the first and second indirect effect. This simplification requires the assumption that it is primarily the magnitude of solar forcing change which affects the oceanic response. We assume there is minimal difference in response between increasing the intensity of existing cloud, compared with assuming the cloud remained over the Reef longer due to, for example supressed precipitation (second indirect effects; (Albrecht 1989; Rosenfeld et al. 2019). The results of this modelling study support this assumption for the ocean hydrodynamic response, it is unclear however if this is also the case in terms of coral stress.

(a)


Morning (08:00-11:00)
Midday (11:00-13:00)
Afternoon (13:00-15:00)
Dec
Jan
Feb
Mar
Apr
5°S
10°S
15°S
20°S
25°S
144°E
150°E
156°E
0
0.1
0.2
0.3
0.4
0.5
Low cloud fraction

(b)

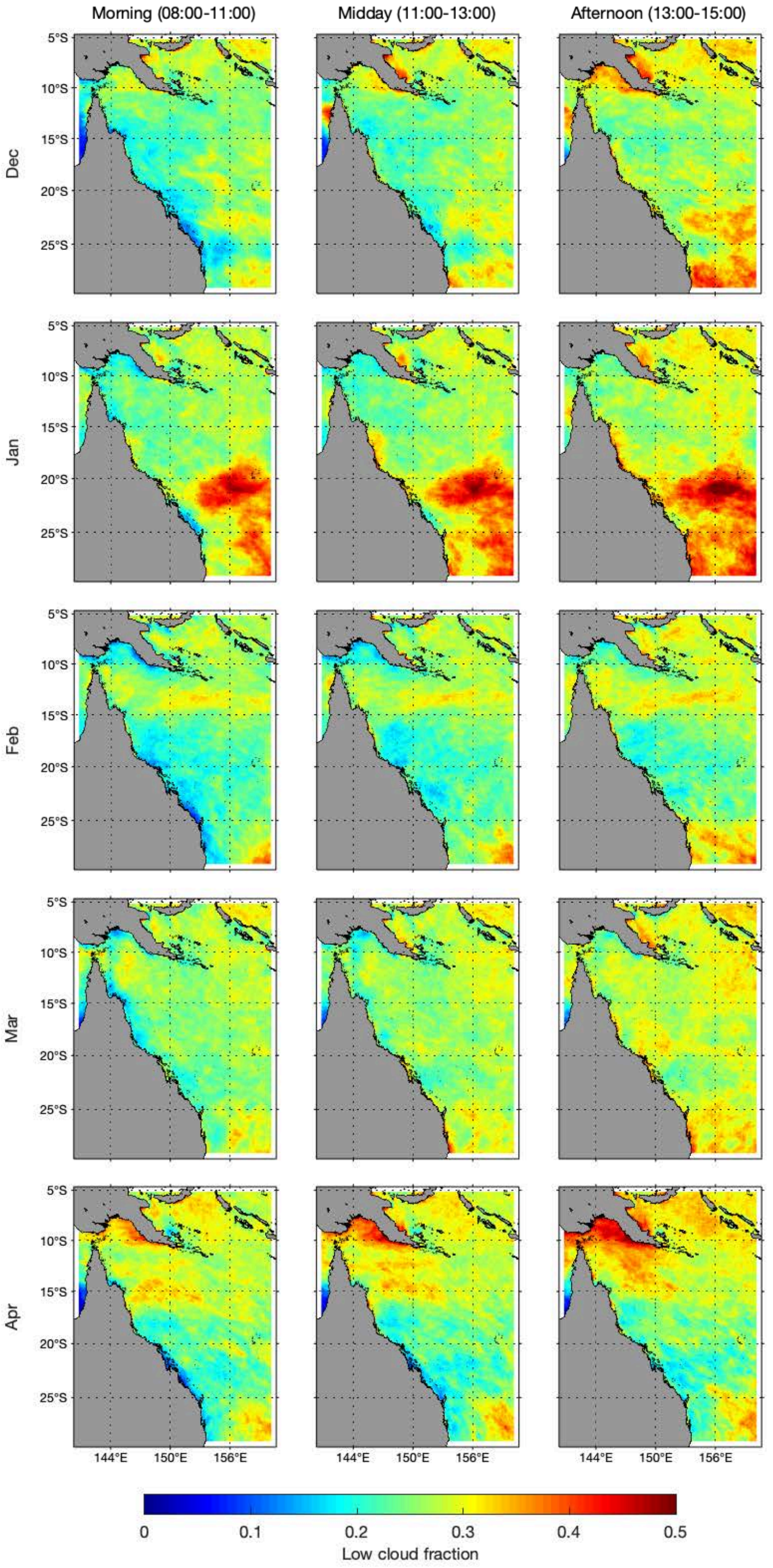


Figure 5: Average monthly low-level cloud fraction as resolved by the ACCESS-R meteorological model during the austral summer when mass bleaching events occurred in (a) 2015/2016 and (b) 2016/2017.

The scenario with a total low-level cloud albedo increase of 0.3 was used in further simulations to explore the effects of scale and interannual variability. This scenario was selected as representative of a reasonable (perhaps aspirational) target for solar radiation management, being equivalent to an average forcing to shortwave radiation of ~ -23 W m^{-2} (in 2015/2016). Recognising however, as mentioned above, this forcing is unlikely to come entirely from the first indirect effect, but rather from the full combination of the first and second indirect aerosol effects, and also the direct scattering of the aerosols themselves. To examine the impact of scale, two new regions of applied forcing were considered, creating a total of three scale scenarios:

- **DOMAIN** assumes the solar forcing is applied over the entire domain of the eReefs Great Barrier Reef 4km grid. As well as representing the maximum spatial scale of forcing possible in the model, this scenario also mitigates the confounding effects of advection when interpreting the magnitude of feedbacks and other responses within in the model.
- **SHELF** is the base case spatial scenario described above, where forcing is assumed to extend to the edge of the continental shelf.
- **REGION** also has the forcing applied to the edge of the continental shelf but over a more limited latitudinal extent of 12°S to 18°S.

The three spatial scenarios are illustrated in Figure 6. To gain an insight into the potential influence of differing atmospheric conditions the A0.3 scenario was also run for the 2016/2017 summer season, recalling that this season had significantly higher low-level cloud cover than the 2015/2016 season.

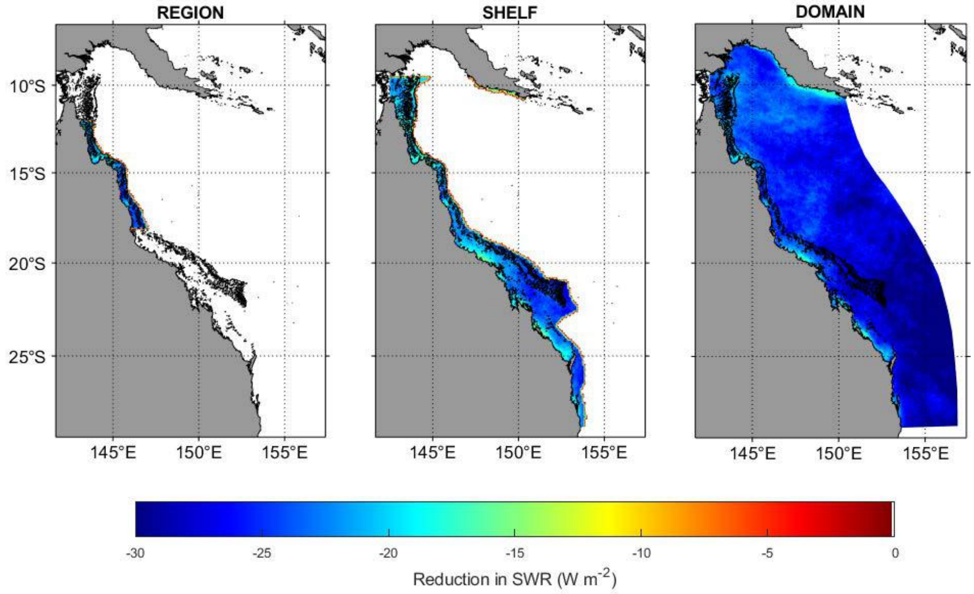


Figure 6: The three spatial scales of solar radiation management modelled (a) REGION (b) SHELF (c) DOMAIN. Figures show the average SWR forcing for an assumed albedo increase of 0.3 to low level cloud during the 2015/2016 bleaching event. Note changed SWR along the coast of Papua New Guinea in SHELF scenario is an artefact of the cloud clipping algorithm not excluding this region.

The second set of scenarios are more generalised than the first as they assume an offset forcing applied over the target area for the duration of the model run. These scenarios serve two functions: they are broadly analogous to the direct effect of marine cloud brightening (although they assume 100 percent temporal and spatial coverage) and they serve as a comparison to the highly cloud-dependent intermittent type mode of forcing in the first set of scenarios, allowing us to examine the relative differences of these two modes on hydrodynamic and coral responses. This set of scenarios includes assumed atmospheric albedo changes of +0.01, +0.05, and +0.1, and are designated D0.01 D0.05 and D0.10, where the prefix D indicates ‘direct’ forcing. These scenarios are run for the base season 2015/2016 and base spatial scenario SHELF only. A fourth direct forcing scenario was created to allow for meaningful comparison between forcing applied intermittently (from the indirect forcing of clouds) and consistently (from the direct aerosol forcing). In this scenario, direct forcing was applied everywhere within the region and set equal to the spatially- and temporally-averaged forcing which resulted from the 15/16 SHELF A03 scenario. This forcing was found to be equivalent to an albedo increase of 0.0676. This scenario was run for both years designated SHELF D0.0676. Finally, as marine cloud brightening is speculated to create net albedo increases due to all three effects, a combined scenario is considered as 15/16 SHELF A0.2 D0.01.

Figure 7 provides a diagrammatic representation of the 10 different scenarios considered for the hydrodynamic response. As the nine RECOM models are fully nested within the GBR4 runs for both hydrodynamics and biogeochemical models, there was only time to execute the RECOM hydrodynamic and biogeochemical models for a limited number of scenarios. The priorities were:

- Examining the variation in reduction to bleaching stress across shelf and latitudinal gradients
- Comparing stress reduction between continuous and intermittent solar forcing modes
- Implications of interannual variability in ocean and atmospheric climates.

To address these priorities, the RECOM hydrodynamic-biogeochemical-bleaching models were run for the following scenarios 15/16 SHELF A0.3, 16/17 SHELF A0.3, 15/16 SHELF D0.0676, and 16/17 SHELF D0.0676

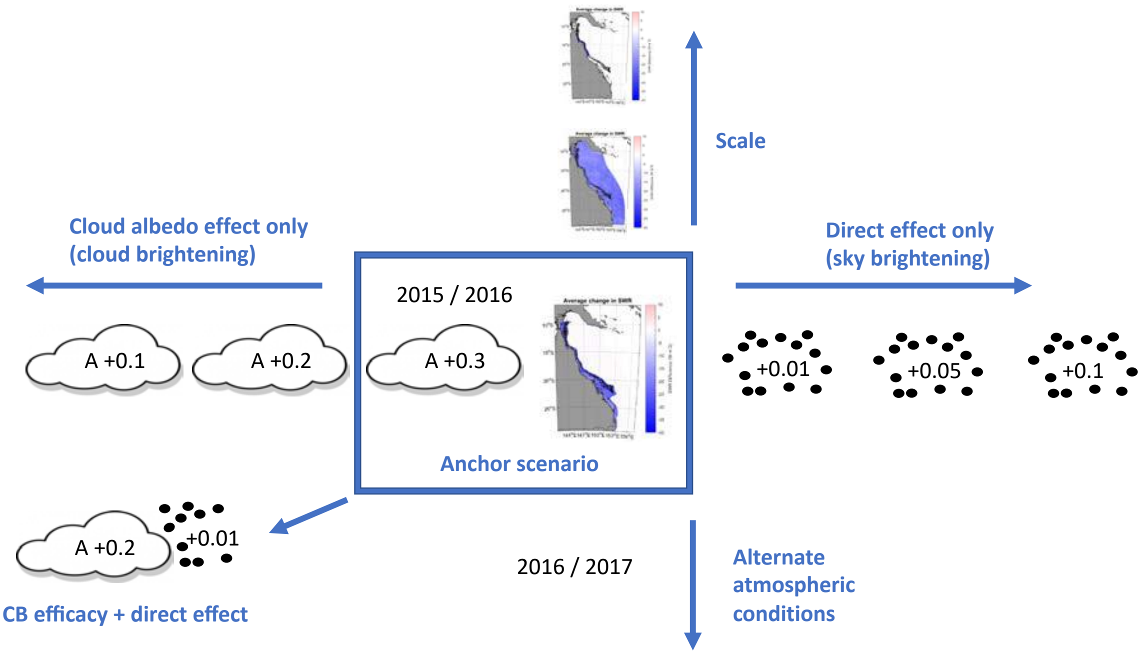


Figure 7: Graphical depiction of the forcing scenarios run in eReefs to represent types and combinations of large-scale solar radiation management.

Table 2: List of hydrodynamic forcing scenarios. Scenarios in bold type used for high resolution RECOM and biogeochemical modelling.

#	CODE	Scale	Year	Cloud albedo increase	Sky albedo increase	Notes
1	15/16 SHELF A0.1	Shelf	2015/2016	0.1	-	
2	15/16 SHELF A0.2	Shelf	2015/2016	0.2	-	
3	**15/16 SHELF A0.3**	**Shelf**	**2015/2016**	**0.3**	**-**	Anchor Scenario
4	**16/17 SHELF A0.3**	**Shelf**	**2016/2017**	**0.3**	**-**	Same as #3 but for 16/17 bleaching event
5	15/16 REGION A0.3	Region	2015/2016	0.3	-	
6	15/16 DOMAIN A0.3	Domain	2015/2016	0.3	-	
7	15/16 SHELF D0.01	Shelf	2015/2016	-	0.01	
8	15/16 SHELF D0.05	Shelf	2015/2016	-	0.05	
9	**15/16 SHELF D0.0676**	**Shelf**	**2015/2016**	**-**	**0.0676**	Equivalent average forcing to #3 15/16 event
10	**16/17 SHELF D0.0676**	**Shelf**	**2016/2017**	**-**	**0.0676**	Equivalent average forcing to #3 but applied to 16/17 event
11	15/16 SHELF D0.1	Shelf	2015/2016	-	0.1	
12	15/16 SHELF A0.2 D0.01	Shelf	2015/2016	0.2	0.01	

Figure 8: Map of individual reefs modelled in high resolution biogeochemical RECOM models.

4.4 Hydrodynamic modelling results

4.4.1 Cloud forcing

In scenarios where a cloud albedo change was imposed, it was only applied to low-level clouds where and when they occurred in the region of forcing. Figure 9 illustrates the average change in total albedo over the five-month simulated period for an imposed low-level cloud albedo increase of 0.3. Forcing applied in this manner is spatially heterogenous over the domain in the 2015/2016 bleaching period, however a comparison with Figure 5, which showed the breakdown of low-level cloud by month, reveals a more homogenous forcing field than might at first be expected. This indicates that much of the day-to-day, or even month-to-month spatial variability in low cloud cover is averaged out over the longer five-month period. The resulting albedo forcing field for the 2015/2016 period is relatively even, representing an averaged albedo increase of around 0.065, with some notable higher intensity of forcing very close to the coastline in the region between Cooktown and Townsville (15°S – 19°S latitude). Cloud forcing was higher in 2016/2017 due to the greater presence of low-level cloud over this period.

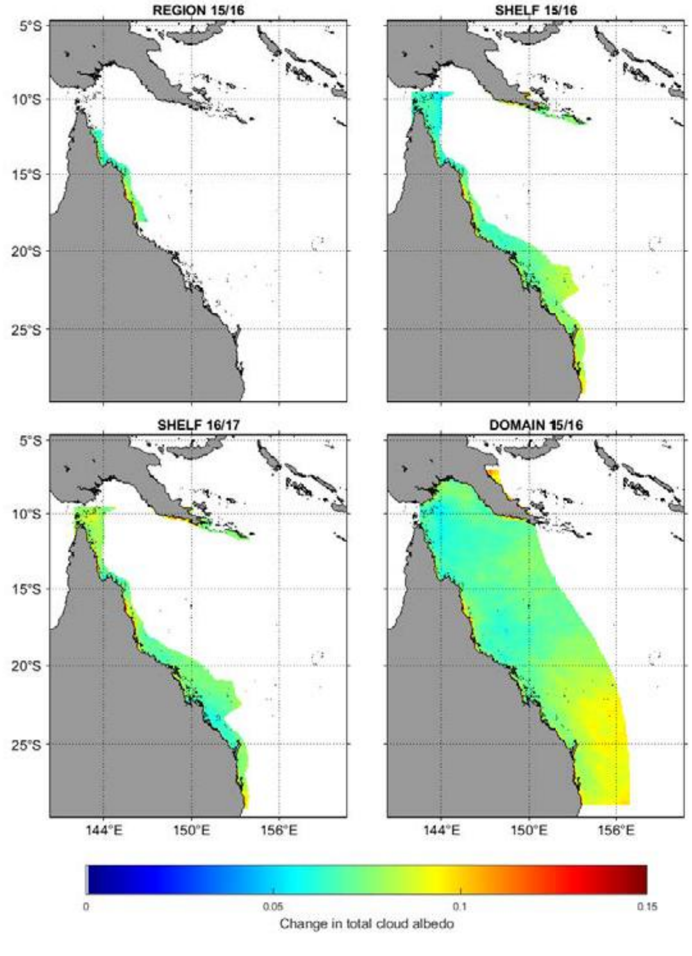


Figure 9: Average change in total cloud albedo for A0.3 scenarios. Note that cloud off the coast of Papua New Guinea was also assumed brightened in SHELF scenarios due to an error in the masking function. This has no impact on results within the Australian EEZ region.

4.4.2 Ocean heat flux components

The scenarios considered resulted in a change to averaged shortwave radiation of between -2.3 and -35.2 W m^{-2}. This change to the heat budget was offset to a degree by changes in other heat flux components of longwave radiation, latent heat flux, and sensible heat flux. These are shown for cases representing each of the spatial scales in Figures 10-12. Longwave radiation (LWR) exhibits both positive and negative feedback, although the positive feedback (further cooling flux) appears to be limited to new water coming into the region of cloud brightening. Sensible heat flux and latent heat flux both exhibit negative feedback, they act to reduce the total change in net flux, and thus reduce the cooling achieved as a result of the reduction in shortwave radiation. Of the two, the most significant is latent heat flux, latent heat flux is a function of ocean sea surface temperature, a cooler SST loses proportionally less latent heat by evaporation.

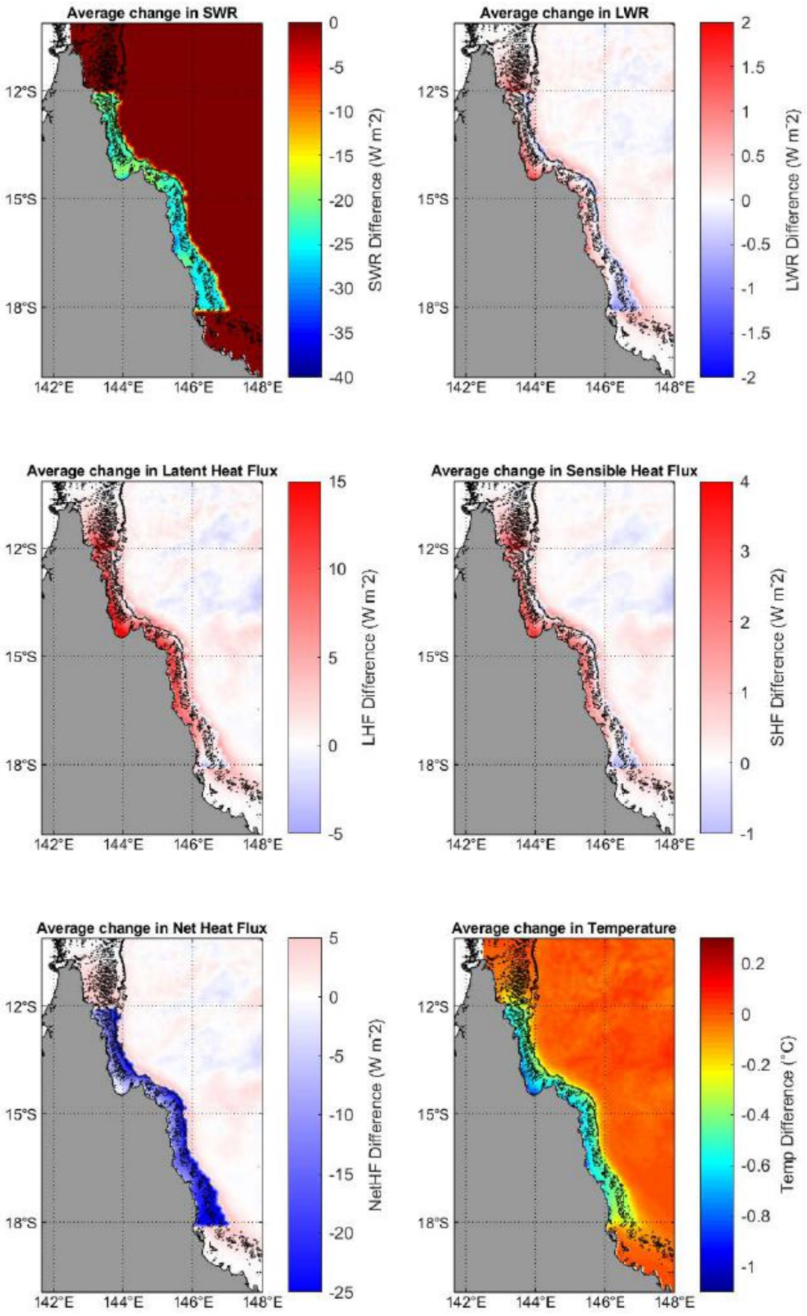


Figure 10: Ocean heat flux components for scenario 15/16 REGION A0.3.

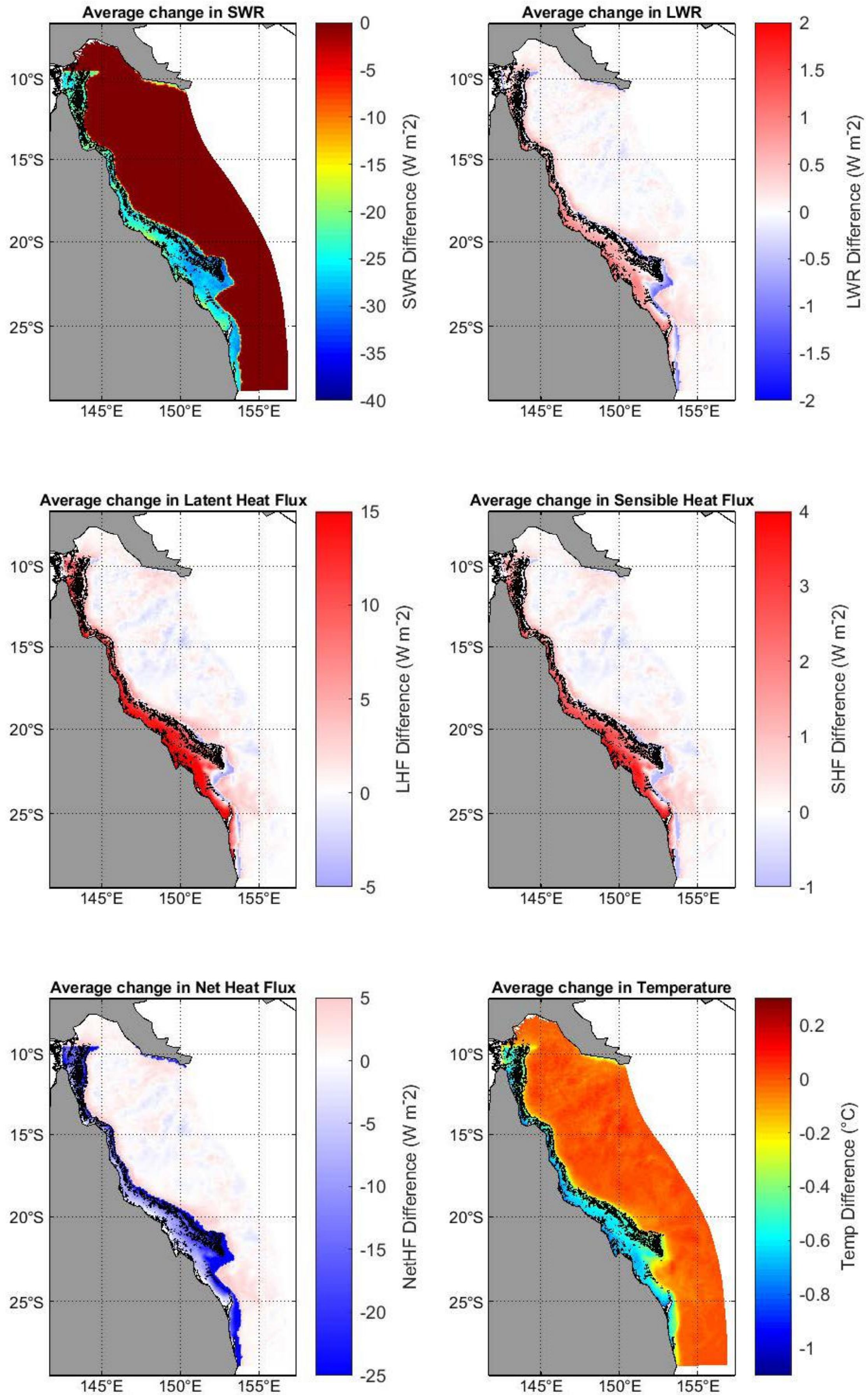


Figure 11: Ocean heat flux components for scenario 15/16 SHELF A0.3.

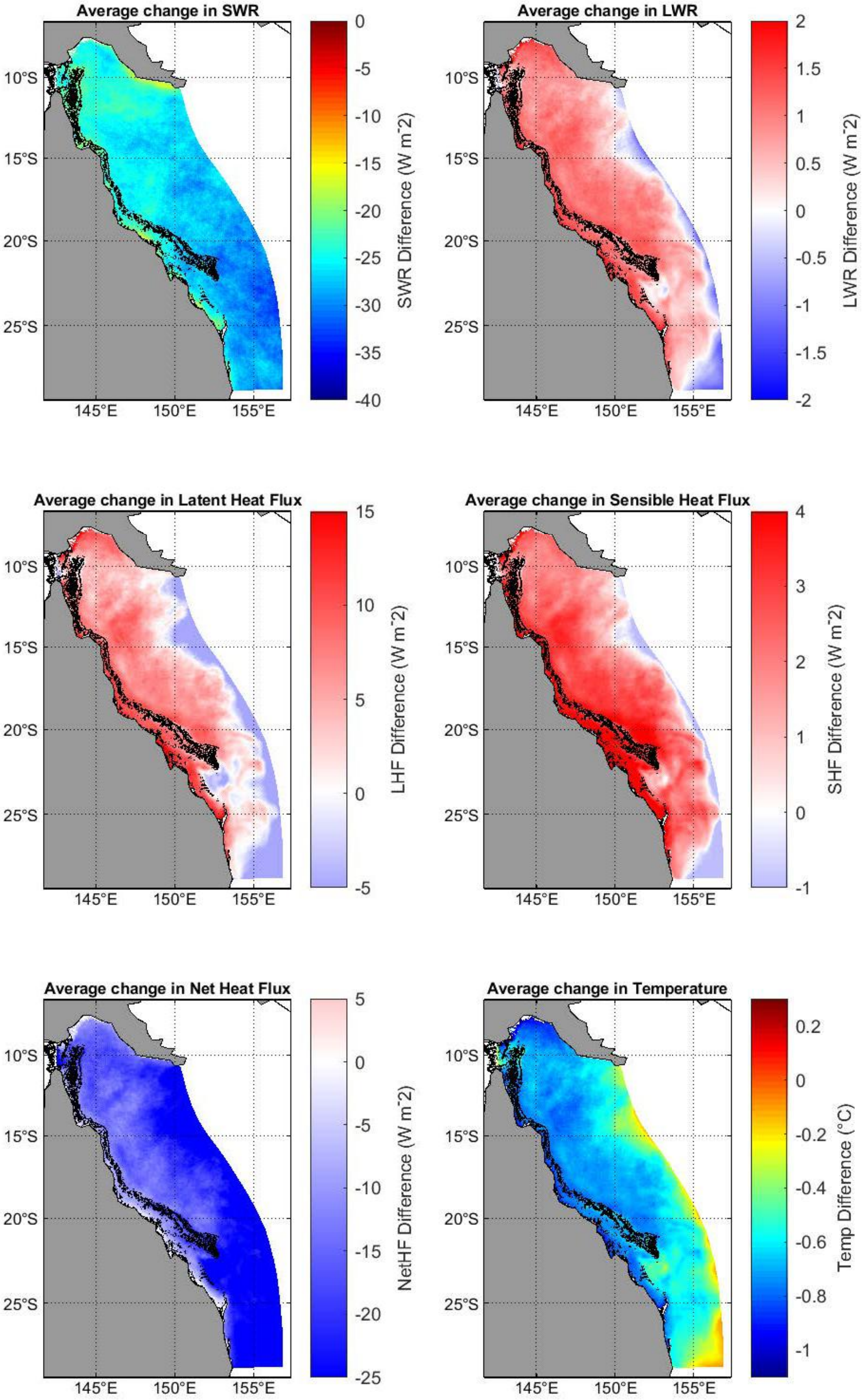


Figure 12: Ocean heat flux components for scenario 15/16 DOMAIN A0.3.

4.4.3 Sea surface temperature

Sea surface temperatures in the eReefs SHOC hydrodynamic model were lowered relative to the control for all forcing scenarios considered. Figure 13 shows the spatial distribution of temporal average (December to April inclusive) sea surface temperature change for each scenario over

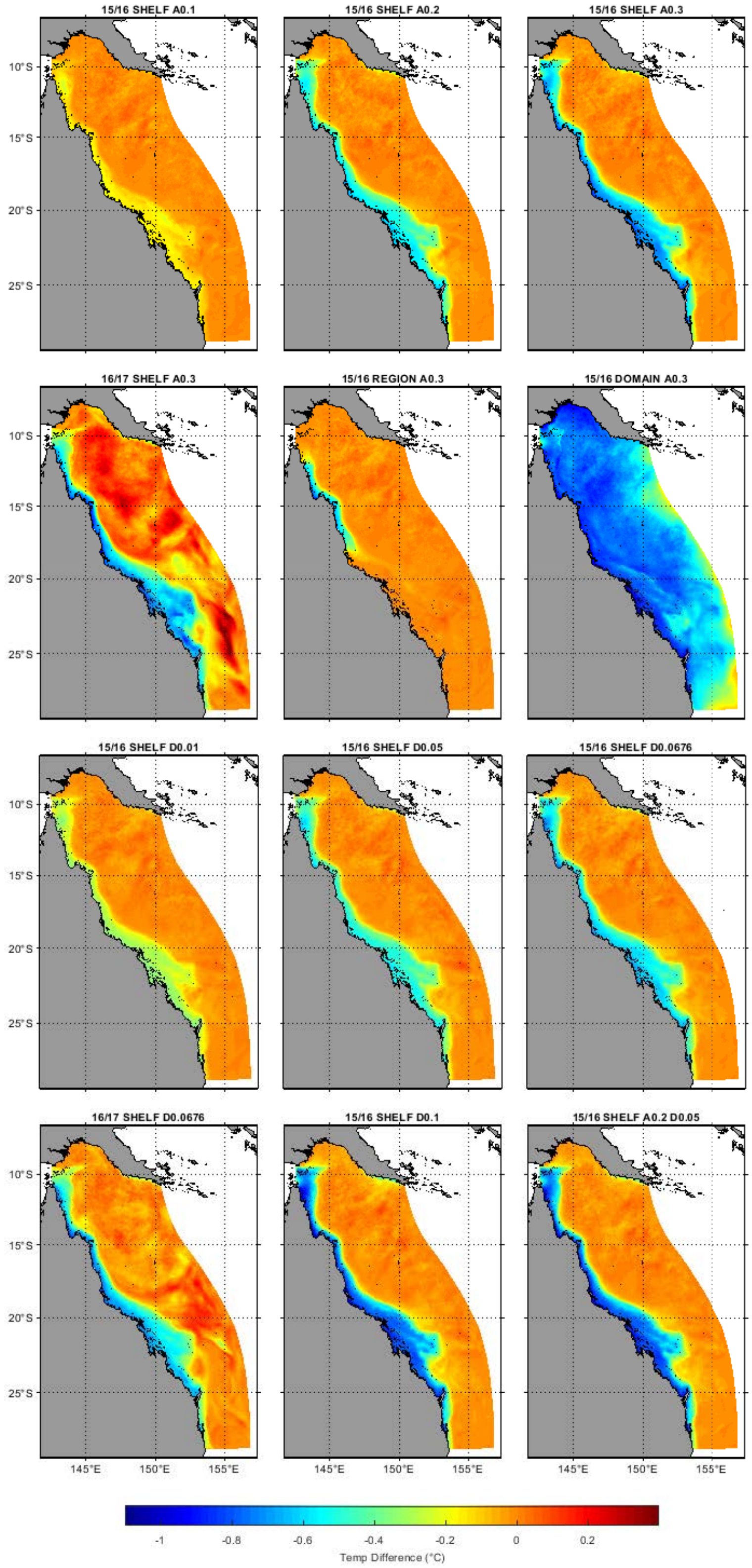


Figure 13: Average sea surface temperature difference for each scenario December-April inclusive.

the GBR4 model domain, excluding the first 10 days after the forcing is first applied. It is apparent that cooling occurs predominately within the region over which cloud brightening is applied. There is surprisingly little consistent carryover of cooler water from within the cloud brightened region to outside it, although a tail of slightly cooler water can be seen extending to the South East of the target area in the regional scenario 15/16 REGION A0.3 Figure 14.

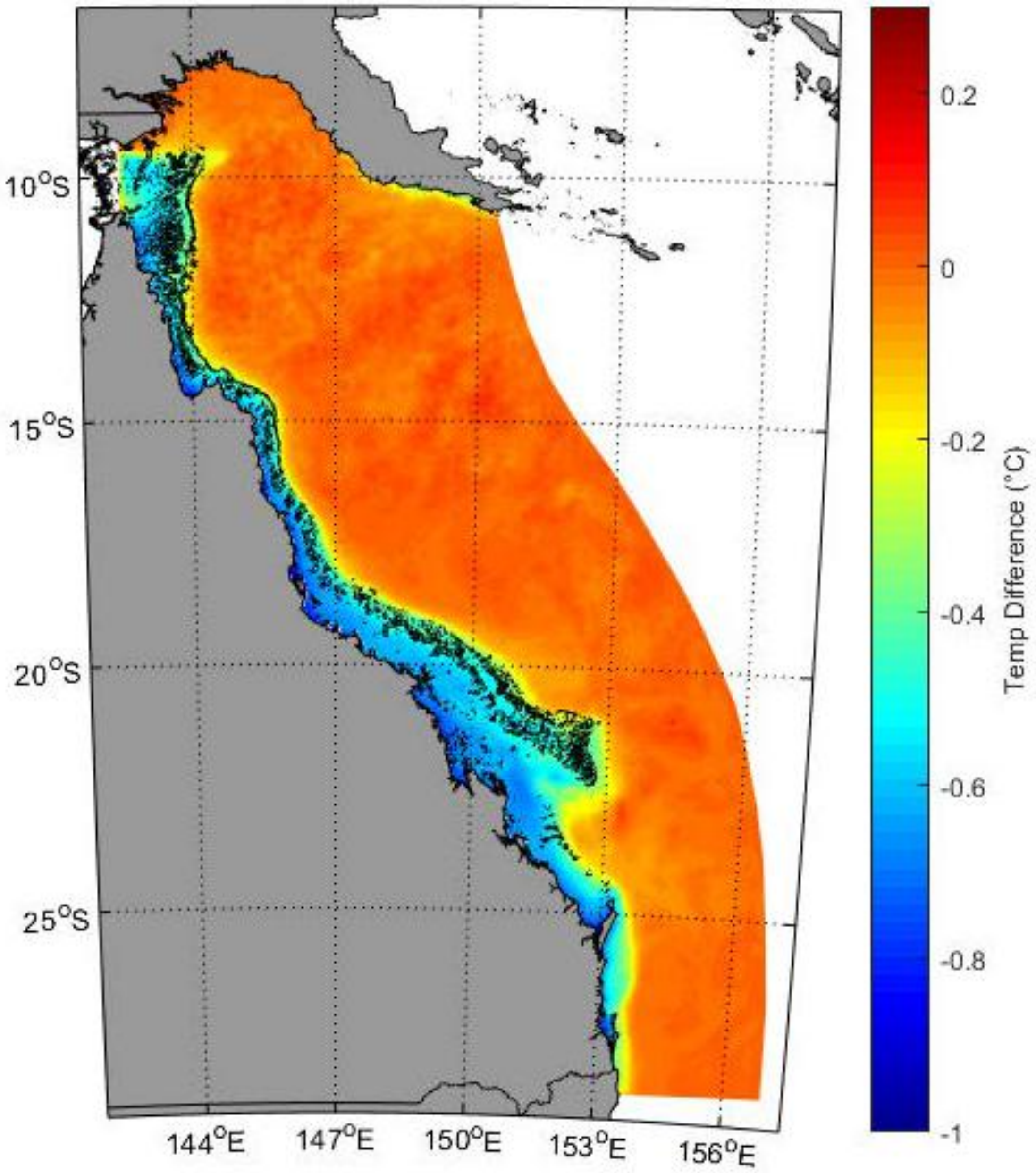


Figure 14: Average sea surface temperature difference for scenario 15/16 SHELF A03. This is an enlarged version of Figure 11(f). Note the cross-shelf gradient in cooling. Operational cooling and shading would be most effective if it extended someway beyond the 200m depth contour to better cool the outer reefs. Note cooling along the coast of Papua New Guinea in SHELF scenario is an artefact of the cloud clipping algorithm not excluding this region.

There is a considerable spatial heterogeneity apparent in average cooling achieved for scenarios representing both the direct and indirect scenarios. This is theorised to be the result of several factors:

1. **Depth:** The shallower the water, the less vertically integrated water column to distribute the reduced energy flux over, hence greater cooling.
2. **Residence time:** The longer the cumulative time a water parcel spends in the region of cloud brightening, the cooler it will become.
3. **Uneven forcing:** This is only applicable to scenarios which include a cloud forcing component for the aerosol indirect effects (those with a value in column 5,

4. Table 2).

The overall trend is of greater cooling closer to the coast in all scenarios. In scenarios where cloud brightening was assumed to the edge of the continental shelf (SHELF and REGION) a transition region is evident where warmer waters are mixing in across the reef from outside the region of cloud brightening. This is illustrated in Figure 14 which shows the average temperature change over the domain under scenario 15/16 SHELF A0.3. This result indicates that in order to provide maximum benefits to the outer reefs, large-scale solar radiation management will need to be conducted some way beyond the edge of the shelf. Such a scenario has not yet been simulated but it is evident from the DOMAIN scenario results that extending cooling and shading beyond the shelf continues to be effective in cooling mixed layer temperatures. Thus, extending the solar radiation management some way beyond the shelf in the order of tens of kilometres could be expected to significantly improve the bleaching stress reductions reported here for the SHELF scenario.

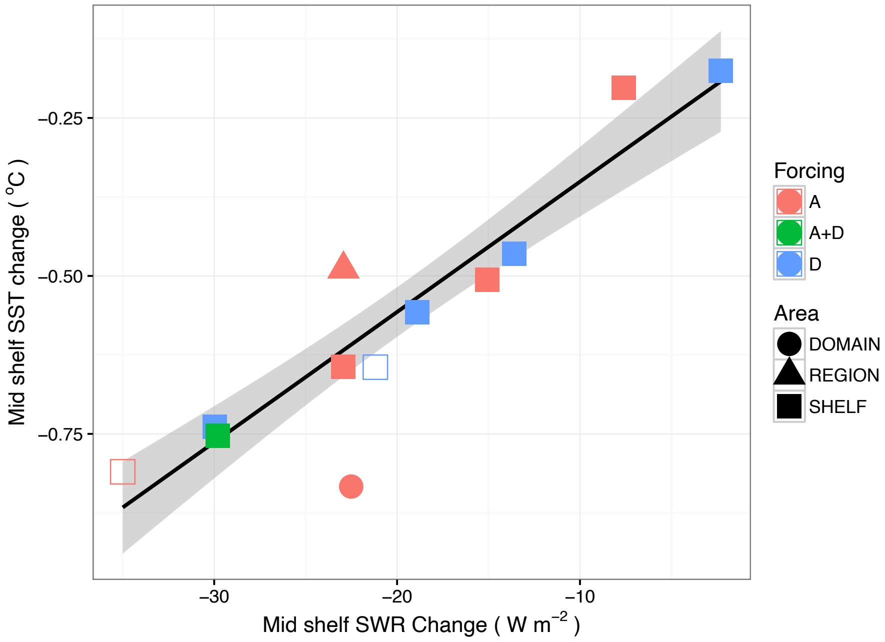


Figure 15: Average SWR reduction plotted against average SST reduction at mid-shelf off Cairns for all scenarios. Solid symbols represent 15/16 period while hollow symbols represent 16/17 period. Shelf scenarios from left to right: 16/17A0.3, 15/16D0.1, 15/16A0.3D0.01, 15/16A0.3, 16/17D0.0676, 15/16D0.0676, 15/16A0.2, 15/16D0.05, 15/16A0.1, 15/16D0.01. A linear fit over this range, for increased forcing at constant spatial scale is shown for SHELF scenarios, shading indicates standard error bounds. Increasing the spatial scale for the same level of forcing (shown, 15/16 A0.3 REGION, SHELF, & DOMAIN) increases the cooling for similar SWR forcing reduction (in this case ~ 23 W m^{-2}).

Temporally averaged sea surface temperature (SST) reduction (mid shelf, approximately centre of REGION) for each of the scenarios are plotted against the average shortwave solar radiation (SWR) reduction in Figure 15. It should be noted when interpreting this plot that the direct and indirect effects are modelled separately. In practice, these would be additive, although we also note that the higher cloud albedo scenarios A02 and A03 may be unrealistically high and were conceived to be representative of the total forcing, but applied intermittently only when low cloud was present. The relationship between SST reduction and SWR forcing is approximately linear for the SHELF case over the range of forcing scenarios considered, with the gradient of 0.225°C per 10 Wm^{-2} reduction in solar forcing. The temperatures shown in this plot are averaged over the summer period for a mid-shelf location offshore of Cairns, there is considerable variability in temperature decreases both spatially, as observed in Figure 14, and temporally, as shown in Figures 20, 21, 22, & 23. The higher cloud cover during 2016/2017 combined with the applied forcing of 0.3 albedo increase led to the largest reduction in mid shelf sea surface temperatures of the scenarios considered, at ~0.8°C.

4.5 Biogeochemical modelling results

The four scenarios selected for nested hydrodynamic and biogeochemical modelling of individual reefs were 15/16 SHELF A0.3, 16/17 SHELF A0.3, 15/16 SHELF D0.0676 and 16/17 SHELF D0.0676. These represent two sets of distinct forcing type: indirect cloud albedo forcing only (A0.3) and direct atmospheric aerosol albedo enhancement (D0.0676). The forcing of scenario D0.0676 was set to be approximately equal in average magnitude to A0.3 in 2015. As forcing in D0.676 is irrespective of cloud cover, the imposed forcing due to the cloud brightening direct effect is equal (domain and temporally averaged) for 15/16 SHELF D0.0676 and 16/17 SHELF D0.0676, but not the forcing due to the cloud albedo which differed between 15/16 SHELF A0.3 and 16/17 SHELF A0.3. The scenarios were selected within the SHELF subset of scenarios to allow comparison across a range of reef locations in both latitude and inner and outer reefs.

The thermal bleaching stress on corals is considered in terms of parameters: photosynthetically active radiation, temperature, temperature difference from climatological value, and the concentration of reactive oxygen species in the coral symbionts.

4.5.1 Photosynthetically active radiation

Photosynthetically active radiation (PAR) was reduced at all reefs for which RECOM (high-resolution) modelling was undertaken. This is as expected, as they all lie within the region over which the atmospheric forcing was applied and there was low-level cloud cover present in all regions at some point during both periods (Figure 5). In the A0.3 scenarios, the PAR forcing is evident as a reduction in PAR during instances when it was already supressed due to the presence of cloud (Figure 16 and Figure 17). For the direct forcing scenarios, one would assume a simple offset in PAR proportional to the forcing applied. That this is not evident at all times in Figure 18 and 19 is presumed to be due to changed hydrodynamic and biogeochemical conditions. At the surface, the change in shortwave solar radiation is an offset from that without forcing, however the PAR is considered at the lowest cell in the model (i.e. seabed) where the corals are located in the model. eReefs contains a complex representation of the underwater light field which is subject to the composition of suspended sediments and plankton in the water column. Because the change in PAR at depth is not always representative of a simple offset in these scenarios, it suggests the spatial and temporal forcing has induced changes in suspended sediment, or biological interactions with the light field, with potential implications for the consideration of environmental impact of large-scale solar radiation management; although we note these changes appear to be small. A detailed investigation of the impacts on underwater light fields is beyond the scope of this study but will be considered during the RRAP R&D Program.

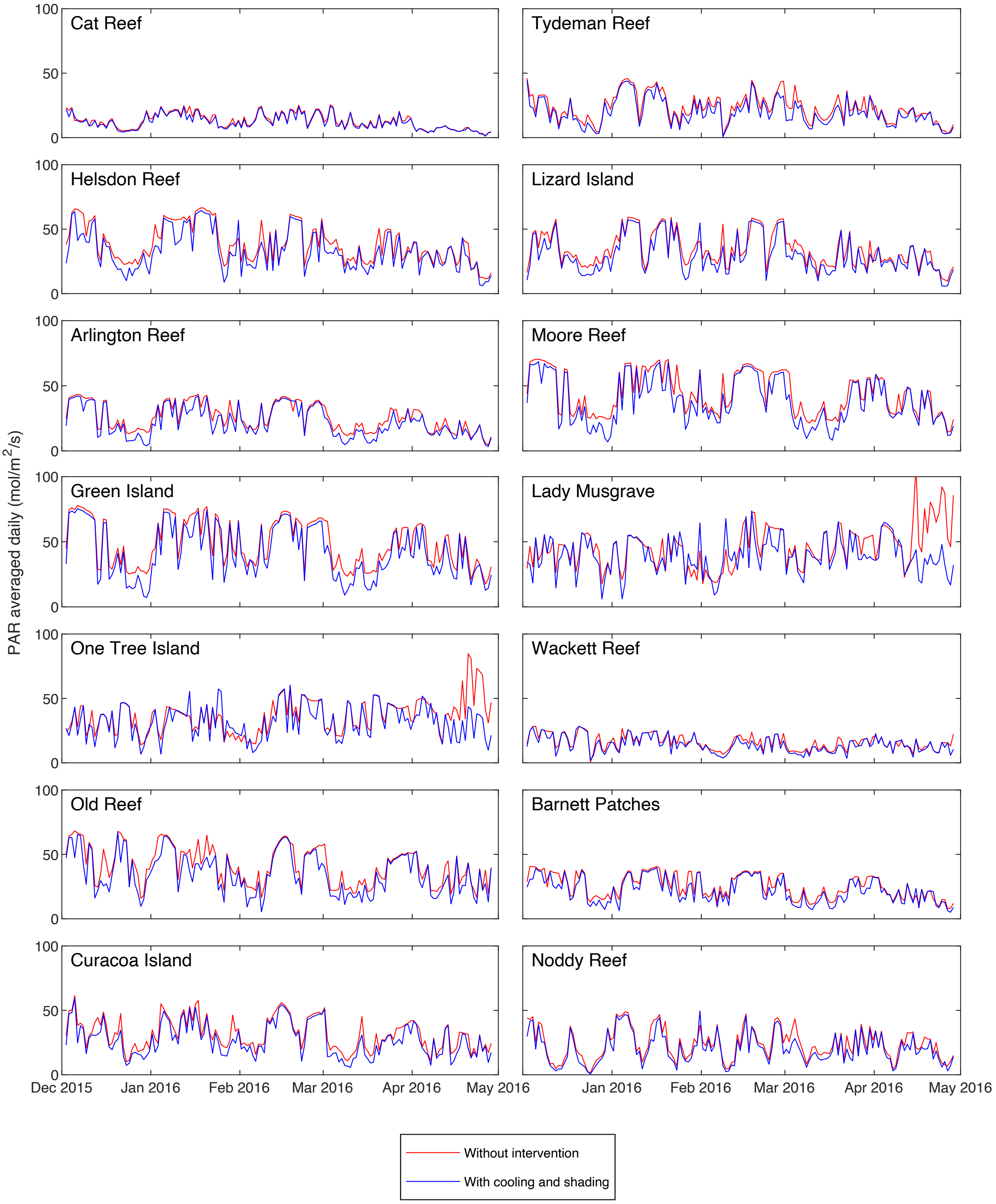


Figure 16: Daily average PAR at RECOM Simulated Reefs for scenario 15/16 SHELF A0.3.

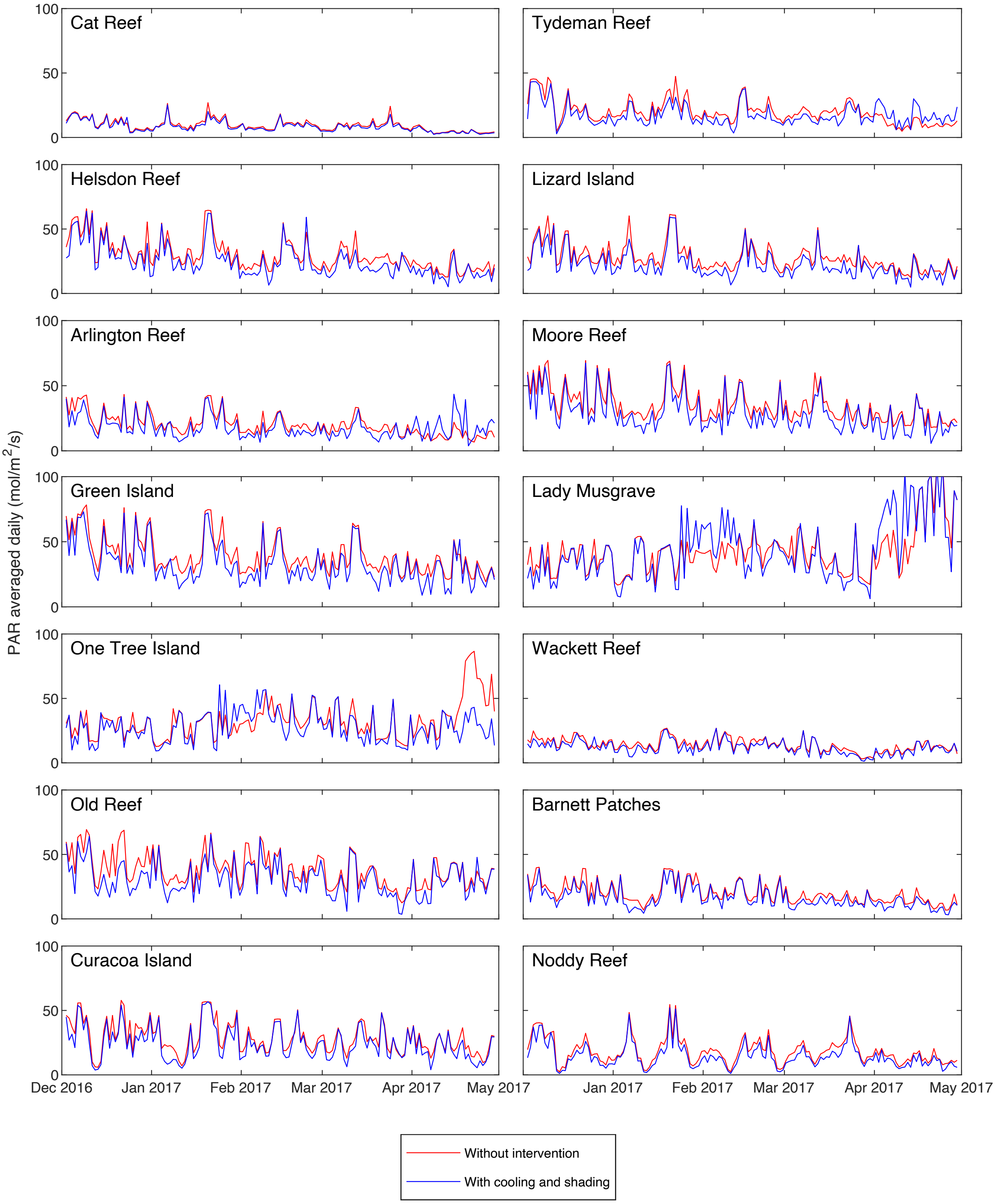


Figure 17: Daily average PAR at RECOM Simulated Reefs for scenario 16/17 SHELF A0.3.

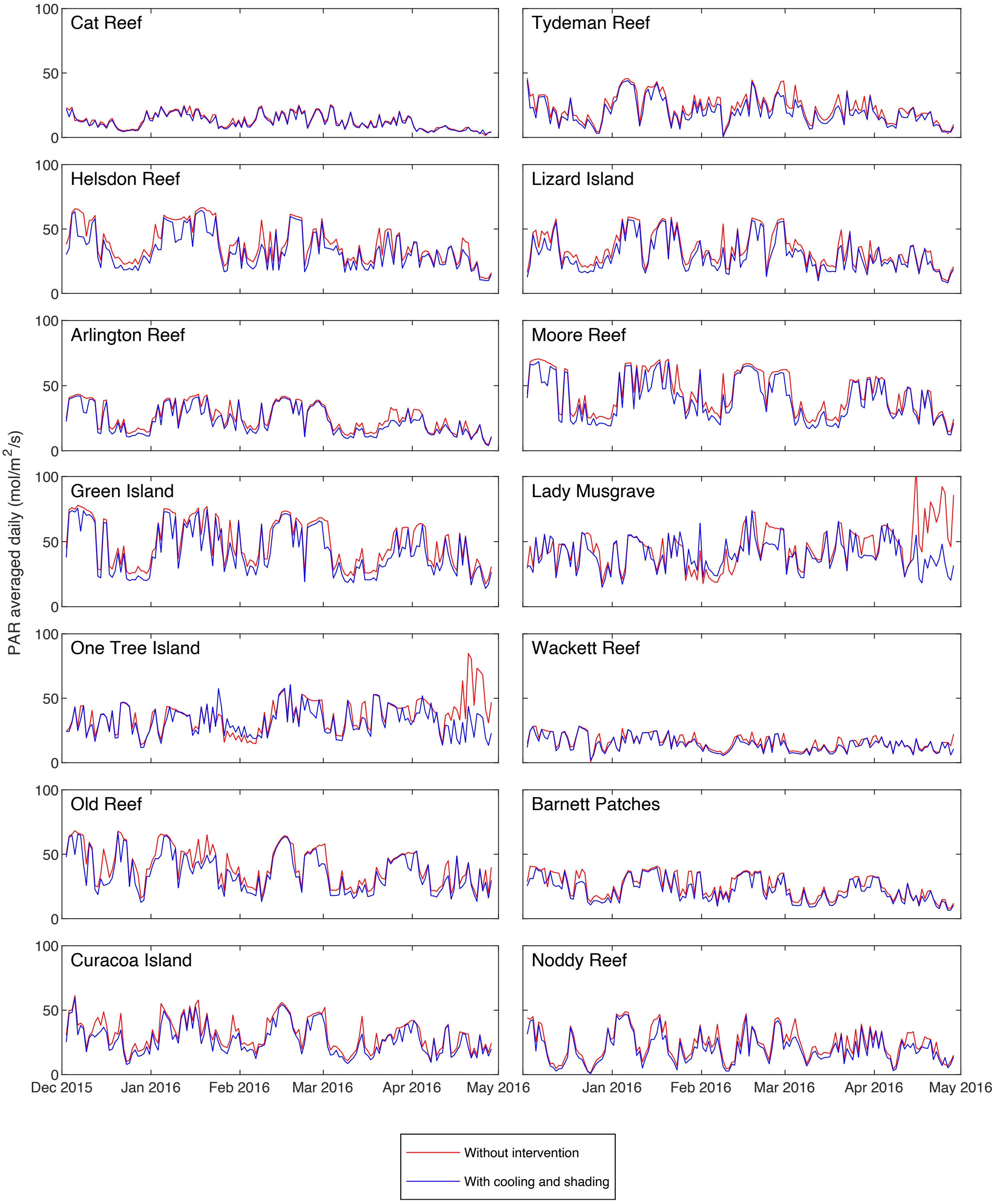


Figure 18: Daily average PAR at RECOM Simulated Reefs for scenario 15/16 SHELF D0.0676.

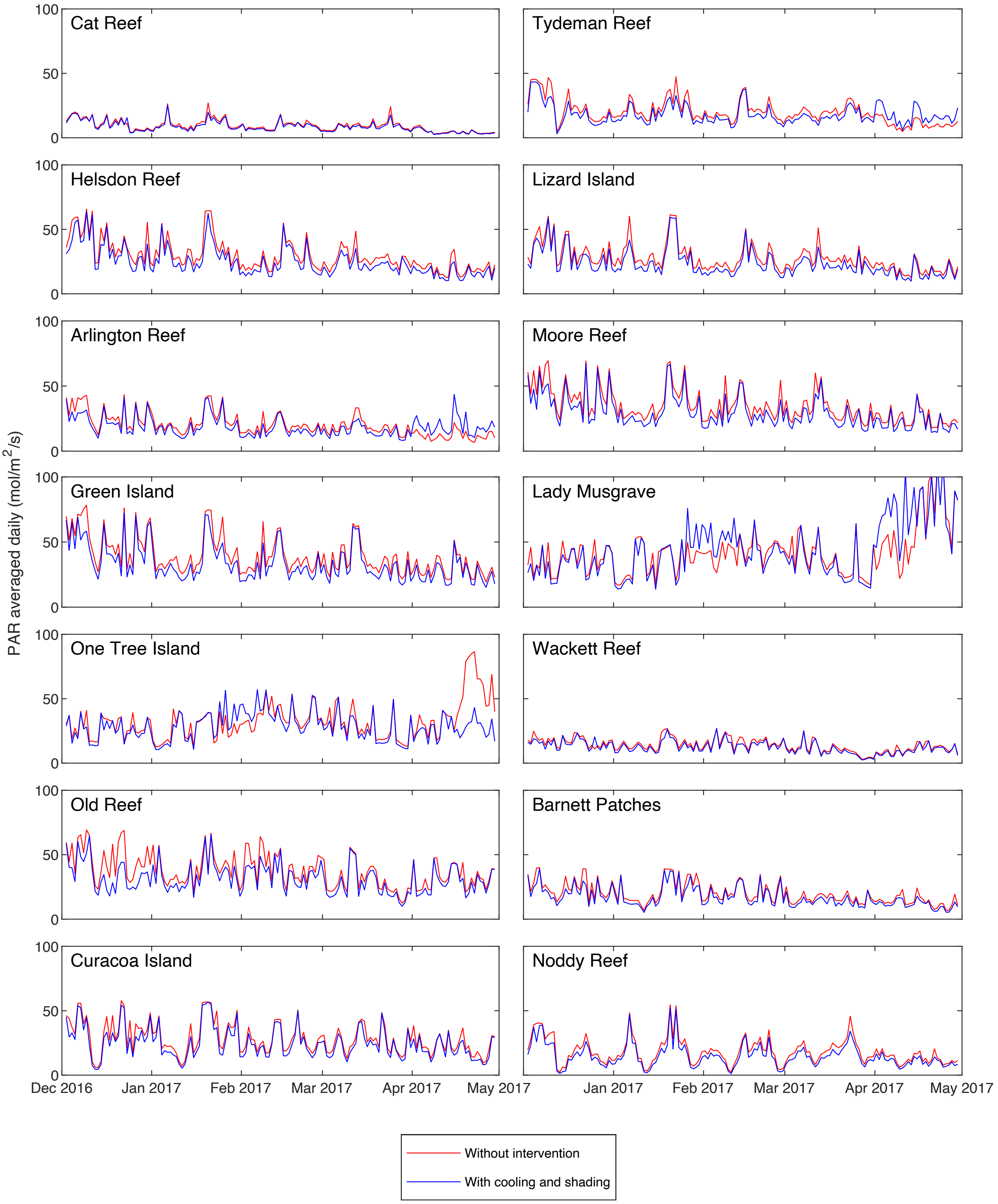


Figure 19: Daily average PAR at RECOM Simulated Reefs for scenario 16/17 SHELF D0.0676.

4.5.2 Bleaching stress

The reduction in sea surface temperature varied across the reefs considered, with outer reefs experiencing less change in temperature stress compared with reefs further inshore for the reasons discussed above. The series of plots below shows bleaching stress in terms of temperature and reactive oxygen species concentration per symbiodinium cell. It can be seen that both the amount of stress and the amount relieved by cloud brightening in these four scenarios is variable across reefs. Roughly, cloud brightening removed around 50 percent of the bleaching stress both in terms of portion of temperature above the 1°C threshold (i.e. degree heating weeks, Figures 24, 25, 26, 27), and reactive oxygen species above the threshold (Figures 28, 29, 30, & 31).

The roughly equivalent scenarios 15/16 SHELF A0.3 and 15/16 SHELF D0.0676 produce a similar SWR forcing change and similar average cooling. However, the difference in bleaching stress that individual reefs experience ranges from almost undetectable, for example in the case of Helsdon and Moore Reefs, to significantly different, as in the case of Arlington Reef. Interestingly Arlington Reef experienced almost no cooling at all in the 15/16 SHELF A0.3 scenario, and cooling of around 0.6°C in the 15/16 SHELF D0.0676 scenario, with the latter leading to considerable reduction in bleaching stress (Figure 30).

It is not yet clear why this reef experienced such a different response between the two scenarios. One clue is the reef is located near the boundary of the region over which solar radiation management was applied, and in a location where the South Equatorial Current often brings warm surface ocean waters flowing towards it. It is possible that the intermittent forcing of the A0.3 scenario was too inconsistent, or cloud cover insufficient to cool this water prior to it reaching Arlington Reef, but that the constant forcing of the D0.0676 was sufficient.

Table 3: Spatially- and temporally-averaged sea surface temperature statistics for each reef modelled in high resolution.

°C	**Control**		**A0.3 SHELF**				**D0.0676 SHELF**			
Reef	**Max**	**Mean**	**Max**	**Change**	**Mean**	**Change**	**Max**	**Change**	**Mean**	**Change**
2015/2016										
Cat Reef	32.35	29.36	34.86	2.51	29.10	-0.26	33.94	2.51	29.11	-0.25
Tydeman Reef	32.54	29.34	32.21	-0.33	28.96	-0.38	32.59	-0.33	28.97	-0.37
Helsdon Reef	33.72	29.43	33.06	-0.66	28.93	-0.50	33.08	-0.66	28.97	-0.46
Lizard Island	34.58	29.46	33.44	-1.14	28.93	-0.53	33.70	-1.14	28.97	-0.49
Arlington Reef	34.69	29.53	34.56	-0.13	29.44	-0.09	34.15	-0.13	29.07	-0.46
Moore Reef	33.33	29.42	32.76	-0.57	28.94	-0.48	32.79	-0.57	28.99	-0.43
Green Island	34.30	29.63	33.86	-0.44	29.04	-0.59	33.72	-0.44	29.10	-0.53
Lady Musgrave	29.45	26.28	28.99	-0.46	25.98	-0.30	28.95	-0.46	26.01	-0.27
One Tree Island	28.54	26.41	27.87	-0.67	26.04	-0.37	28.01	-0.67	26.07	-0.34
Wackett Reef	29.54	27.74	28.88	-0.66	27.32	-0.42	28.85	-0.66	27.34	-0.40
Old Reef	32.54	28.77	31.19	-1.35	28.22	-0.55	31.25	-1.35	28.27	-0.50
Barnett Patches	31.64	29.09	31.52	-0.12	28.68	-0.41	31.50	-0.12	28.72	-0.37
Curacoa Island	35.25	29.77	34.01	-1.24	29.13	-0.64	33.99	-1.24	29.20	-0.57
Noddy Reef	33.22	29.63	32.18	-1.04	29.17	-0.46	32.36	-1.04	29.19	-0.44
2016/2017										
Cat Reef	31.50	28.97	31.28	-0.22	28.64	-0.33	31.71	-0.22	28.63	-0.34
Tydeman Reef	32.28	29.08	31.69	-0.59	28.54	-0.54	31.66	-0.59	28.55	-0.53
Helsdon Reef	34.41	28.99	32.10	-2.31	28.45	-0.54	33.29	-2.31	28.50	-0.49
Lizard Island	34.89	29.02	33.92	-0.97	28.50	-0.52	33.71	-0.97	28.51	-0.51
Arlington Reef	38.69	29.14	37.45	-1.24	28.59	-0.55	37.58	-1.24	28.58	-0.56
Moore Reef	35.75	29.01	35.29	-0.46	28.50	-0.51	35.56	-0.46	28.52	-0.49
Green Island	38.28	29.33	37.70	-0.58	28.69	-0.64	37.71	-0.58	28.70	-0.63
Lady Musgrave	32.77	26.12	31.91	-0.86	25.79	-0.33	32.06	-0.86	25.97	-0.15
One Tree Island	28.32	26.46	27.87	-0.45	26.05	-0.41	27.79	-0.45	26.14	-0.32
Wackett Reef	31.08	27.58	30.50	-0.58	27.16	-0.42	30.23	-0.58	27.24	-0.34
Old Reef	35.87	28.61	34.65	-1.22	28.04	-0.57	34.79	-1.22	27.99	-0.62
Barnett Patches	29.45	28.34	29.22	-0.23	27.93	-0.41	29.16	-0.23	27.95	-0.39
Curacoa Island	34.83	29.57	34.02	-0.81	28.90	-0.67	34.04	-0.81	28.89	-0.68
Noddy Reef	33.96	29.15	33.26	-0.70	28.60	-0.55	33.36	-0.70	28.61	-0.54

Table 4: Spatially-averaged and temporally-integrated reef temperature* exposure statistics for each reef modelled in high resolution.

Degree heating weeks *	Control	A0.3 SHELF			D0.0676 SHELF		
Reef	**Max**	**Max**	**Change**	**Reduction**	**Max**	**Change**	**Reduction**
	DHW	DHW	DHW	%	DHW	DHW	%
2015/2016							
Cat Reef	27.1	22.6	-4.5	17	22.7	-4.4	16
Tydeman Reef	26.9	19.6	-7.3	27	19.8	-7.1	26
Helsdon Reef	26.2	16.5	-9.8	37	17.1	-9.1	35
Lizard Island	27.7	17.7	-10.0	36	18.3	-9.4	34
Arlington Reef	33.4	31.5	-1.9	6	24.2	-9.2	28
Moore Reef	30.2	21.3	-8.9	30	22.1	-8.1	27
Green Island	36.0	23.9	-12.1	34	25.0	-11.0	31
Lady Musgrave	2.9	0.9	-2.0	70	1.0	-1.9	67
One Tree Island	5.9	1.6	-4.3	73	1.9	-4.0	69
Wackett Reef	10.9	4.4	-6.5	60	4.7	-6.2	57
Old Reef	19.1	10.0	-9.1	48	10.8	-8.3	43
Barnett Patches	19.9	13.8	-6.1	31	14.4	-5.5	28
Curacoa Island	37.5	24.0	-13.5	36	25.5	-12.0	32
Noddy Reef	26.2	17.7	-8.5	32	18.0	-8.2	31
2016/2017							
Cat Reef	18.7	13.0	-5.7	31	13.4	-5.3	29
Tydeman Reef	21.2	10.9	-10.3	49	11.4	-9.8	46
Helsdon Reef	16.8	6.9	-9.9	59	8.7	-8.1	48
Lizard Island	18.4	8.6	-9.8	53	9.4	-9.0	49
Arlington Reef	25.1	13.9	-11.2	45	14.0	-11.1	44
Moore Reef	21.3	11.5	-9.8	46	12.7	-8.6	40
Green Island	29.7	16.4	-13.3	45	16.4	-13.2	45
Lady Musgrave	3.1	1.3	-1.8	58	3.0	-0.1	4
One Tree Island	7.3	3.2	-4.1	56	3.9	-3.3	46
Wackett Reef	8.1	3.8	-4.3	53	4.3	-3.9	47
Old Reef	15.7	6.8	-8.8	56	6.3	-9.4	60
Barnett Patches	6.0	2.0	-4.0	67	2.3	-3.7	61
Curacoa Island	33.3	19.3	-13.9	42	19.0	-14.3	43
Noddy Reef	16.5	7.4	-9.1	55	7.9	-8.6	52

* Reef temperature exposure is a temperature stress metric used in eReefs. It is calculated as the temperature above the daily climatological value for each day at each location, multiplied by timestep, and accumulated over the entire summer from 1 December to 30 April. For further information see: https://research.csiro.au/ereefs/models/model-outputs/gbr4/salinity-and-temperature/

Table 5: Spatially-averaged and temporally-integrated reactive oxygen species statistics for each reef modelled in high resolution.

	Control		A0.3 SHELF						D0.0676 SHELF					
Reef	Max (mg O /cell)	Cumulative (mg O weeks / cell)	Max (mg O /cell)	Diff (mg O /cell)	Reduction %	Cumulative (mg O weeks / cell)	Diff (mg O weeks / cell)	Reduction %	Max (mg O /cell)	Diff (mg O /cell)	Reduction %	Cumulative (mg O weeks / cell)	Diff (mg O weeks / cell)	Reduction %
	$x10^{-6}$	$x10^{-6}$	$x10^{-6}$	$x10^{-6}$		$x10^{-6}$	$x10^{-6}$		$x10^{-6}$	$x10^{-6}$		$x10^{-6}$	$x10^{-6}$	
2015/2016														
Cat Reef	99	407	59	-40	40	243	-163	40	58	-40	41	246	-161	40
Tydeman Reef	59	298	43	-16	27	147	-151	51	43	-16	27	148	-150	50
Helsdon Reef	215	1363	175	-39	18	713	-650	48	171	-39	20	721	-642	47
Lizard Island	155	1107	120	-35	23	572	-534	48	117	-35	25	584	-523	47
Arlington Reef	373	2228	316	-57	15	1710	-518	23	181	-57	51	1155	-1074	48
Moore Reef	238	1182	105	-133	56	587	-594	50	103	-133	57	606	-576	49
Green Island	283	1709	154	-129	46	807	-902	53	147	-129	48	827	-882	52
Lady Musgrave	52	198	51	-1	1	124	-74	37	50	-1	4	125	-73	37
One Tree Island	59	132	54	-5	8	73	-59	44	54	-5	8	79	-53	40
Wackett Reef	4	14	2	-2	43	9	-4	30	3	-2	38	9	-5	33
Old Reef	98	335	70	-28	29	167	-168	50	65	-28	34	165	-171	51
Barnett Patches	102	298	55	-47	46	113	-185	62	53	-47	48	118	-181	61
Curacoa Island	42	135	16	-26	61	42	-93	69	16	-26	61	48	-87	65
Noddy Reef	111	426	42	-70	63	163	-263	62	42	-70	62	177	-249	59
2016/2017														
Cat Reef	17	21	13	-4	24	10	-11	51	13	-4	24	12	-10	46
Tydeman Reef	24	97	13	-11	45	24	-73	75	13	-11	46	29	-68	70
Helsdon Reef	88	250	60	-28	32	88	-162	65	55	-28	38	89	-161	64
Lizard Island	77	244	52	-25	32	82	-162	66	51	-25	33	91	-153	63
Arlington Reef	144	633	89	-55	38	217	-416	66	90	-55	37	239	-394	62
Moore Reef	41	221	30	-11	27	71	-150	68	29	-11	29	89	-132	60
Green Island	115	578	64	-51	44	203	-375	65	63	-51	45	205	-373	65
Lady Musgrave	31	131	27	-4	14	88	-43	33	27	-4	13	84	-47	36
One Tree Island	11	12	6	-5	44	2	-10	85	5	-5	57	1	-11	89
Wackett Reef	10	18	6	-5	45	5	-13	74	5	-5	51	5	-13	73
Old Reef	53	180	35	-17	33	78	-101	56	35	-17	34	77	-102	57
Barnett Patches	11	9	3	-8	71	2	-8	83	3	-8	74	1	-8	88
Curacoa Island	19	76	9	-10	52	16	-60	79	9	-10	52	15	-62	81
Noddy Reef	27	49	11	-15	57	11	-37	77	10	-15	63	12	-37	76

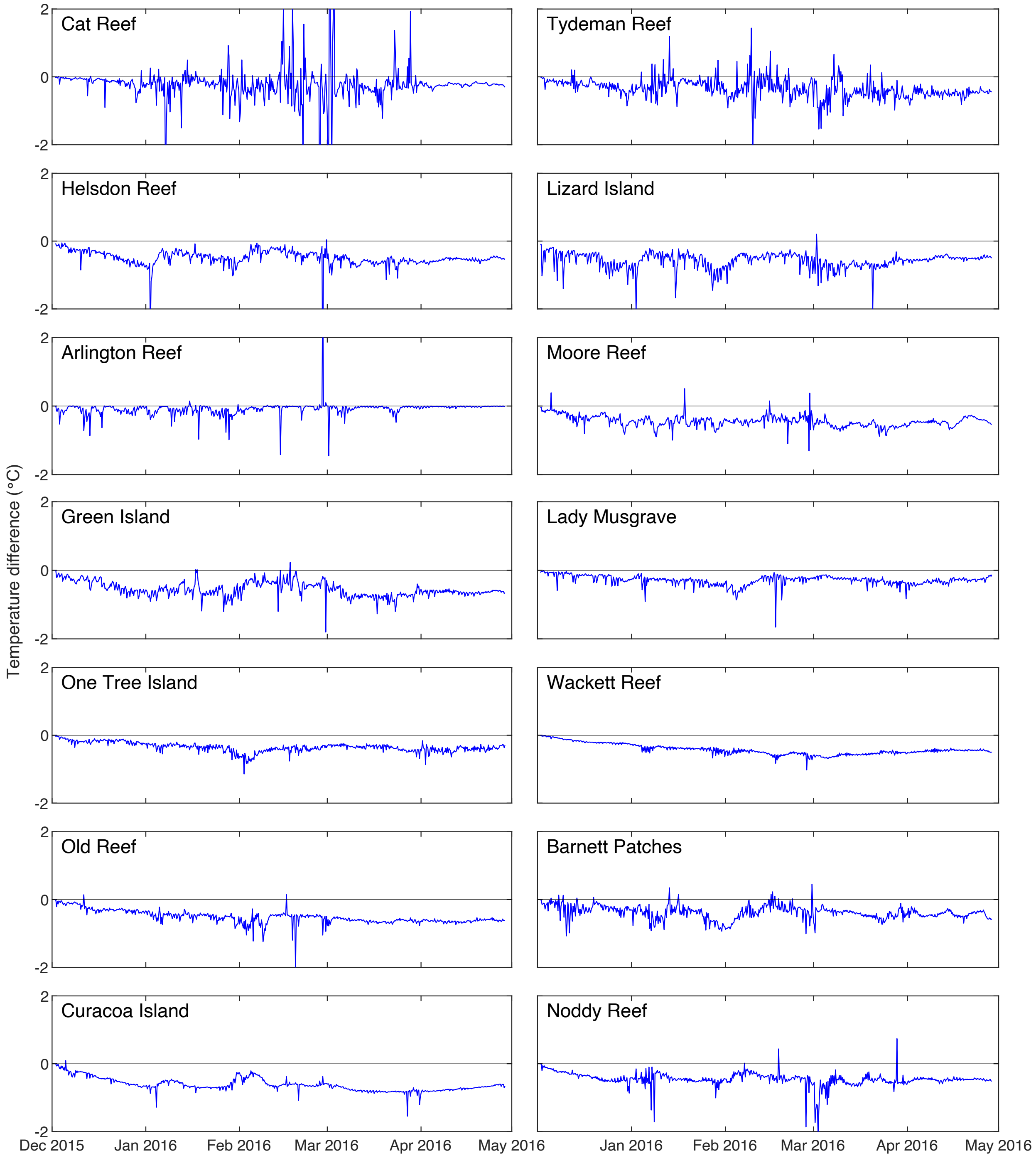


Figure 20: Time series of difference in temperature at each reef, scenario 15/16 SHELF A0.3.

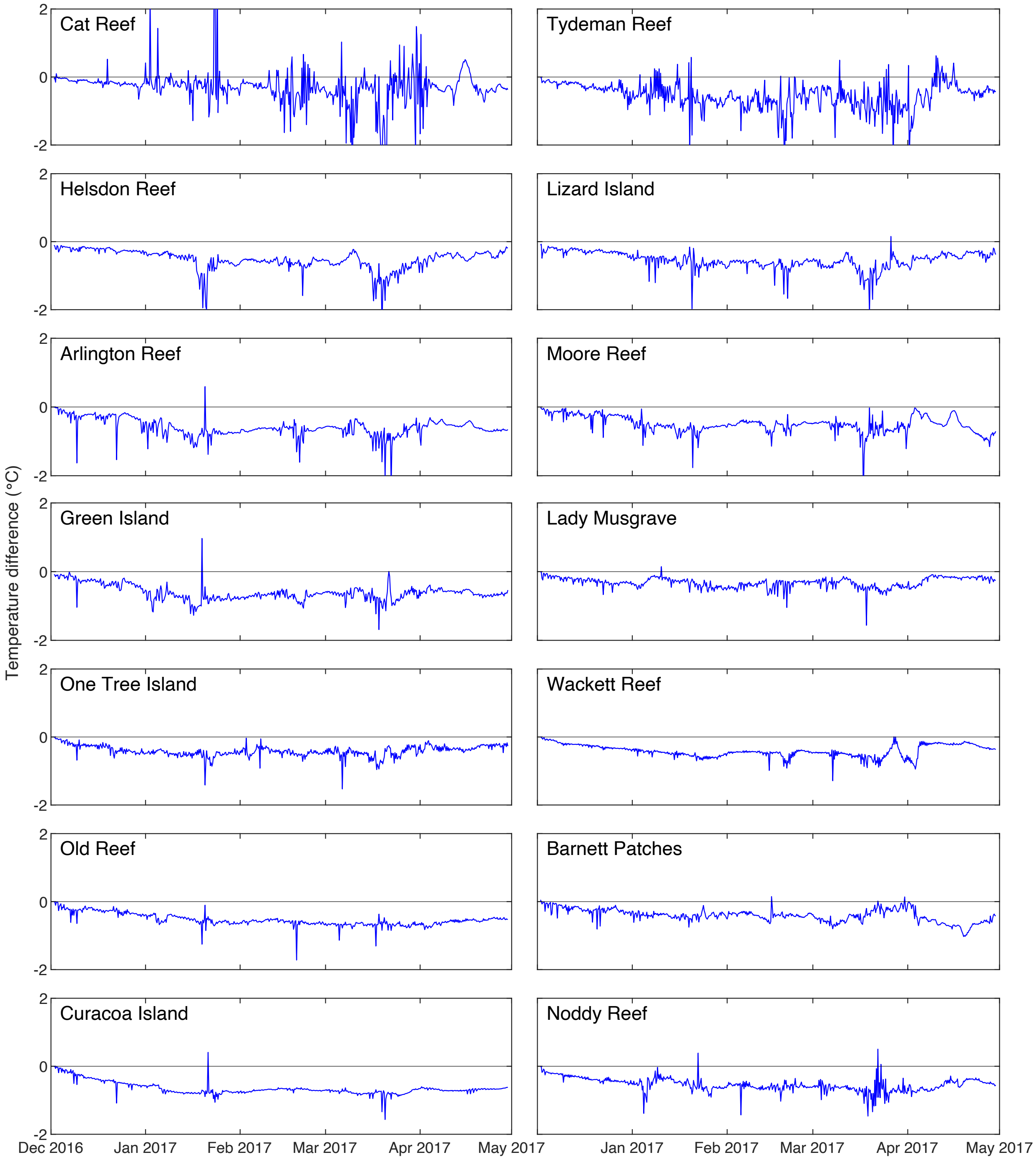


Figure 21: Time series of difference in temperature at each reef, scenario 16/17 SHELF A0.3.

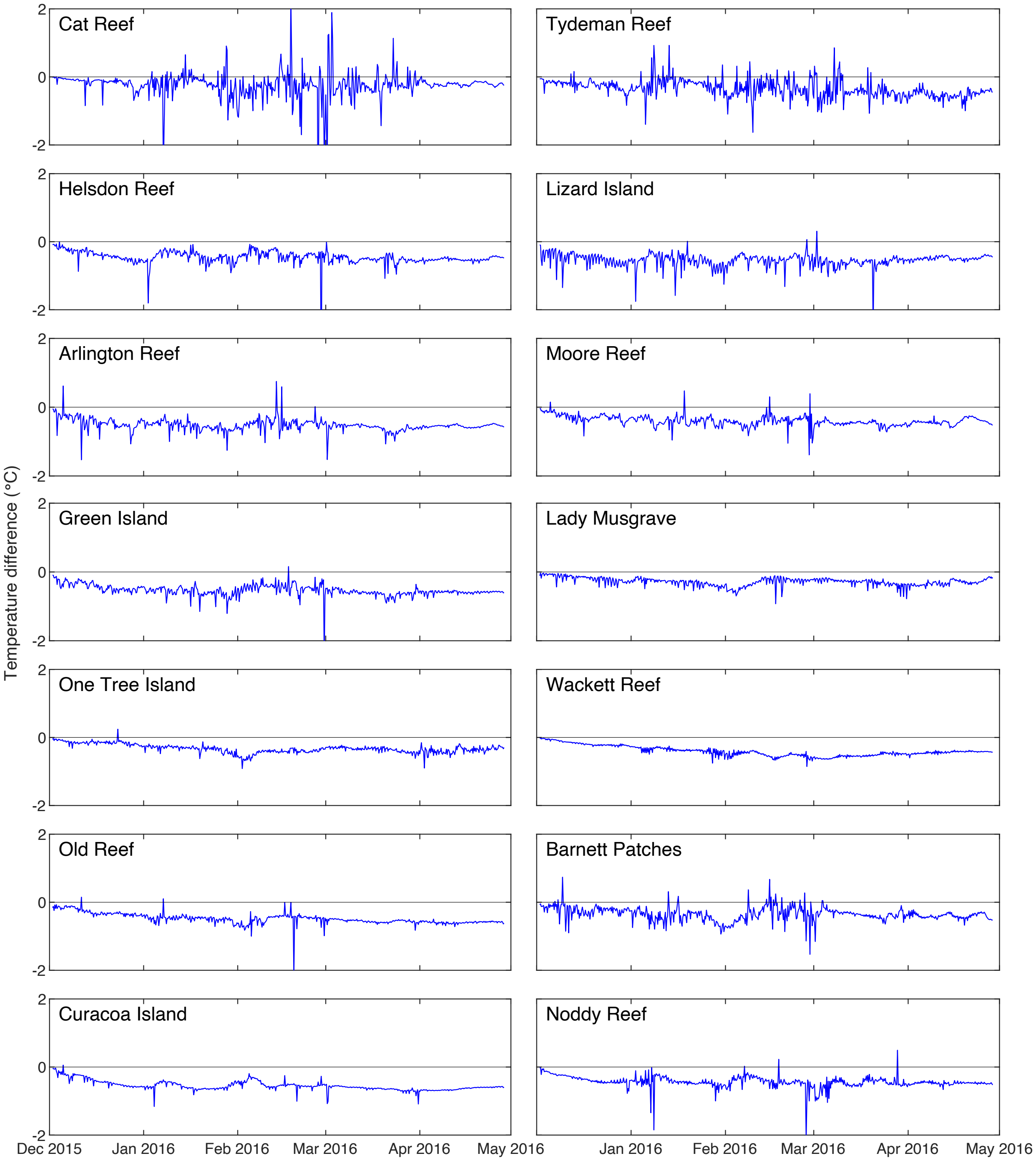


Figure 22: Time series of difference in temperature at each reef, scenario 15/16 SHELF D0.0676.

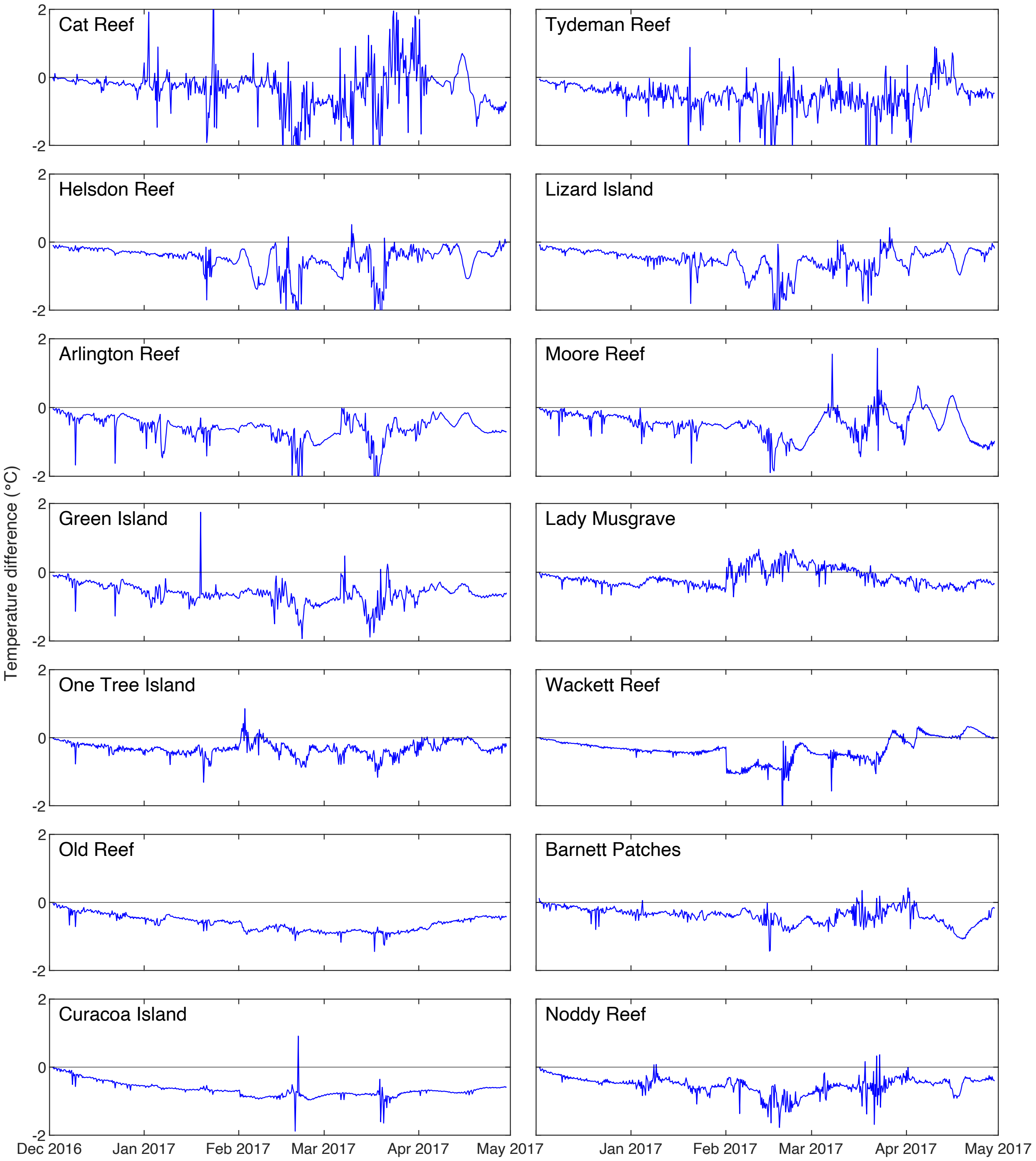


Figure 23: Time series of difference in temperature at each reef, scenario 16/17 SHELF D0.0676.

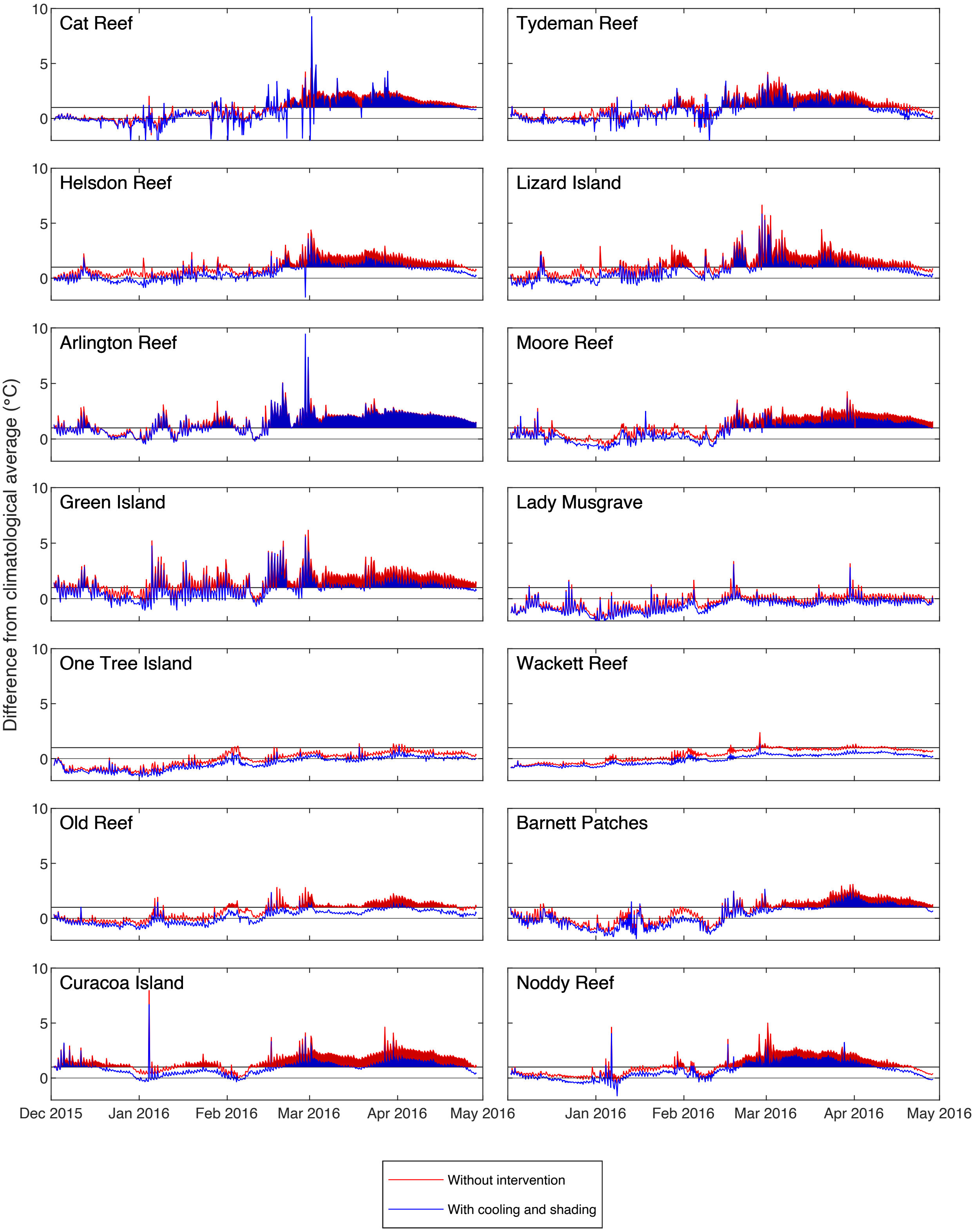


Figure 24: Difference from daily climatological temperature at coral depth on RECOM simulated reefs for scenario 15/16 SHELF A0.3. Shading is indicative of temperature above 1°C higher than the climatological value for that day at that location. Red is temperature stress avoided by cooling and shading intervention, while blue shading is indicative of remaining stress. Red + Blue shading is indicative of the original stress.

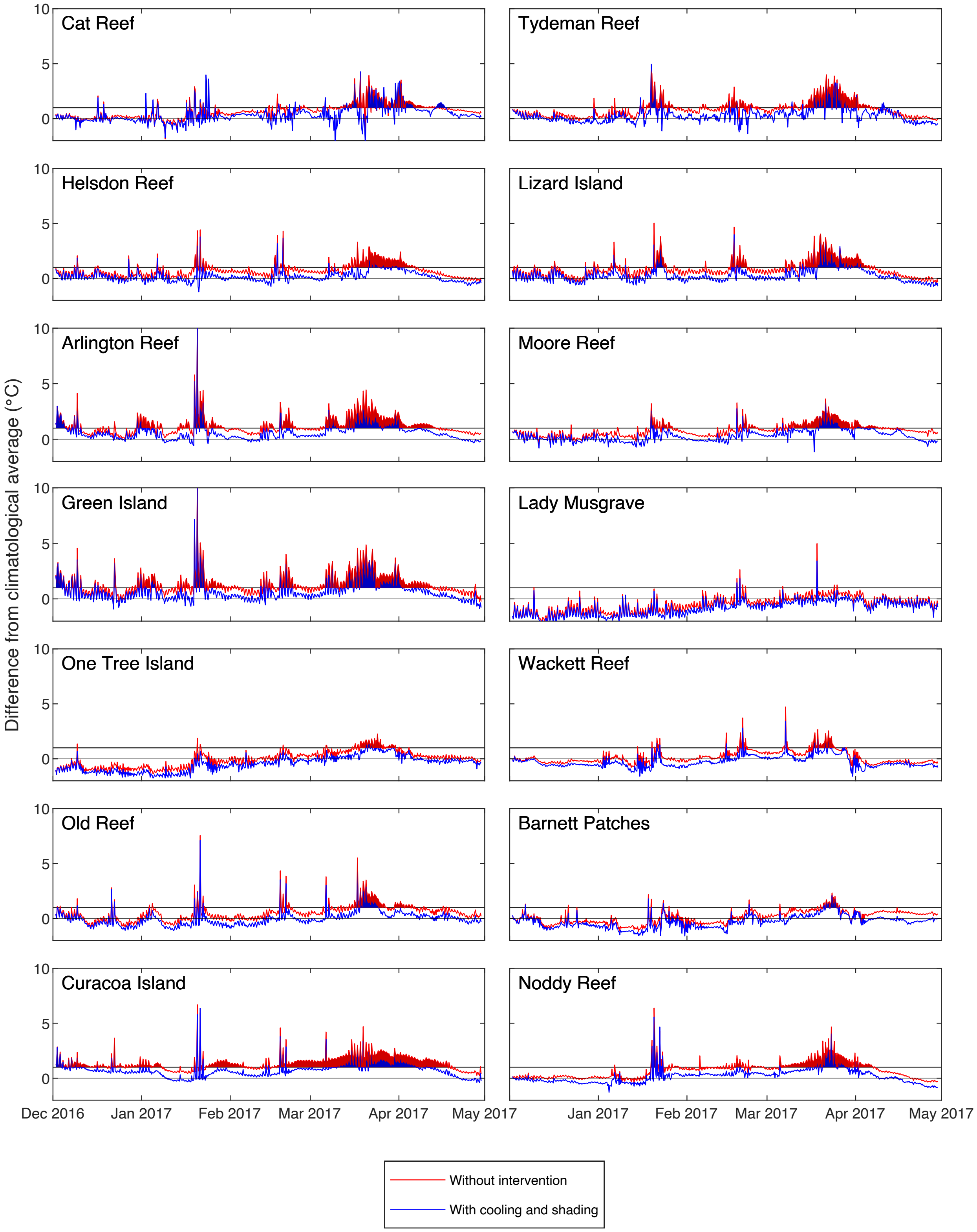


Figure 25: Difference from daily climatological temperature at coral depth on RECOM simulated reefs for scenario 16/17 SHELF A0.3. Shading is indicative of temperature above 1°C higher than the climatological value for that day at that location. Red is temperature stress avoided by cooling and shading intervention, while blue shading is indicative of remaining stress. Red + Blue shading is indicative of the original stress.

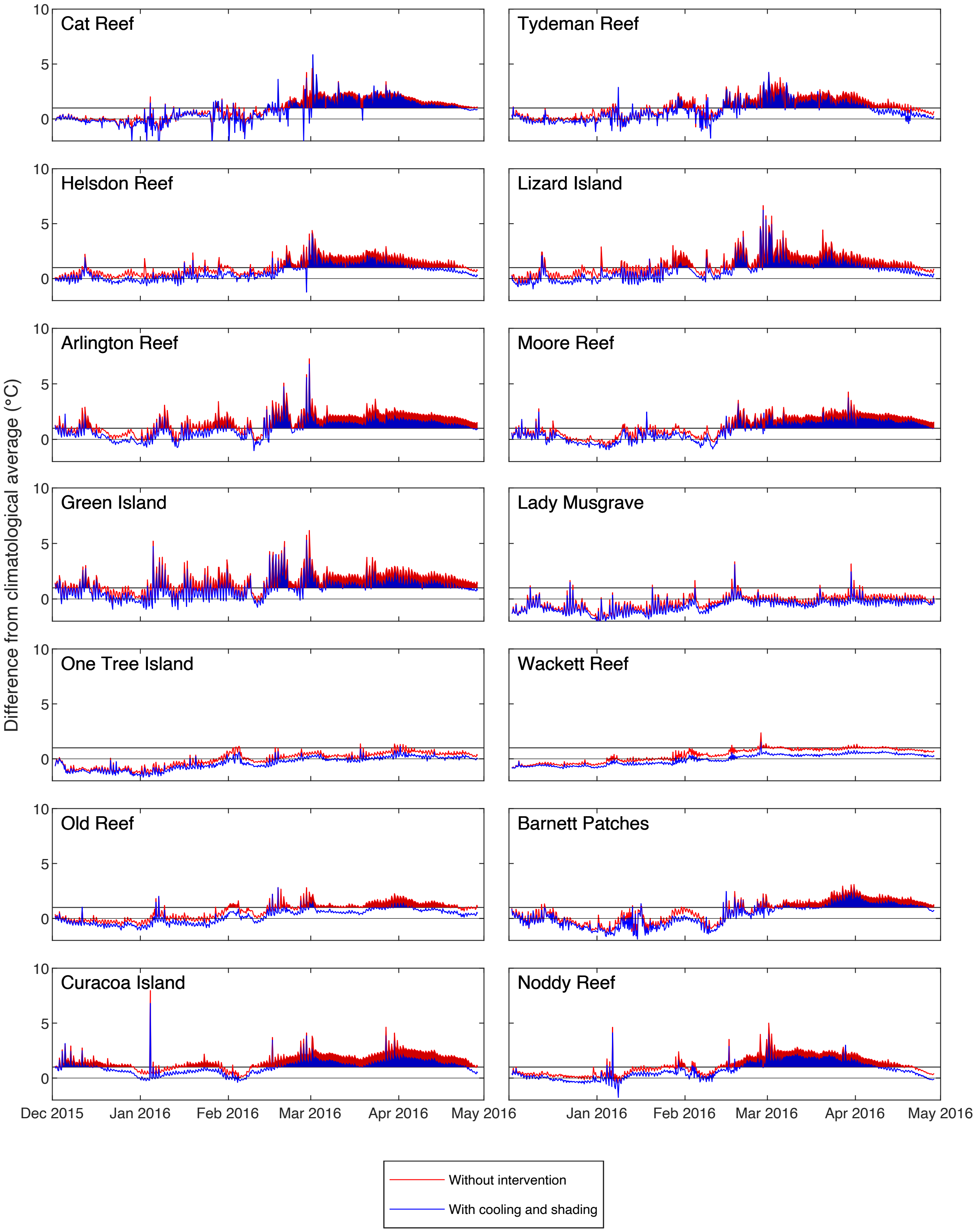


Figure 26: Difference from climatological temperature at coral depth on RECOM simulated reefs for scenario 15/16 SHELF D0.0676. Shading is indicative of temperature above 1°C higher than the climatological value for that day at that location. Red is temperature stress avoided by cooling and shading intervention, while blue shading is indicative of remaining stress. Red + Blue shading is indicative of the original stress.

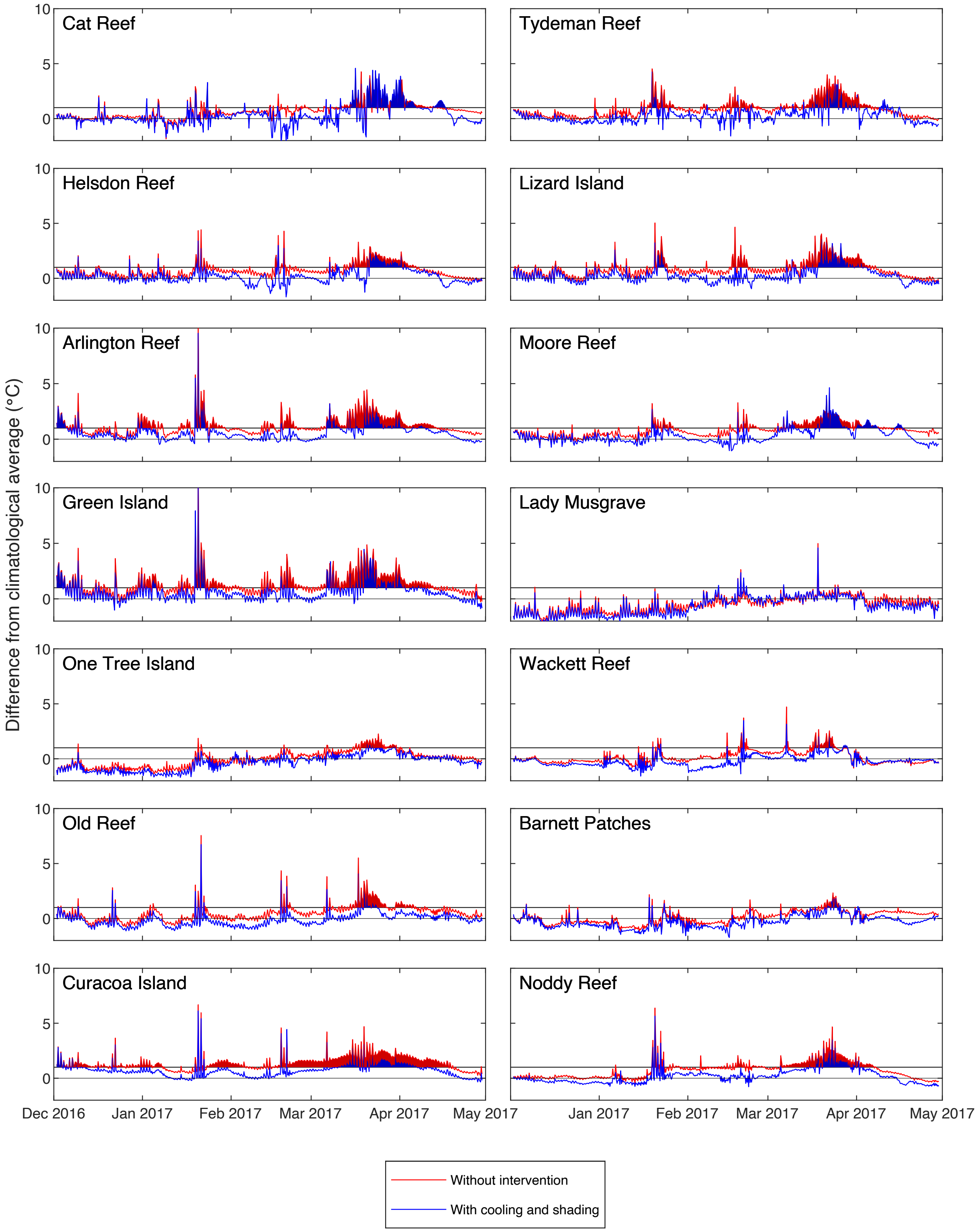


Figure 27: Difference from climatological temperature at coral depth on RECOM simulated reefs for scenario 16/17 SHELF D0.0676. Shading is indicative of temperature above 1°C higher than the climatological value for that day at that location. Red is temperature stress avoided by cooling and shading intervention, while blue shading is indicative of remaining stress. Red + Blue shading is indicative of the original stress.

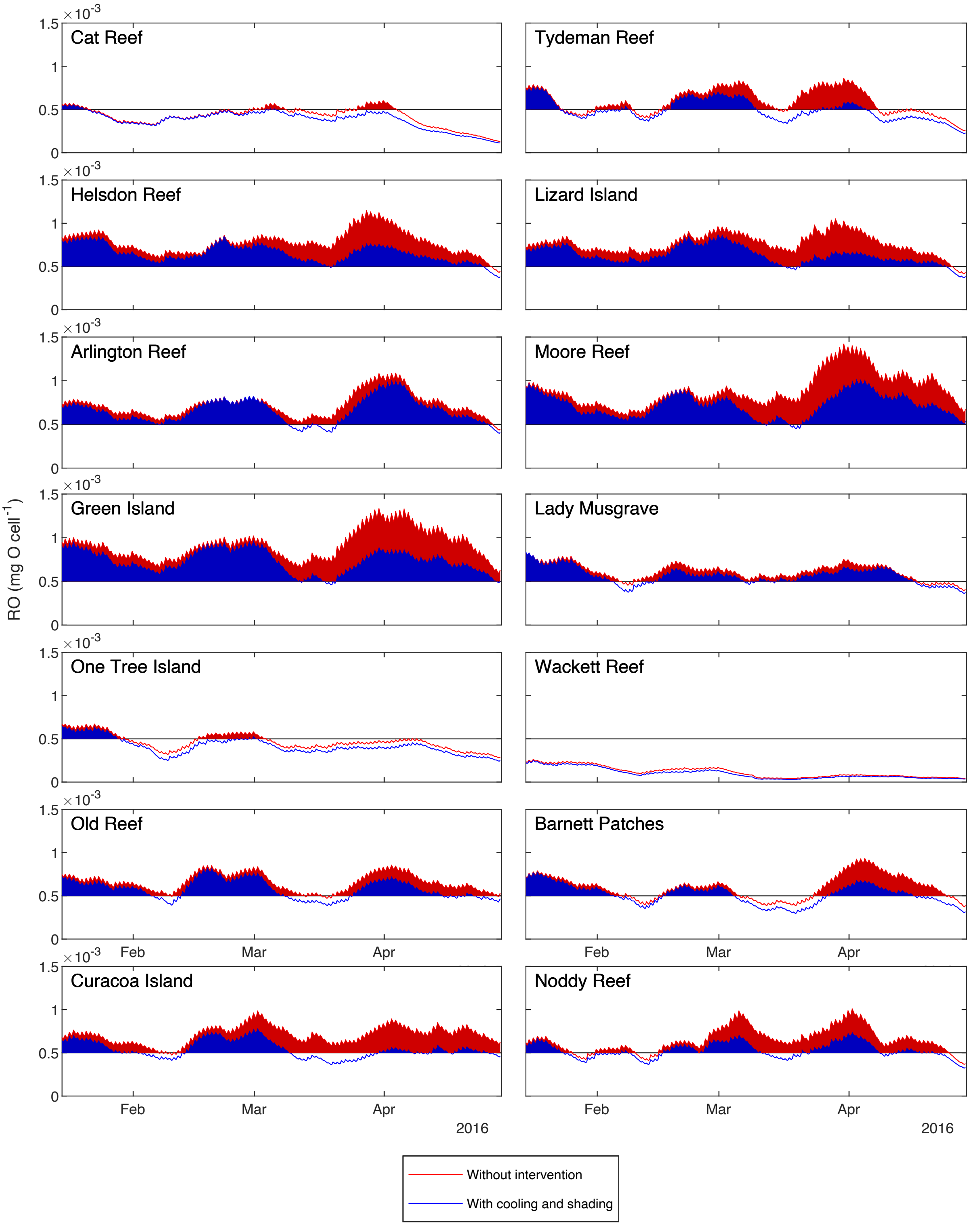


Figure 28: Reactive oxygen species concentration/cell at a representative location on RECOM simulated reefs for scenario 15/16 SHELF A0.3. The plot is shaded when the value is above the bleaching threshold of 0.0005 mg O cell^{-1} as defined in Baird et al. (2018). Thus, red shaded area represents bleaching stress avoided by cooling and shading, and blue shading represents bleaching stress that was not avoided. Red + Blue shading shows original bleaching stress.

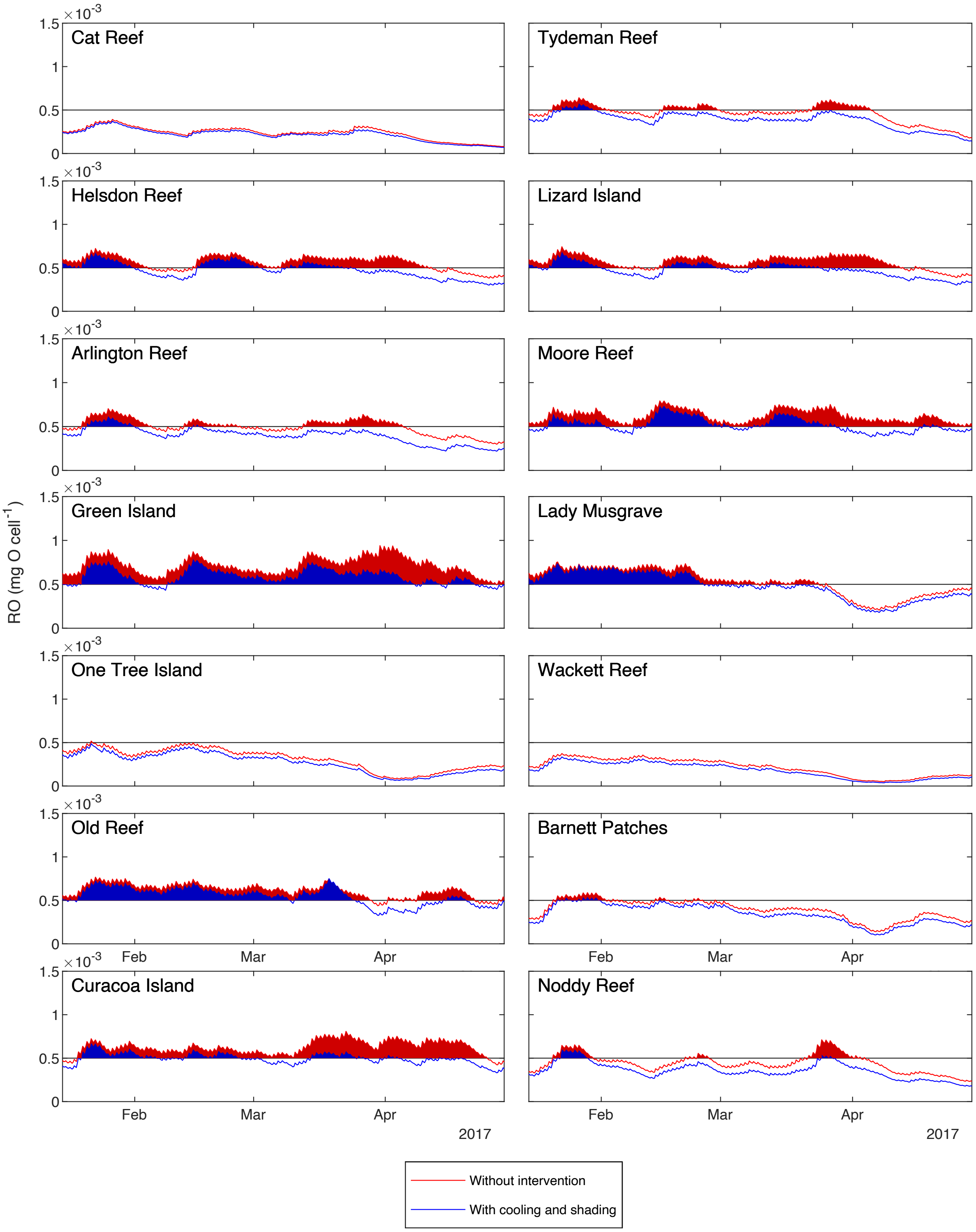


Figure 29: Reactive oxygen species concentration/cell at a representative location on RECOM simulated reefs for scenario 16/17 SHELF A0.3. The plot is shaded when the value is above the bleaching threshold of 0.0005 mg O cell^{-1} as defined in Baird et al. (2018). Thus, red shaded area represents bleaching stress avoided by cooling and shading, and blue shading represents bleaching stress that was not avoided. Red + Blue shading shows original bleaching stress.

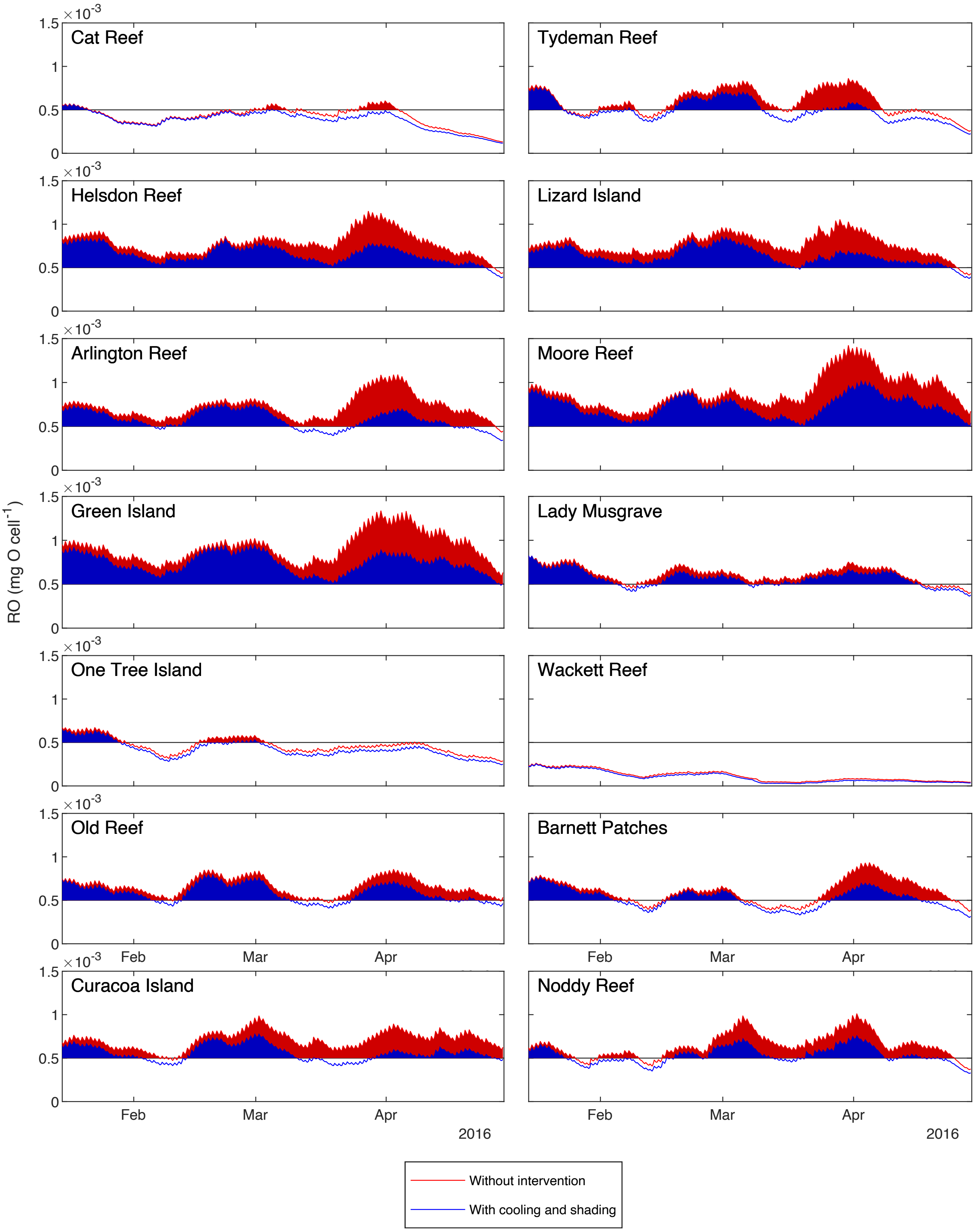


Figure 30: Reactive oxygen species concentration/cell at a representative location on RECOM simulated reefs for scenario 16/16 SHELF D0.0676. The plot is shaded when the value is above the bleaching threshold of 0.0005 mg O cell^{-1} as defined in Baird et al. (2018).

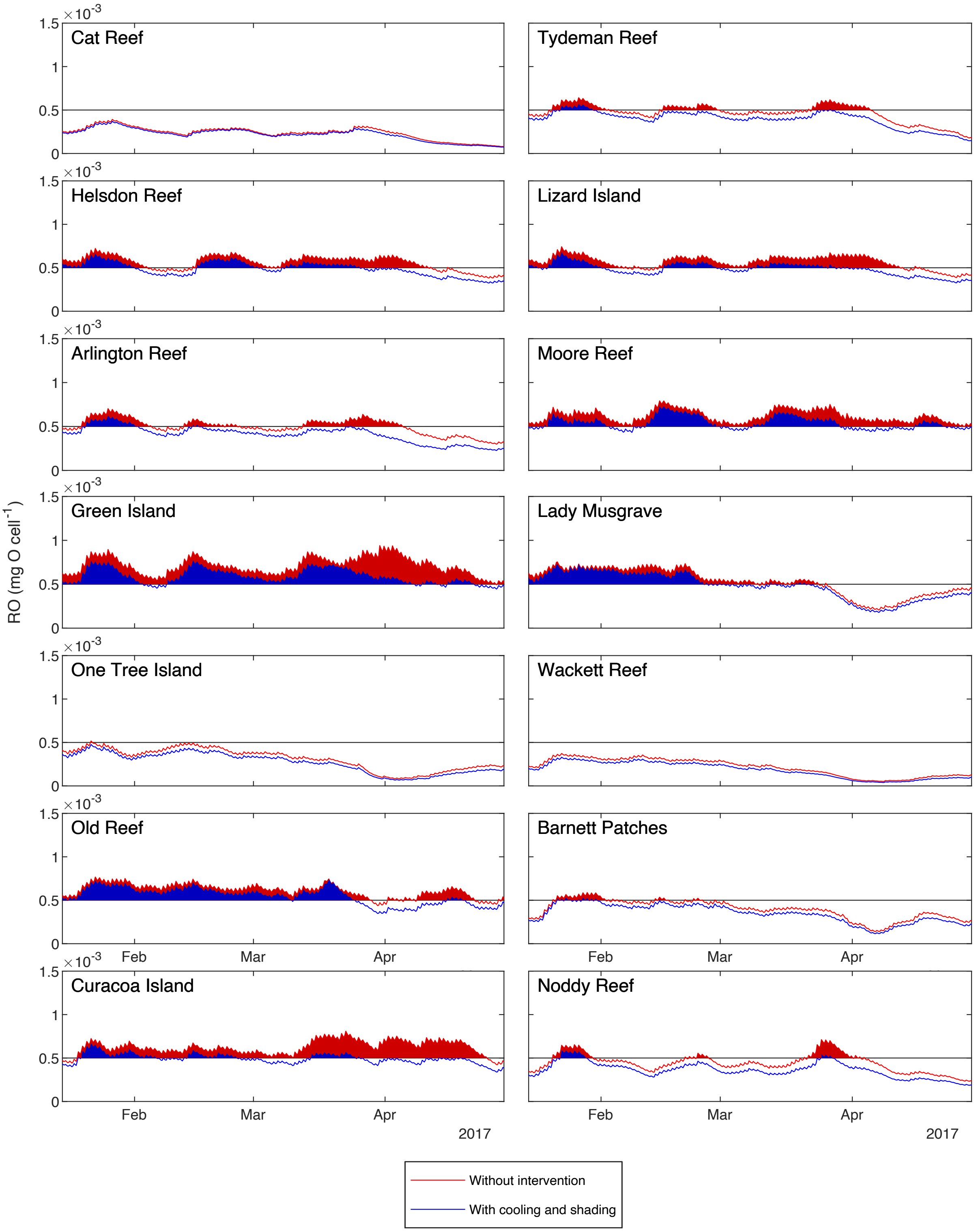


Figure 31: Reactive oxygen species concentration/cell at a representative location on RECOM simulated reefs for scenario 16/17 SHELF D0.0676. The plot is shaded when the value is above the bleaching threshold of 0.0005 mg O cell^{-1} as defined in Baird et al. (2018).

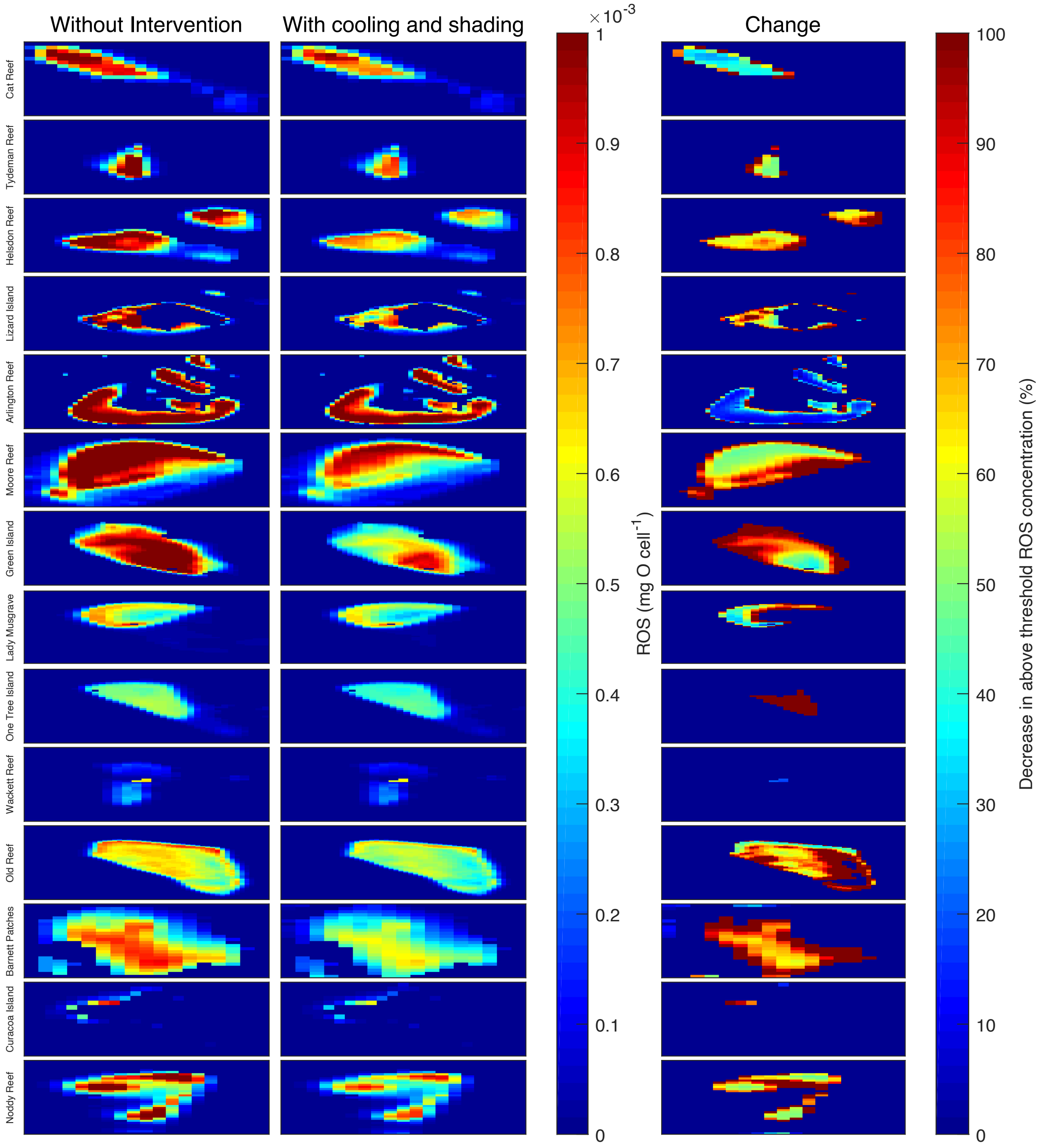


Figure 32: Spatial distributions of peak ROS (1 April 2015) for RECOM reefs with and without cloud brightening for scenario 15/16 SHELF A0.3. Yellow and red indicate bleaching stress (> 0.0005 mg O cell^{-1}). The panel on the right indicates the proportion of bleaching stress removed, dark red is 100 percent, dark blue areas did not have any stress in the base case, other colours are proportion of stress removed.

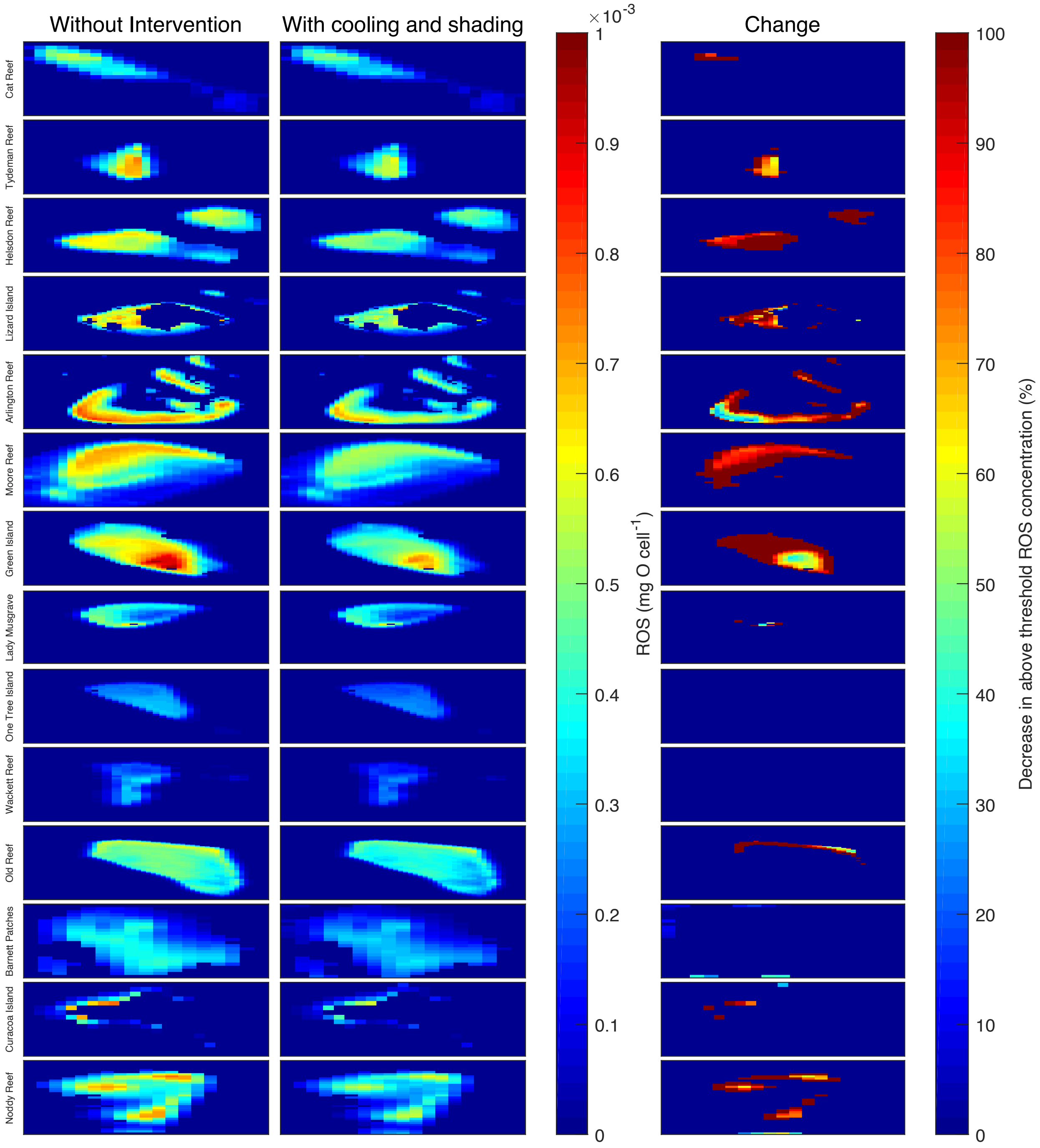


Figure 33: Spatial distributions of peak ROS (1 April 2015) for RECOM reefs with and without cloud brightening for scenario 16/17 SHELF A0.3. Yellow and red indicate bleaching stress (> 0.0005 mg O cell^{-1}). The panel on the right indicates the proportion of bleaching stress removed, dark red is 100 percent, dark blue areas did not have any stress in the base case, other colours are proportion of stress removed.

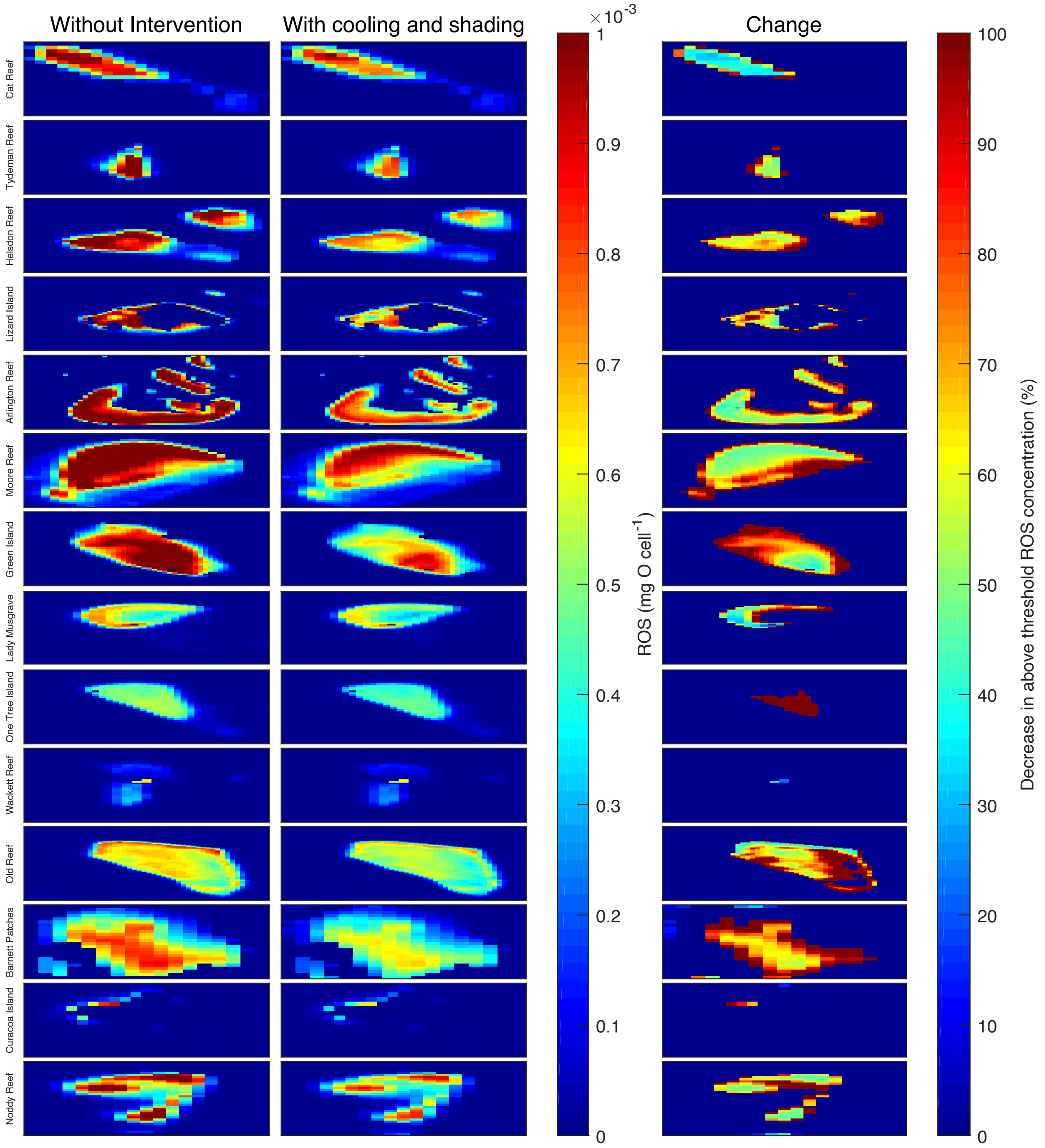


Figure 34: Spatial distributions of ROS on 24 March 2017 for RECOM reefs with and without cloud brightening for scenario 15/16 SHELF D0.0676. Yellow and red indicate bleaching stress (> 0.0005 mg O cell^{-1}). The panel on the right indicates the proportion of bleaching stress removed, dark red is 100 percent, dark blue areas did not have any stress in the base case, other colours are proportion of stress removed.

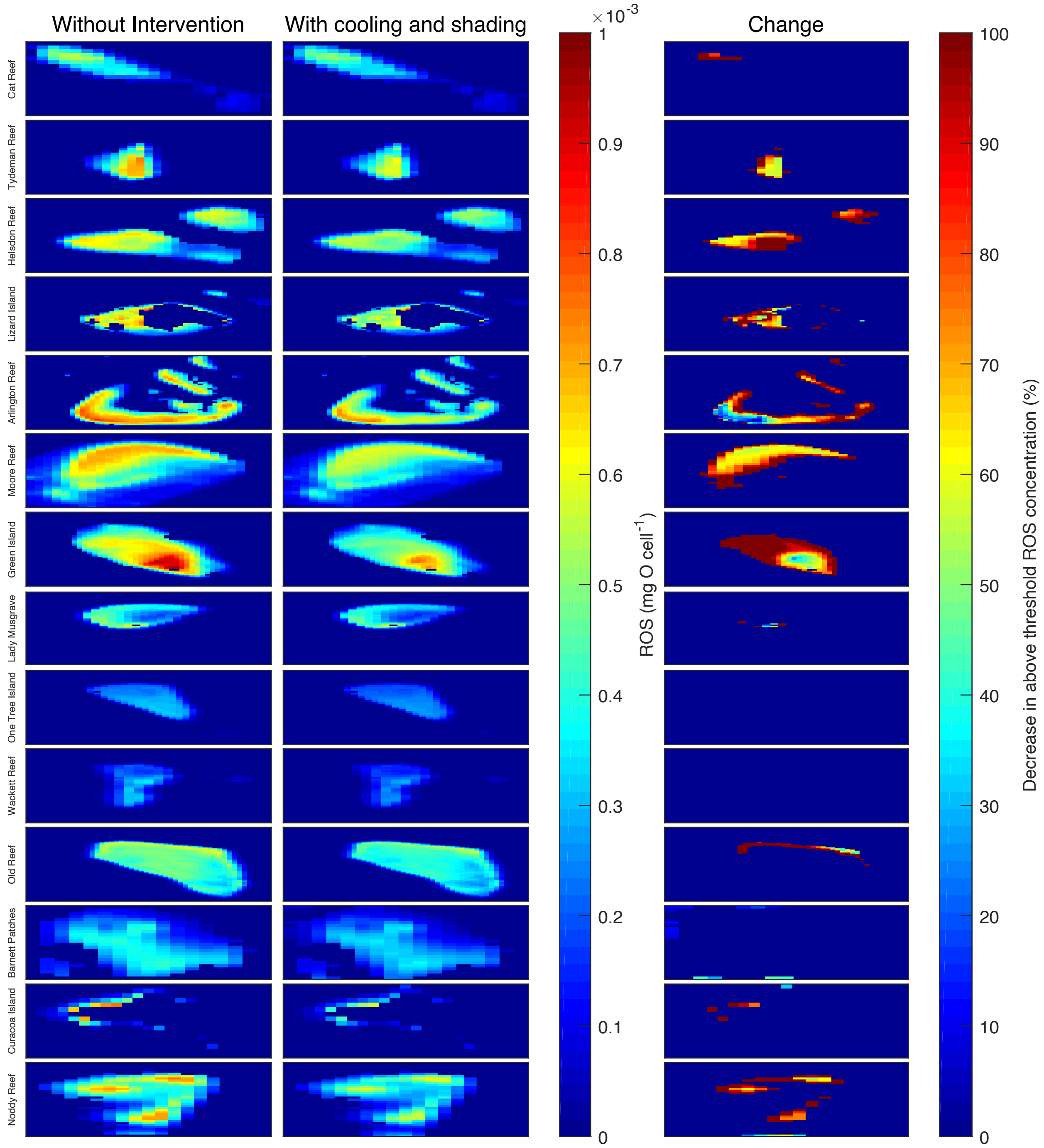


Figure 35: Spatial distributions of peak ROS on 24 March 2017 for RECOM reefs with and without cloud brightening for scenario 16/17 SHELF D0.0676. Yellow and red indicate bleaching stress (> 0.0005 mg O cell^{-1}). The panel on the right indicates the proportion of bleaching stress removed, dark red is 100 percent, dark blue areas did not have any stress in the base case, other colours are proportion of stress removed.

4.6 Summary of findings

We found there is sufficient response in the oceanic system to perturbations in solar forcing to make a significant positive impact in mitigating mass bleaching episodes on the Reef. A reduction of around 6.7 percent of incoming shortwave solar radiation over the latitudinal extent of the Reef and out to the 200m depth contours would achieve an approximate average 0.63°C cooling to sea surface temperatures mid-shelf off the Cairns region, and an average of about 0.45°C for the 14 individual reefs modelled in high resolution. Extending the target footprint some tens of kilometres beyond the edge of the shelf would increase the cooling, as would combining more than one cooling and shading technology.

Cooling showed no appreciable latitudinal gradient but a strong cross-shelf gradient with greater cooling closer to the coast. This suggests that in order to achieve similar cooling on the outer fringe reefs, the region of forcing should be extended beyond the edge of the continental shelf. Reducing the scale of application to the much smaller regional area simulated resulted in reducing the cooling efficacy by around 20 percent. However, this result likely depends on the specific region targeted due to local hydrodynamic conditions. Conversely, increasing the target area to the entire domain of the GBR4 model increased efficacy in cooling by around 40 percent but involves operating solar radiation management over a much larger region. The two years simulated indicated that between-year differences in low-level cloud cover could lead to a significantly altered forcing due to the indirect cloud albedo effects.

In general, the differences between direct (sky brightening) and indirect (cloud albedo response) scenarios were small when the domain and time averaged forcing was equivalent. This suggests that how the total forcing is achieved (whether, by direct, indirect, or in combination) is of minor importance to the bulk average cooling achieved. When considered in spatial detail for specific individual reefs, the outcome can change dramatically for some reefs. However, this seems to be confined to reefs near the forcing boundary.

Relative to the change in water temperature, the reduction in both temperature stress (i.e. degree heating weeks) and bleaching stress (as estimated by build-up of reactive oxygen species in the coral symbionts) showed higher heterogeneity. A causal factor is that there were large differences in how much stress reefs were subjected to without intervention (i.e. in the control simulation), both by location and between years. The location of the reef is an important factor with reefs near the boundary of applied forcing generally experiencing less stress reduction than those farther from the ocean boundary, especially if the reef is in the path of water flowing from outside to inside the region. Thus, the spatial heterogeneity can be explained conceptually as largely a function of the residence time of the surface waters within the footprint of intervention. The between year variation is related to both the effectiveness of intervention and the underlying conditions, i.e. the profile of stress corals were subjected to in that year under the control.

Generally, an average reduction in incoming solar shortwave radiation of around 6.7 percent (relative to clear sky) applied from shore to the shelf break, resulted in an average reduction in bleaching stress of ~50 percent in 2015/2016 and ~65 percent in 2016/2017, although these results are based on a small sample size of 14 reefs with considerable variation between reefs (as discussed above).

The modelling indicates there will be a limit to the amount of net forcing which can be achieved from the cloud brightening indirect effects, and this will vary from year to year, depending on the quantity and consistency of suitable and susceptible low-cloud cover. However, the limit to direct albedo forcing does not suffer the same constraint and is likely to be set by logistical, cost, social, or environmental constraints. The amount of radiative forcing (direct and indirect) applied could potentially be increased as the impacts of climate change worsen. The scenarios presented here are not intended to represent the maximum, median, or minimum feasible cooling. Currently these values are impossible to estimate with any certainty given the considerable unknowns in the engineering and technical aspects.

5. ATMOSPHERIC LAGRANGIAN PARTICLE TRACKING

5.1 Background and objectives

To inform the engineering system design of the ideal location of spraying stations to optimise the coverage of cloud brightening sea-salt aerosol over the target domain, modelling simulations were performed using HYSPLIT. These simulations were designed to provide insight into several questions:

- From which direction and with what consistency are the prevailing winds over the Great Barrier Reef during summer?
- From where does the boundary layer air over the Reef originate during summer, and does it pass over land within the preceding few days of arriving at the Reef?
- What is the typical fate of the air after it passes over the Reef?

5.2 HYSPLIT model description

We used the model HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) version 4 to simulate atmospheric particle advection over the Reef. HYSPLIT is a modular program able to compute trajectories of particles by complex dispersion mechanisms developed by the National Oceanic and Atmospheric Administration, USA (https://ready.arl.noaa.gov/HYSPLIT.php). As input, the model requires meteorological formatted files. We used daily files of the NCEP Global Forecast System (GFS0p25 files) from March 2016 to June 2018 (737 files). Each file is gridded in latitude-longitude with a quarter-degree spatial resolution and three-hour temporal resolution (http://www.ready.noaa.gov/archives.php).

5.3 Simulations

We performed two experiments using 29 points located by an even grid of 1° x 1° over the Great Barrier Reef (Figure 36), at an altitude of 10m. The particles were then tracked backwards in time to estimate the direction of airflow over the Reef to inform potential siting for atmospheric intervention stations, and backwards for days to trace the recent history and source of the air over the Reef.

The two experiments consisted of:

1. Backward tracking the particles for six hours, from 02:00 UTC (12:00 Qld time). The purpose was to inform consideration of potential placement of atmospheric intervention stations so that six hours of wind advection would locate the spray evenly over the Reef.

2. Backward tracking for source airmass. A backward simulation for five days from 20:00 UTC (06:00 Qld time).

Figure 36: The 29 locations used in the tracking experiments with HYSPLIT4.

5.4 Results and summary of findings

The backward trajectories of the particles show air movement in a general north-west trend (towards land, consistent with south-easterly winds). On average, particles advect from one to two degrees (~100-200km) in 12 hours with a maximum ~four degrees (~400km). The location of the air six hours prior to reaching the reef is between one and three degrees of distance from the source. Red areas in Figure 38 are areas from where the majority of particles reach the Great Barrier Reef. Therefore, these areas represent the ideal location for releasing the particles in order that they arrive over the Reef at 12:00 (Qld time).

The backward tracking of five days shows that particles come predominately from remote ocean areas (which generally have low concentrations of aerosols). This result is encouraging because the lower the natural abundance of aerosols, the more sensitive cloud albedo to cloud brightening (Rosenfeld et al. 2019). It should be noted however that the wind input for backward tracking in these simulations was from a relatively coarse global model. Work conducted during September and October 2016 indicated a significant influence of continental airmass over the Reef (pers. comm. Z. Ristoviski). Although representing only a single sampling well outside of summer bleaching season, these unreported results suggest that future work should repeat these simulations using higher resolution wind data, construct a climatology of summertime wind patterns, and compare simulations with measured survey data. This work is planned to occur during the RRAP R&D Program.

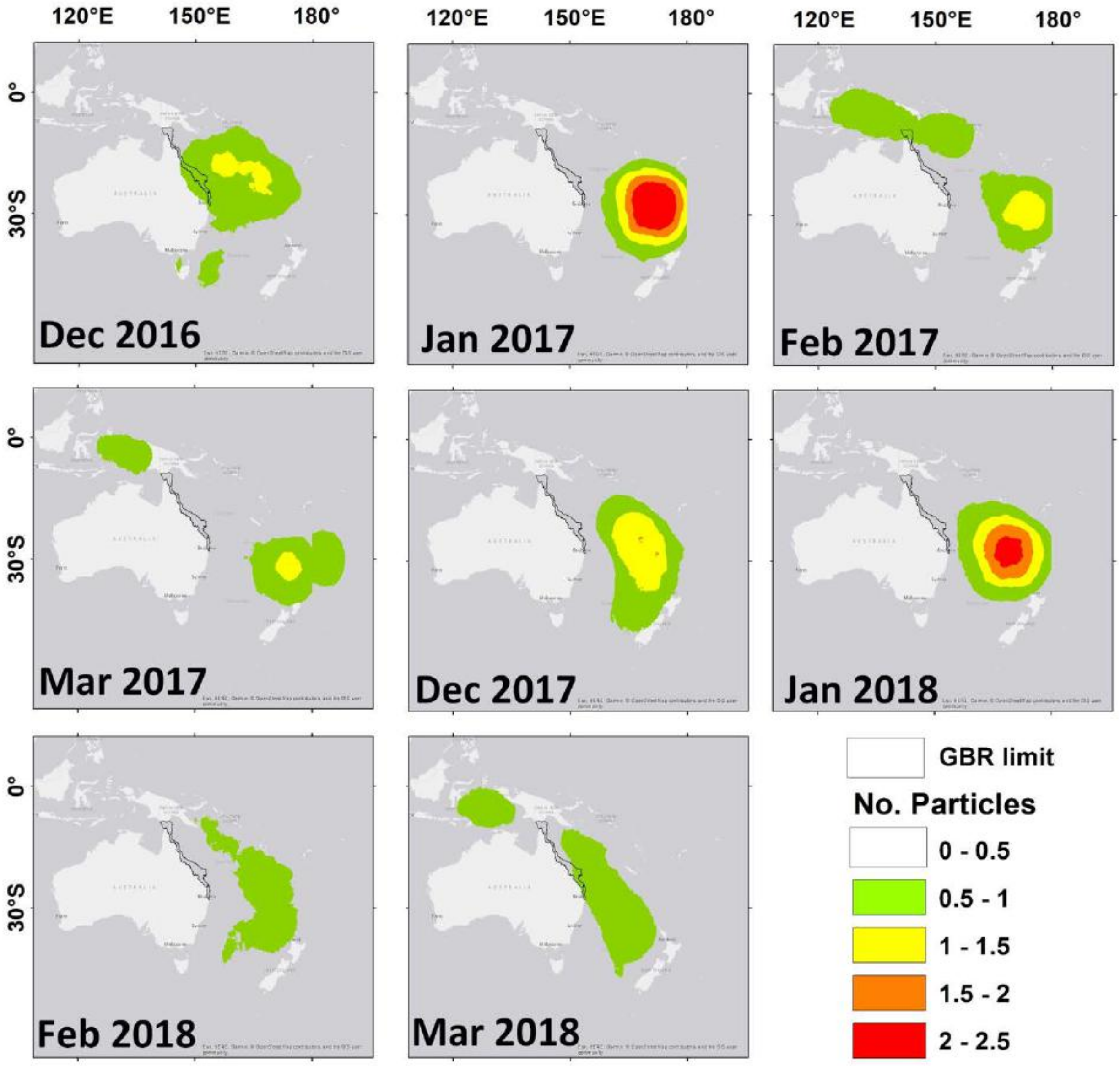


Figure 37: Five days backward tracking of the airmass over the Great Barrier Reef. The experiment was repeated for each day in the month and the results plotted as relative density of source location.

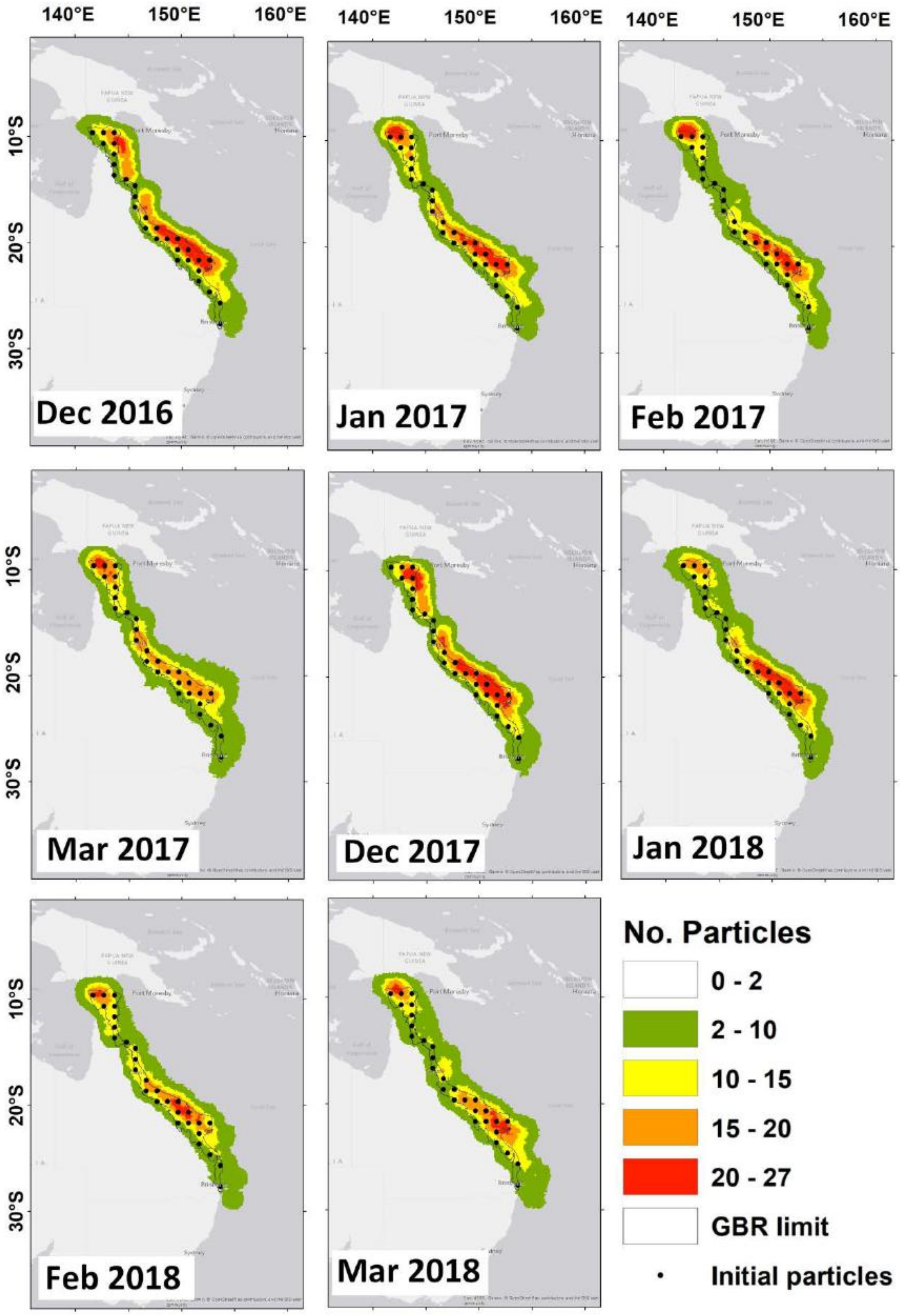


Figure 38: Density maps for the source of particles tracked backward for six hours from midday.

6. ATMOSPHERIC MODELLING

In this section we limit ourselves to providing an overview of the atmospheric modelling and interpretation of the results as they relate to the ocean modelling, atmospheric particle tracking, and implications for the feasibility of cloud brightening as a RRAP intervention. The full technical description of the atmospheric modelling is provided in Appendix A.

6.1 Background and objectives

A critical unknown in estimating the efficacy of cloud brightening is the magnitude of the sea-salt aerosol indirect effects on clouds. While the forcing of direct effects can be estimated using well established optical physics, the indirect effects on clouds involve complicated and, as yet, not fully understood meteorological, chemical, physical and microphysical interactions. Theoretical consideration and numerical modelling studies of marine cloud brightening have so far concentrated exclusively on low-level marine stratocumulus clouds. These types of stable boundary layer cloud were suggested as the most suitable target for cloud brightening by the original proponent of the technique (Latham 1990). Satellite observation of albedo enhancement in these relatively homogenous cloud decks, resulting from anthropogenic aerosols emitted in the exhausts of large ocean-going cargo vessels, provides compelling evidence of the aerosol-cloud albedo mechanism which underpins the concept of intentional marine cloud brightening (e.g. Wood and Ackerman (2013). Previous studies have focused on marine stratocumulus clouds as, globally, these provide the ideal candidates for achieving the maximum radiative forcing change (Alterskjær et al. 2012; Rosenfeld et al. 2019). Due to their homogeneity they are also particularly suitable for conducting field experiments (Wood and Ackerman 2013). However, the microphysics of other types of low-level marine clouds can also be sensitive to aerosol-cloud interactions, and therefore potentially susceptible to enhancement of net albedo through the addition of further highly effective cloud condensation nuclei (CCN) as originally suggested by Latham (1990).

The primary necessary conditions are a low background concentration of CCN and that the clouds are low boundary layer clouds, such that they exert a net cooling radiative impact, and can entrain additional CCN which have been introduced to the atmospheric boundary layer. The predominate winds during the summer bleaching period blow from the south-east, bringing air from the Tasman Sea over the subtropical south Pacific Ocean onto the Reef, while the far northern region is occasionally supplied with air sourced from the Indonesian archipelago via the Coral Sea (see Section 5). The subtropical south Pacific Ocean and Coral Sea regions have some of the lowest natural CCN concentrations in the world (Vallina et al. 2007), indicating a high likelihood of low-level cloud susceptibility to additional CCN. Several studies support this assertion, Alterskjær et al. (2012) performed a study using satellite-derived data and a global earth system model to examine the susceptibility to cloud brightening. Unsurprisingly they found the most susceptible areas to be the stratocumulus regions off the west coast of the major continents along with large regions over the Pacific and Indian Oceans, the region of the Reef showed good susceptibility (Alterskjær et al., 2012, Figure 1). Further, the modelling results showed the northern region of the Reef to be in the highest band of radiative forcing reduction, and the remainder in the second highest band (Alterskjær et al., 2012, Figure 4a). A recent study by Rosenfeld et al. (2019) challenged the paradigm by showing the cloud cover effect was much more susceptible to aerosol interactions than previously believed (Sato and Suzuki 2019). The study showed the cloudiness susceptibility of low-level cumulous clouds (such as those which characterise the summer cloud conditions over the Reef) is roughly half of the most susceptible marine stratocumulus clouds (Rosenfeld et al. 2019). The empirical relationships derived suggest an aerosol indirect radiative forcing of around -10 to -100 W m^{-2} might be possible for these types of clouds, depending on cloud thickness and initial droplet concentration (Rosenfeld et al., 2019, Figure 4l).

Representing cloud microphysical processes explicitly, with sufficient detail in model simulations, is computationally very expensive even with current generation high-performance computing. For a given amount of computational resources, trade-off must be made between the high resolution required to fully resolve these processes and a sufficiently large simulation domain in space and time. With the resources available to our group during the RRAP Concept Feasibility Study, including at the Australian National Computing Infrastructure, and local university-owned high performance Linux clusters, atmospheric models fully resolving cloud microphysical processes would be limited to very small spatial areas (kms x kms), and very short runtimes (days). Models running over larger regions or longer periods require that cloud microphysical processes not be fully resolved. To balance the need to examine multiple exploratory scenarios over an adequately large area and sufficient time period, with the desire to adequately represent cloud microphysics and meteorology, the model was run in a cloud-enabling rather than cloud-resolving resolution for this preliminary study. This severely limited the accuracy of the simulations mainly with respect to the cloud coverage and aerosol effects on it (i.e. the second indirect aerosol effects). Similarly, to reduce computing resources and time to a manageable load, we limited the region to a section of the northern Reef for 10 days representative of the most common synoptic conditions which occur during summer.

The aim was to test the properties of low-level clouds forming over the Reef during typical austral summertime synoptic conditions for sensitivity to additional sea-salt aerosol fluxes. Further we sought to ascertain the envelope of cloud microphysical response, and to inform some simple engineering parameters to aid in the preliminary engineering assessment of the technology, process rates, and required distribution of spraying stations which might be required for such an undertaking to provide input to the RRAP cost benefit analysis (T9: Cost Benefit Analysis).

6.2 Brief model description

The Weather Research and Forecasting model (WRF), is a popular regional-scale atmospheric transport model widely used for atmospheric research as well as operational forecasting applications. WRF-Chem is an online coupled model so that meteorological, chemical and aerosol fields are integrated at the same time. For this study, version 3.9.1 of WRF-Chem was used. The domain for the atmospheric modelling study is shown in Figure 39.

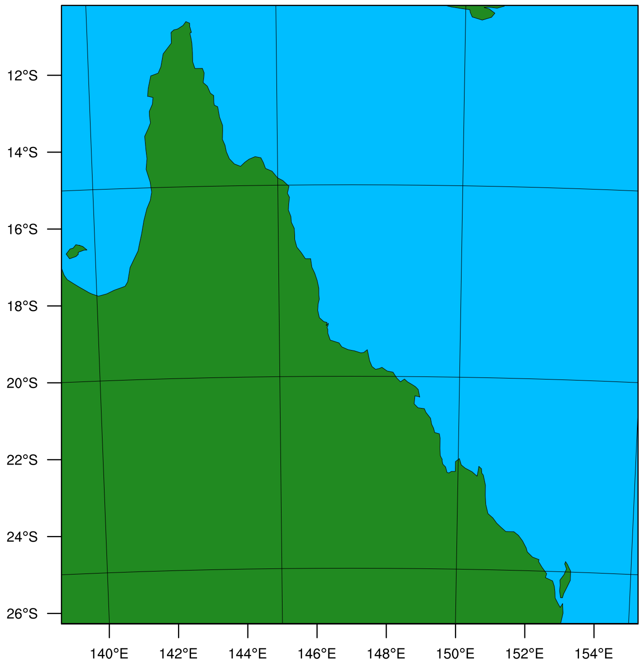


Figure 39: WRF Great Barrier Reef domain, the grid consists of 450 x 450 cells at a horizontal resolution of 4km.

The model boundaries are forced using the Bureau of Meteorology ACCESS-R atmospheric model as for the ocean modelling described above. For the chemistry scheme, the model was run with the Carbon Bond Mechanism (CBMZ) coupled to the Model for Simulating Aerosol Interactions and Chemistry (MOSAIC) aerosol scheme. MOSAIC is the most widely used and most actively developed aerosol module in WRF-Chem. MOSAIC predicts mass of aerosol components such as sulphate, nitrate, ammonium, sea salt, organic carbon, black carbon and dust. MOSAIC is coupled with atmospheric radiation (direct effects) and cloud microphysics (indirect effects).

We used the NOAH land surface model (Chen and Dudhia 2001), the Morrison Double Moment microphysics parameterisation scheme (Morrison et al. 2009), which carries both the number and mass loadings of the hydrometeors, and the Rapid Radiative Transfer radiation scheme (Mlawer et al. 1997). We chose the YSU Planetary Boundary Layer scheme (Hong et al. 2006) because it has been observed to simulate stronger vertical mixing especially in unstable conditions (e.g. (Xie et al. 2012)

For a full description of the WRF model setup and validation against available measured data please see the detailed atmospheric modelling report, Appendix A.

6.3 Scenarios

The goal of this preliminary atmospheric modelling was to test the hypothesis that the albedo of low-level clouds over the Great Barrier Reef during the prevailing synoptic conditions can be increased by the provision of additional sea-salt aerosols. As sea-salt aerosols generated from breaking waves at the ocean surface are a primary natural source, the WRF model includes a scheme where these are generated as a function of wind speed.

In our perturbation scenarios, an additional even flux of sea-salt aerosols was applied over the ocean. The additional sea-salt aerosol flux was imposed in aerosol bin 3 (56-312 nm diameter) of 0.025, 0.05, 0.1, 0.2, 0.3, 0.4 and 0.5 μg m^{-2} s^{-1}.

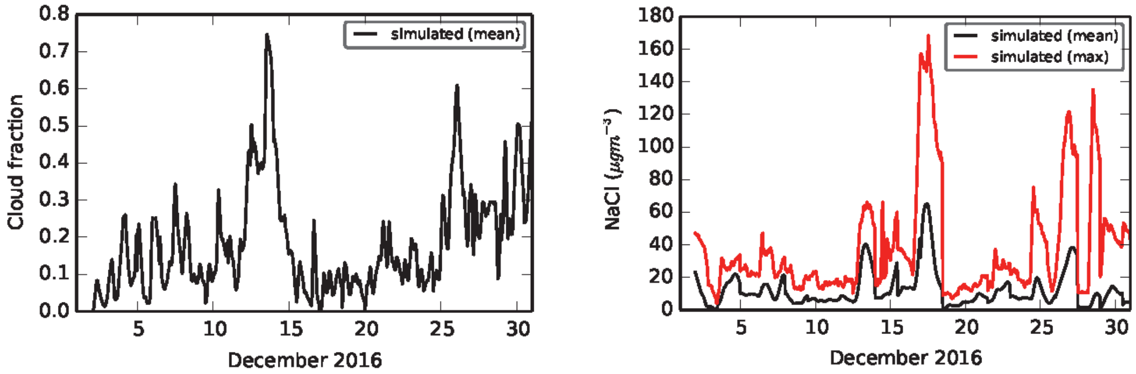
Further scenarios were carried out to examine the impact of varying the sea-salt flux in sizes other than 200nm. In these scenarios the largest flux of 0.5 μg m^{-2} s^{-1} was applied to each size bin individually.

To inform the engineering requirements of cloud brightening, scenarios were also conducted where instead of an increased uniform flux applied over the ocean, the source of the additional sea-salt flux was isolated to disparate grid cells, more representative of a network of individual spraying stations.

6.4 Brief summary of results and discussion

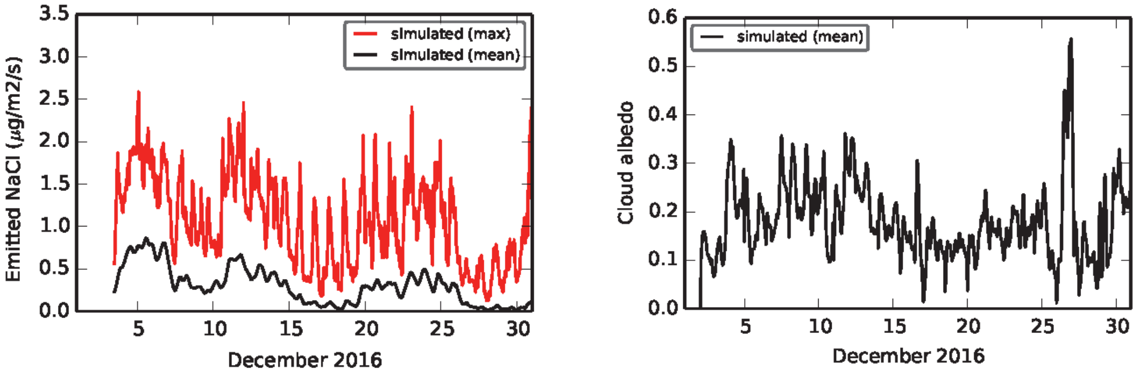
For the full results and technical discussion, the reader is referred to the report provided in Appendix A. What follows in this section is a summary of the results targeted to a technical but non-atmospheric specialist audience, and discussion of the results most relevant to cloud brightening as an intervention on the Reef.

Figure 40 shows cloud properties for the base case run which extends throughout December 2016. The cloud brightening sensitivity scenarios were run over the first 10 days (1–10 December 2016), a period dominated by low cloud (Figure 40f). Average cloud albedo is relatively low throughout the period, at values ranging from 0.1 to 0.3 except for a spike to about 0.55 on the 27 December 2016. During the first 10 days, the cloud is dominated by low boundary layer associated cloud which preliminary investigation has identified as potentially suitable for cloud brightening (and which was assumed to respond to cloud brightening in the ocean modelling described above). During this first 10-day period however, there are two periods when cloud top height increases to about 8km (8 and 10 December). On these days, cloud brightening is unlikely to be effective in increasing cloud albedo, and this type of cloud is assumed to be unchanged by cloud brightening in the ocean modelling. The control run cloud droplet number is high compared with median values for this region estimated from satellite data (i.e. Rosenfeld et al., 2019), we believe this is due to the low temporal and spatial resolution in the global datasets used to provide model boundary conditions for aerosol and atmospheric chemistry parameters. The model may also be too sensitive to wind-generated sea spray. The impact of overestimated background cloud droplet concentrations is a lower albedo sensitivity to additional CCN, and therefore a conservative result in the current study.



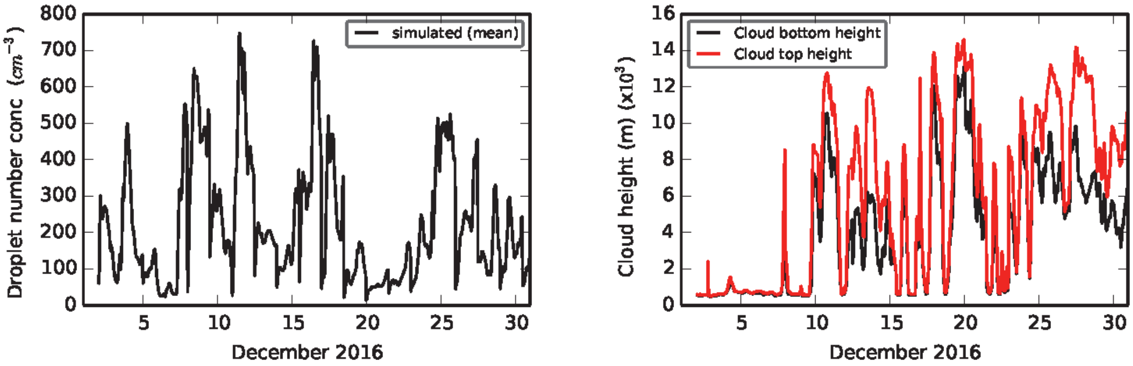
(a) Cloud fraction

(b) NaCl concentration



(c) NaCl emissions

(d) Cloud albedo



(e) Droplet number concentration

(e) Cloud bottom and top heights

Figure 40: Timeseries of simulated domain averaged (excluding land) cloud fraction, NaCl (sodium chloride) concentration, NaCl emissions, cloud albedo, droplet number concentration and cloud bottom and top heights for the base case run, December 2016.

The domain-averaged control simulation sea-salt flux varied from around 0.07 to 0.4 µg m^{-2} s^{-1} (for all size bins) over the 10 days of simulated scenario experiments (Figure 41). Thus, the maximum additional cloud brightening salt mass flux of 0.5 µg m^{-2} s^{-1} represents an increase of around double the maximum modelled natural flux which occurred over this period. The flux of 0.2 µg m^{-2} s^{-1} which was found to deliver 90 percent of the benefit is an increase of 50 percent to the maximum natural flux over the 10 days.

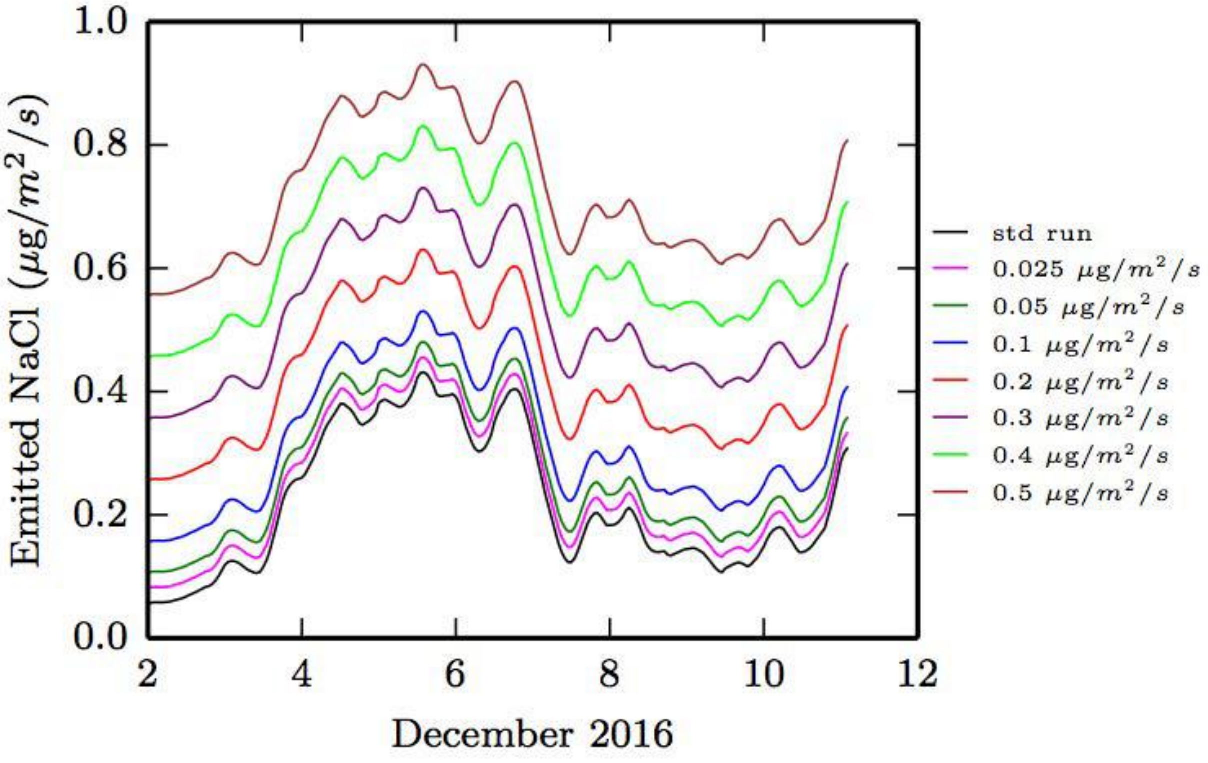


Figure 41: Timeseries of domain averaged sea-salt fluxes for the sensitivity runs during December 2016.

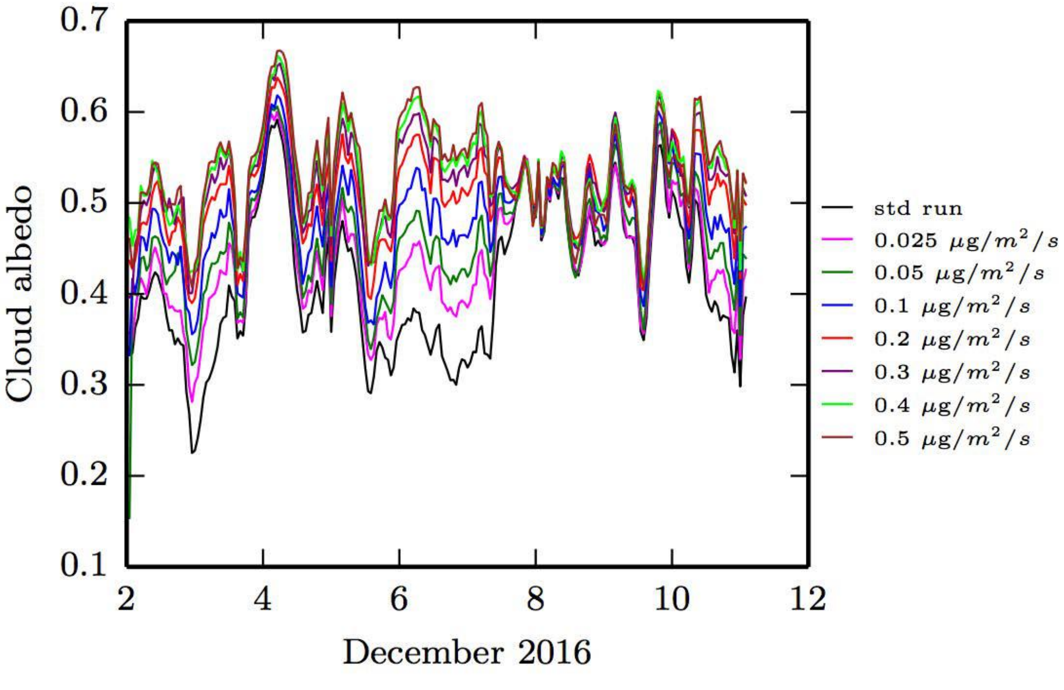


Figure 42: Comparison between domain averaged albedo for base case run and sensitivity runs.

Figure 42 shows the domain averaged albedo for the base case and scenario runs. The injection of additional sea-salt aerosols of 56-312nm increases the cloud albedo for the period of the run where low cloud is dominant (1-8 December, and 11 December). The magnitude of albedo change is around 0.1, ranging from 0.01–0.3. There is a trend of higher albedo increase when the natural albedo is lower. The mean albedo response begins to become saturated at the 0.2 μg m^{-2} s^{-1} scenario. For engineering purposes, this indicates a system producing an additional flux of 0.2 μg m^{-2} s^{-1} is sufficient to obtain most of the cloud droplet concentration and albedo response during this period. This is a relatively modest flux increase of 30 percent of the maximum domain averaged naturally occurring flux during the period (Figure 43).

The maximum domain and temporally averaged mean albedo change over the 10 days was 0.12 (Appendix A, Table 4) resulting from a prescribed additional sea-salt flux of 0.04 μg m^{-2} s^{-1} to bin 3 (156-312nm diameter) of the aerosol scheme. However, in scenarios where the same mass flux was applied individually to each size class, bin 2 (78-156nm) and bin 4 (312-625nm) gave mean albedo increases of 0.01 and 0.05 respectively. No scenarios were conducted with the flux increased in multiple aerosol size bins, however the implication is that the albedo change could possibly be increased further if this was implemented. It is also important to note the period included two days of high cloud (8 and 10 December, Figure 40). These days are included in the averaged results although, as would be expected, they did not experience significant albedo increase (Figure 42). The implication is that the albedo results given in Appendix A should be scaled up by about 20 percent if one wishes to consider the mean change to low clouds only, which is the most relevant statistic for marine cloud brightening. The conclusion is that over this very short period considered in the atmospheric modelling, the maximum mean albedo change for low cloud observed in our scenarios was 0.14 (maximum of 0.31) resulting from an imposed additional surface sea-salt flux of 0.05 μg m^{-2} s^{-1} in the diameter size range of 156-312nm (see also Appendix A, Table 6). The additional aerosol effects on cloud cover and liquid water path are not well addressed in these preliminary simulations and could add substantially to the cooling. This can be investigated in future work by satellite observations such as of Rosenfeld et al. (2019) and by high resolution model simulations with explicit microphysical processes.

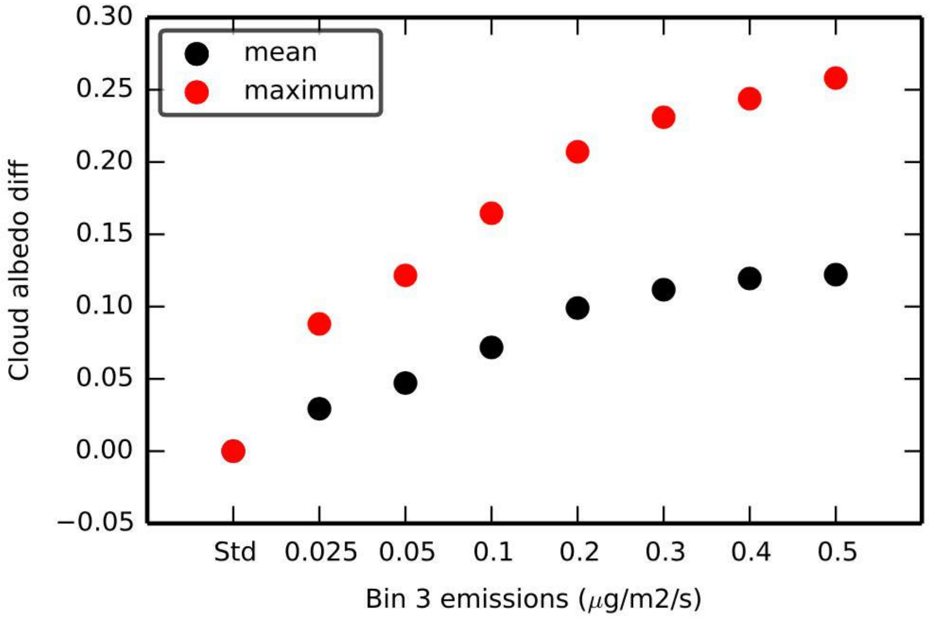


Figure 43: Cloud albedo difference from control for each of the sensitivity runs.

A series of experiments applying the same total sea-salt flux within the domain but to progressively fewer grid cells in the model showed no appreciable reduction in mean cloud albedo increase (Appendix A, Table 5). The sparsest placement of stations trialled was every fifth grid cell in the model, equating to a station spacing of 20km in both x and y directions (Appendix A, figure 23). This is the same spacing which was considered in preliminary conceptualisations of marine cloud brightening for the purposes of evaluating the potential engineering feasibility of marine cloud brightening in the RRAP concept feasibility study. Modelling results therefore indicate that such a spacing of stations is adequate to get the maximum available cloud brightening effect, providing they can be engineered to supply sufficient sea-salt fluxes, not an insignificant challenge (Salter et al. 2008; Cooper et al. 2013; Cooper et al. 2014).

6.5 Summary of findings

Atmospheric meteorological and cloud microphysical modelling of marine cloud brightening was conducted for 10 days of typical synoptic conditions in December 2016. During this period, low-level marine clouds were the dominant cloud type. The results provide evidence that low-level clouds occurring over the Reef during this period were sensitive to the first indirect effect of cloud brightening (the Twomey effect). This is significant because it is the first work we are aware of that demonstrates a significant albedo enhancement in clouds which are not marine stratocumulus, validating a key assumption that supports the theoretical basis of cloud brightening for the Reef. This finding is consistent with recently-published research: “Although aerosol effects on marine stratocumulus cloud cover are relatively well documented (13, 36, 37), aerosol effects on cumulus clouds have been more elusive… the susceptibility of cumulus properties to droplet number is similar to the susceptibility of marine stratocumulus, although somewhat weaker.” (Rosenfeld et al. 2019).

The domain and time averaged albedo increase of ~0.14 (for low-level cloud) is consistent with the assumptions used in the ocean modelling. Note that this component represents primarily the first indirect effect. Second indirect effects resulting from increased cloud lifetime, increased liquid water path, suppression of precipitation, and increased cloud cover along with the direct aerosol forcing effect, were not evaluated in the atmospheric modelling during this project. As such, the albedo change observed represents only a portion of that which could potentially be achieved from the imposed sea-salt fluxes simulated.

The time period, and resolution which was cloud permitting, rather than cloud resolving, were limited by the compromise between sufficient spatial domain, computational time, and resources available. This model setup was considered appropriate for this preliminary investigation, which sought to gain a sense of the potential for albedo increase over the Reef. Cloud albedo responded positively to scenarios of enhanced sea-salt flux imposed at the ocean surface. Maximum domain and time averaged cloud albedo increase was estimated as 0.14 for an imposed flux of 0.5 $\mu g\ m^{-2}\ s^{-1}$ of sea-salt nuclei in the size bin of 156 to 312nm. However, the response started to become saturated at lower fluxes around 0.2 $\mu g\ m^{-2}\ s^{-1}$. Experiments considering increased sea- salt flux of other size classes suggest that the albedo might be increased further if a broader size distribution of sea spray was generated. This result is in contrast to previous studies. Spacing spraying stations up to 20km apart (the furthest spacing considered) was found not to lessen the albedo change.

Combining the atmospheric and ocean modelling results allows consideration of the magnitude of potential forcing. If the cloud albedo increase observed in the atmospheric modelling was applied to all low-level cloud cover during summer, the average shortwave solar forcing would be approximately -12 W m^{-2} in 205/2016.

We emphasise, however, that this preliminary study was not intended to rigorously asses the magnitude of cloud albedo response for the purposes of assessing potential efficacy of cloud brightening. The model setup and calibration/validation were hampered by the lack of summertime aerosol concentration, size distribution, and composition data. This complete lack of data (we could find no measurements for the summer atmosphere over the Reef) required the downscaling of global model fields for key aerosol characteristics. Therefore, there was also no data for calibration and verification of aerosol or cloud microphysical process in the model. However, the model was assessed for skill in predicting the meteorology and cloud albedo against satellite observations. Collecting the required data to calibrate, validate, and asses model performance should be a key priority for future work to improve confidence in atmospheric modelling over the Great Barrier Reef.

The WRF modelling here is limited to the consideration of a single set of boundary layer, cloud microphysical, aerosol, and other parametrisation schemes. Future work should examine the sensitivity of these modelling results to choices made in parameterisation of the model, as well as consider a wider range of atmospheric and climatic conditions. Higher resolution (LES) modelling is required to better resolve the clouds and their response to increased sea-salt flux, including the evaluation of second indirect effects. Finally, in light of recent research, it is necessary to re-evaluate the common parameterisations used and their sensitivity to additional cloud condensation nuclei (Rosenfeld et al. 2019). The empirical methods developed by Rosenfeld et al. (2019) could also be employed specifically to the region over the Reef, and combined with atmospheric data collection as suggested above, would improve empirical estimates of the forcing which might be achieved by cloud brightening.

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APPENDIX A – TECHNICAL REPORT ON ATMOSPHERIC MODELLING

APPENDIX B – RRAP DOCUMENT MAP

Reef Restoration and Adaptation Program

- **RRAP Investment Case**
  - **R1 | Engagement & Regulatory Dimensions**
    - T1: Stakeholder, Traditional Owner & Community Engagement Assessment
    - T2: Regulatory Assessment Findings
  - **R2 | Intervention Summary**
    - T3: Intervention Technical Summary
    - T4: Current Practices
  - **R3 | Intervention Analysis & Recommendations**
    - T5: Future Deployment Scenarios & Costing
    - T6: Modelling Methods & Findings
    - T7: Decision Support Findings
    - *T8: Consolidated into other reports*
    - T9: Cost Benefit Analysis
    - T10: Benefit Streams
    - T11: Automated Aquaculture Production & Deployment
    - T12: Cool Water Injection
    - T13: Ultra Thin Surface Films
    - T14: Environmental Modelling of Large Scale Solar Radiation Management
  - **R4 | Research & Development Program**
  - **R5 | International Engagement & Partnering**
  - **R6 | Governance & Program Delivery**

KEY:

🟪 Investment and R&D Strategy

🟦 Summary of findings and key recommendations

🟥 Technical process and detailed findings

Reef Restoration and Adaptation Program

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Reef Restoration and **Adaptation Program**, a partnership:

Australian Government | Australian Institute of Marine Science | Australian Government Great Barrier Reef Marine Park Authority | Great Barrier Reef Foundation | CSIRO | QUT | James Cook University Australia | The University of Queensland Australia