T12: COOL WATER INJECTION

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

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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

The most straightforward means to reduce thermal-stress induced bleaching is to cool the water at the seabed above coral communities. The feasibility of reducing the seabed temperature through local interventions is considered first by analysing the feasibility of doing so on 20 reefs with differing physical environments using both simple current-based estimates and residence time metrics. We then concentrate on Lizard Island, the most promising candidate of the 20 reefs, and develop a high-resolution hydrodynamic model to investigate the effect of the injection of cool water at differing volumetric rates. Injecting 27°C at a rate of $5m^3s^{-1}$ at four sites cooled 97ha of the reef by 0.15°C or more. The energy costs alone of pumping $20m^3s^{-1}$ 3km from a nearby channel in order to cool 97ha of seabed surrounding Lizard Island by one-degree heating week (DHW) is approximately $1.6M per year. A more precise costing will require further expert engineering design of the pumping equipment and energy sources. As a result of less favourable hydrodynamic properties, cooling seabed temperatures on most reefs on the Great Barrier Reef would be more expensive per hectare than at Lizard Island.

This process shows that even for the most physically-favourably reefs, cool water injection is expensive, and that cool water injection cannot be scaled up to any meaningful fraction of the 3100 reefs of the Great Barrier Reef. Should value be seen in reducing thermal stress on one or a few individual reefs this report provides a means to identify the most promising sites.

3. INTRODUCTION, BACKGROUND AND OBJECTIVES

The temperature of the water surrounding any of the reefs on the Great Barrier Reef results from a balance of meteorological and oceanographic processes that can be well captured in numerical models. As an illustration of the precision of these models, the mean error in predicted temperature of the eReefs hydrodynamic model is less than 1°C (Herzfeld et al., 2016). Numerical models can also be used to represent interventions that will lead to changes in temperature, such as shading or cold water injection.

In this study, we are primarily concerned with local changes in temperature. A separate RRAP report considers the effect of regional scale solar radiation management on the temperature of the water over at regional scales **(T14—Environmental Modelling of Large-scale Solar Radiation Management, T3—Intervention Technical Summary).** In considering local interventions in this report, we assume that the water surrounding our intervention site the water has not been cooled. That is, the water flowing onto the chosen reef from deeper inter-reef areas is the same temperature as if no intervention existed. Thus, to cool water a specific site, we need to cool both the water that initially resides at that site, and any water that moves across the site from outside the area of influence of the intervention. Most reefs are exposed to significant tidally driven circulation, so cooling the water moving across the site becomes the primary challenge.

4. METHODS

4.1 Mapping feasibility of thermal stress reduction across the Great Barrier Reef

A suite of hydrodynamic models of the Great Barrier Reef over a range of scales have been set up in the eReefs and RRAP projects (for more information on the eReefs coupled physical/sediment/optical/biogeochemical models refer to eReefs.info).

The first step in assessing the feasibility of cool water injections was to find the type of reefs where the oceanographic conditions provide the greatest change in seabed temperature for a set cooling load. To quantify this, we have developed two metrics:

1. Site cooling load (SCL) that is useful for small scale intervention such as a patch reef,
2. Reef cooling load (RCL) that considers the cooling of the full depth of water above an entire reef.

The site cooling load (SCL, J $m^{-1}s^{-1}$ = W $m^{-2}m$) required to cool the water flowing past a site is given by:

$$SCL = C_p \rho \int_{bot}^{top} \Delta \mathrm{T}\ \mathrm{u}\ \mathrm{dz}$$

where ΔT is the difference between the present temperature and 1°C above the 15 January climatological mean (to align with the degree heating metric, Baird et al., 2018), *u* is the water velocity (m/s), C_p *is* the heat capacity of seawater (C_p = 4.186 x 10^3J°$C^{-1}kg^{-1}$), ρ is the density of seawater (ρ ~ 1000kg m^{-3}), z is vertical co-ordinate (m), and *top* and *bot* are the top and bottom depths in metres. This represents the per m^2 rate of cooling that needs to be applied to the flow upstream of the site to achieve the target temperature – i.e. the rate needed to be applied one metre upstream of the site (hence the unit W m^{-2} over a metre). If this cooling rate was applied over 1000 m upstream of the site, by for example a 1000m long shade cloth, then the area over that larger area would be site SCL / 1000.

Site cooling load quantifies to the energy need to be extracted from a full depth flow impacting on a site to meet the temperature requirement every instant. Implicit in this calculation is that there is no artificial cooling on the reef except on the flow directly upstream of the site in question. This is a reasonable assumption if the water being cooled is unlikely to be return to the site by the circulation. The smaller the area being cooled, the less likely flow will return to the site.

The reef cooling load (RCL, J m^{-2} s^{-1}) is given by:

$$RCL = C_p \rho \int \frac{\Delta T}{\tau} dz$$

where τ is the 'reef age'[d m^{-3}]. 'Reef age' is the time a parcel of water has spent above the reef (defined by seabed < 10m), subject to advection and diffusion processes.[1]

Reef cooling load quantifies the cooling load that would need to be applied evenly across the whole reef in order to meet the temperature requirement every instant. Note that reef cooling load is still spatially- and temporally- resolved. That is because to cool the water close to where it flows onto the reef using a constant cooling rate across the entire reef requires a large rate, while cooling the water at the downstream end requires a smaller reef-integrated rate.

Site cooling load and reef cooling load can be roughly equated for a box that is one metre thick in the flow direction. Under this condition, *V / A* is equal to the layer thickness *dz*, and u ~ 1 / τ. That is, it takes u seconds to fill a one metre deep box with flow at u m s^{-1}, and SCL ~ RCL. Reef cooling load is generally a few orders of magnitude less than Site cooling load, essentially because the cooling load is applied over a larger area.

For more information on the tracer 'reef age', see the Appendix of the RRAP **T6—Modelling Methods and Findings** that uses the same metric to quantify the time a surface film will be retained on a reef. In particular, this report shows the reef age of the same 20 reefs from which we chose Lizard Island as the best candidate site. Lizard Island was chosen because it had a relatively high reef age for a small reef area. Thus, Lizard Island is a site where injected cool water will stay in the vicinity of the injection site for a relatively longer period, increasing the effectiveness of the injection.

Sample analysis

The cool load metrics are temporally and spatially resolved. We configured high resolution hydrodynamic models for 20 reefs on the Great Barrier Reef, where the site and reef cooling loads were calculated. Based on these models, we selected Lizard island as the most promising candidate reef based on x, y and z.

These models allow a number of generic points to be made from the analysis at Lizard Island (Figure 1 a-f). First, the site cooling load is three orders of magnitude greater than the solar radiation flux (Figure 1c). The site cooling load represents the load of cooling required upstream of a site and depends strongly on the current speed. This illustrates the high energy per unit area of cooling required in the water above a small area of reef. Further, areas with high current speeds and deep water, during spring tides, are even more difficult to cool.

[1] Reef age, t, is defined by:

$$\frac{\partial \tau}{\partial t} + \boldsymbol{u} \cdot \nabla\tau = \nabla \cdot (\nabla \mathrm{K})\tau + \emptyset, \emptyset = 1 \text{ (above reef)}, \emptyset = 0 \text{ (open ocean)}$$

where Ñ $= \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial x}$ is the gradient operator, ***u*** is the velocity vector, *K* is the spatially and temporally-resolved diffusion coefficient, *V* is the volume of water in a model cell, *A* its area (thus V/A = layer thickness), and F is the source term is defined as 1 d d^{-1} above the reef and zero in the open ocean. We have defined the reef as areas with bottom depth less than 10m.

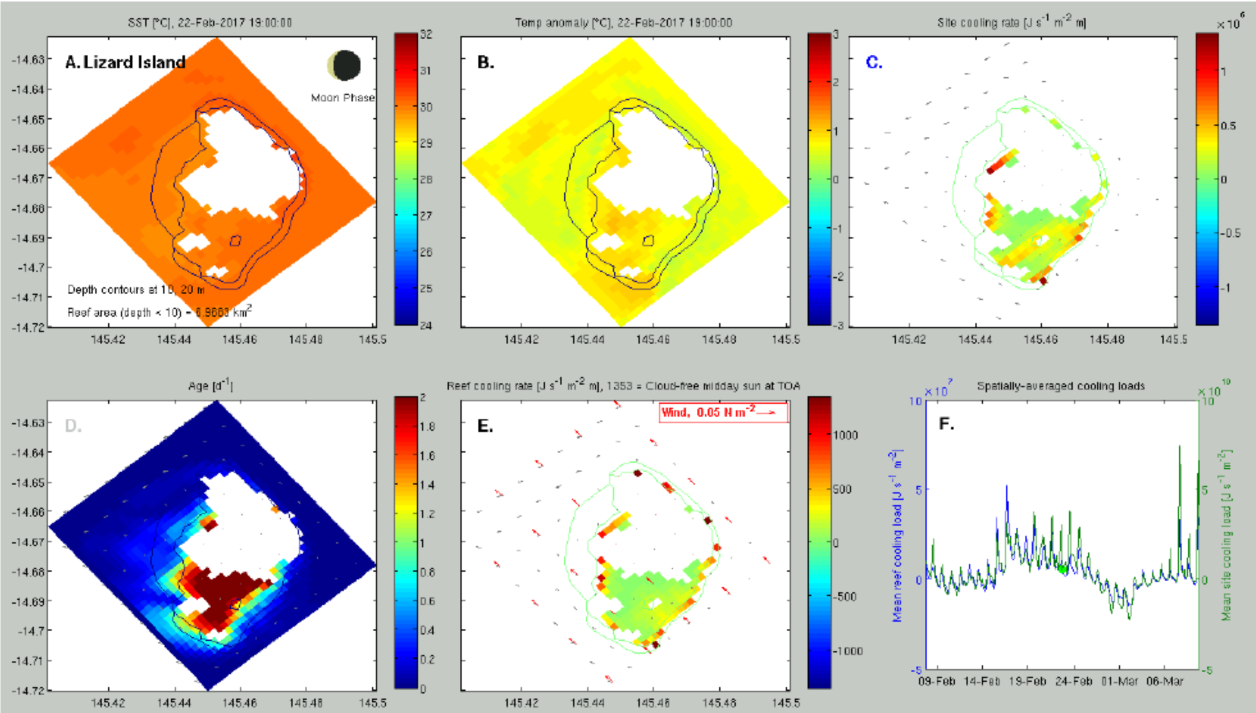

Figure 1: Cooling load metrics for Lizard Island in 2017, a) reef name, bathymetry (10 and 20m isobaths), reef area and the SST and phase of the moon of the time of the snapshot, given in local time in the panel title; b) temperature anomaly, $\Delta T = T - T_{15\ Jan} - 1°C$; c) site cooling load; d) Reef age, a spatially-resolved measure of the time water has been above the reef; e) Reef cooling load, with the colour bar scaled to 1353 J m^{-2} s^{-1}, the solar constant giving the mean solar forcing at a zenith of 0°, and at the top of the atmosphere (TOA); and f) a time-series of the spatially-integrated reef cooling load (blue) and site cooling load (green).For an animation see: https://research.csiro.au/ereefs/wp-content/uploads/sites/34/2019/02/Cool_Lizard_Island.gif.

The reef cooling loads are much more achievable (Figure 1E). The image for 22 February on Lizard Island shows that for much of the Lizard Island lagoon the cooling required per unit area is much less than the clear sky solar heat flux (that is the maximum energy from the sun in summer). The regions for which the reef cooling loads are smallest are the shallower regions with the greatest age (i.e. greatest residence time of water). It is important to note that this is for a cooling load applied across the whole reef (such as might be possible with a cloud brightening or misting intervention) as opposed to a more local cooling load (from cool water for example). Even so, the reef cooling loads become large at the edges of the reef. Here cooling water on the reef has less impact, because water has moved from off the reef recently, so the reef cooling load on the edges of the reef approaches the site cooling load.

Similar analyses have been undertaken for a large number off reefs (for example Arlington, Lizard and Warton Reefs. See: https://research.csiro.au/ereefs/models/models-about/recom/reef-restoration-and-adaptation-program-rrap-cooling-load-metrics/). The results across reefs show that Lizard Island is the most promising candidate reef. Given this, we undertook a more detailed study which modelled the process of injecting cold water onto the reef.

4.2 Simulating cold water injection onto Lizard Island

Lizard Island is an offshore reef near the continental shelf break, north of Cape Tribulation. It was chosen for further investigations because of the long residence time over coral communities, with a nearby ~40m deep channel that could provide a source of cool water (Figure 2).

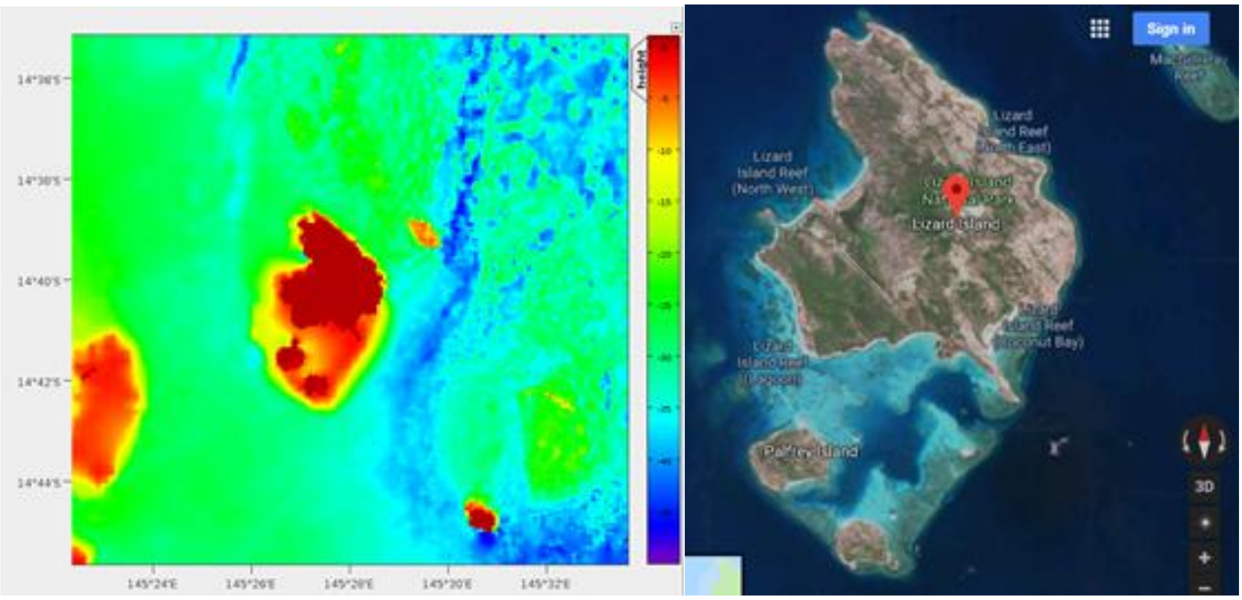

Figure 2: (left) Bathymetry of the water surrounding Lizard Island (which appears as dark red in the centre of the figure) and (right) a true colour satellite image, with high coral cover areas appearing as underwater brown features. The 40m deep channel lies approximately 3km (at 14°S, 1.67 minutes of longitude) to the east of the lagoon.

Methods

In order to model hydrodynamic processes at close to the scale of a plume from an inlet pipe, the Delft3D Flexible Mesh (Delft3D FM) modelling suite was used to nest a finer resolution model of Lizard Island into the one kilometre eReefs hydrodynamic model simulation (GBR1_H2p0). Delft3D FM is an open source unstructured grid model maintained by Deltares (http://oss.deltares.nl/web/delft3dfm) that solves the 2D and 3D shallow water equations using finite volume schemes (Martyr-Koller et al., 2017), representing a major redevelopment of the widely used Delft3D (structured grid) model (Lesser et al., 2004).

The model domain covered the extent of the RECOM Lizard Island configuration (~7 x 8km) used above and was mapped onto a grid composed of triangular cells, with a horizontal resolution varying between 40-50m, and four sigma layers in the vertical (Figure 4). High resolution (30m) bathymetry compiled from LiDAR, multibeam and satellite data (Geoscience Australia, 2017) was interpolated to the grid. Boundary conditions were defined using eReefs GBR1_H2p0 output, and tidal constituents obtained from the TPXO7.2 global tide solution (Egbert and Erofeeva, 2002). The model ran over a full spring-neap cycle in January 2017, during which time meteorological conditions (solar radiation, humidity, air temperature, cloud coverage and wind) were prescribed using the same BoM ACCESS-R products used by the one kilometre eReefs model.

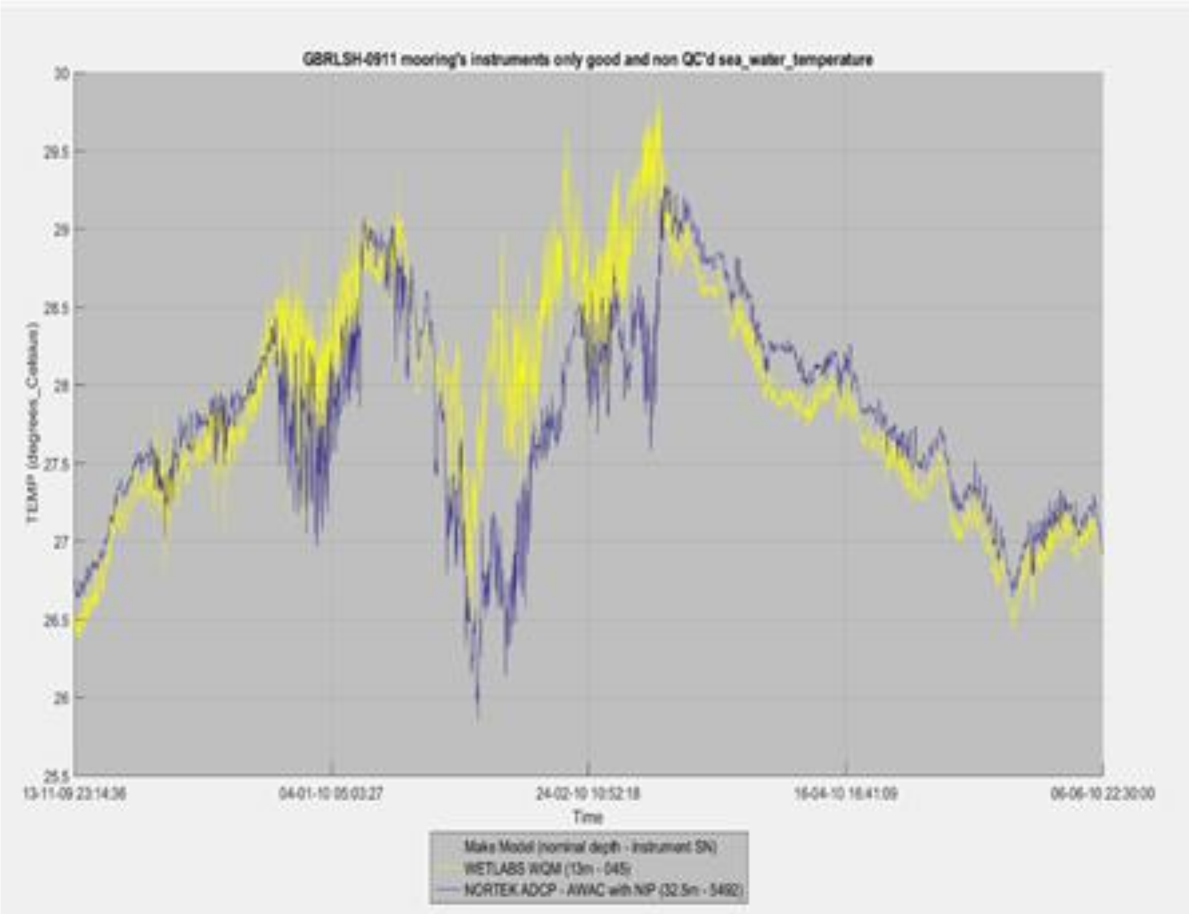

Figure 3: Observations of temperature a 30 m depth in the vicinity of Lizard Island from Nov 13, 2009 – 6 Jun, 2010 (thanks to C. Steinberg, AIMS).

To investigate the effect of pipes delivering cool water to reduce thermal stress on the reef, we first ran a control (or no injection) simulation, which is our best estimate of the conditions through the two weeks. We then ran additional simulations in which we injected 27°C water (based on a typical temperature of water in a nearby 40m deep channel, Figure 3). The difference in hydrodynamic properties between the control and injection scenarios is taken to be the effect of the cool water injection.

Different injection scenarios (from $2m^3\,s^{-1}$ to $50m^3\,s^{-1}$) of 27°C water were trialled at varying time intervals. Both periodic (e.g. when solar radiation was strongest between 11:00 – 14:00) and continuous (e.g. over the two-week simulation period) injections of cooler water were tested. For simplicity, we present results from three simulations with continuous, feasible flow rates (2, 5, $10m^3\,s^{-1}$).

For this primary investigation, four pipe locations in the reef waters surrounding Lizard Island were chosen, at depths between 2.3–16.6m (Figure 4). The source water was introduced continuously over the simulation period from outside the model domain into the bottom layer of the model. The average temperature difference with an injection of cool water was calculated over the spring-neap cycle, as well as the area of reef where temperature was reduced.

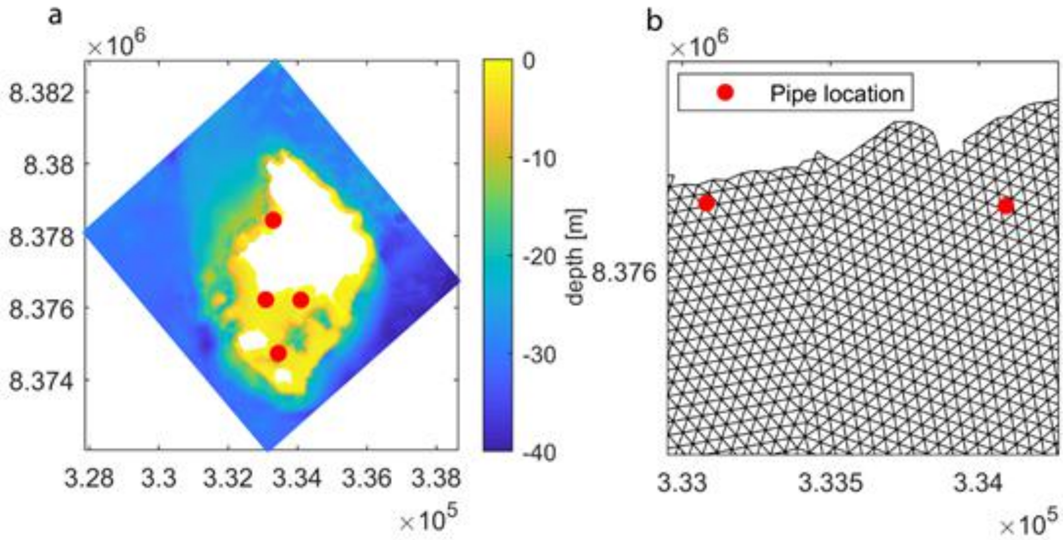

Figure 4: Delft 3D FM Lizard Island model. (a) Model domain with interpolated bathymetry, location of cold water pipes shown in red. N.B white areas indicate dry land. (b) Zoom in on grid south of the main island. See text for more details.

Results

Results from three continuous discharge scenarios (2, 5, 10 m^3s^{-1}) are shown in Figure 5. Left panel: temperature change when pipes are included with continuous discharge (a) $2m^3 s^{-1}$ (b) $5m^3 s^{-1}$ (c) $10m^3 s^{-1}$. Crosses denote location of the four source pipes. Middle panel: total reef area subject to specific temperature reduction (± 0.05°C) for discharges (d) $2m^3 s^{-1}$ (e) $5m^3 s^{-1}$ (f) $10m^3s^{-1}$. Note that the reef area where temperature reduction is < 0.05°C is displayed at the top of the bar graphs, and only values where area > 1ha are displayed. Right panel: spatial distribution of temperature reduction over the reef for discharges (g) $2m^3 s^{-1}$ (h) $5m^3 s^{-1}$ (i) $10m^3 s^{-1}$.

The total reef area (1334ha) was defined as the area where depth < 20m. Overall, greater discharges correspond to both a larger temperature reduction over the whole reef, and a larger area of reef influenced (Figure 5, bottom row versus top row). There was minimal interaction between the northeastern injection site, and the three injections sites in the lagoon.

For the $2m^3s^{-1}$ scenario, the area of reef where the temperature is reduced by > 0.05°C is 117ha, and > 0.25°C is three hectares (Figure 5d). In comparison, for the 10 $m^3 s^{-1}$ scenario, the area of reef where the temperature reduction is > 0.05°C is 571ha, and for a reduction > 0.25°C is 111ha (Figure 5f).

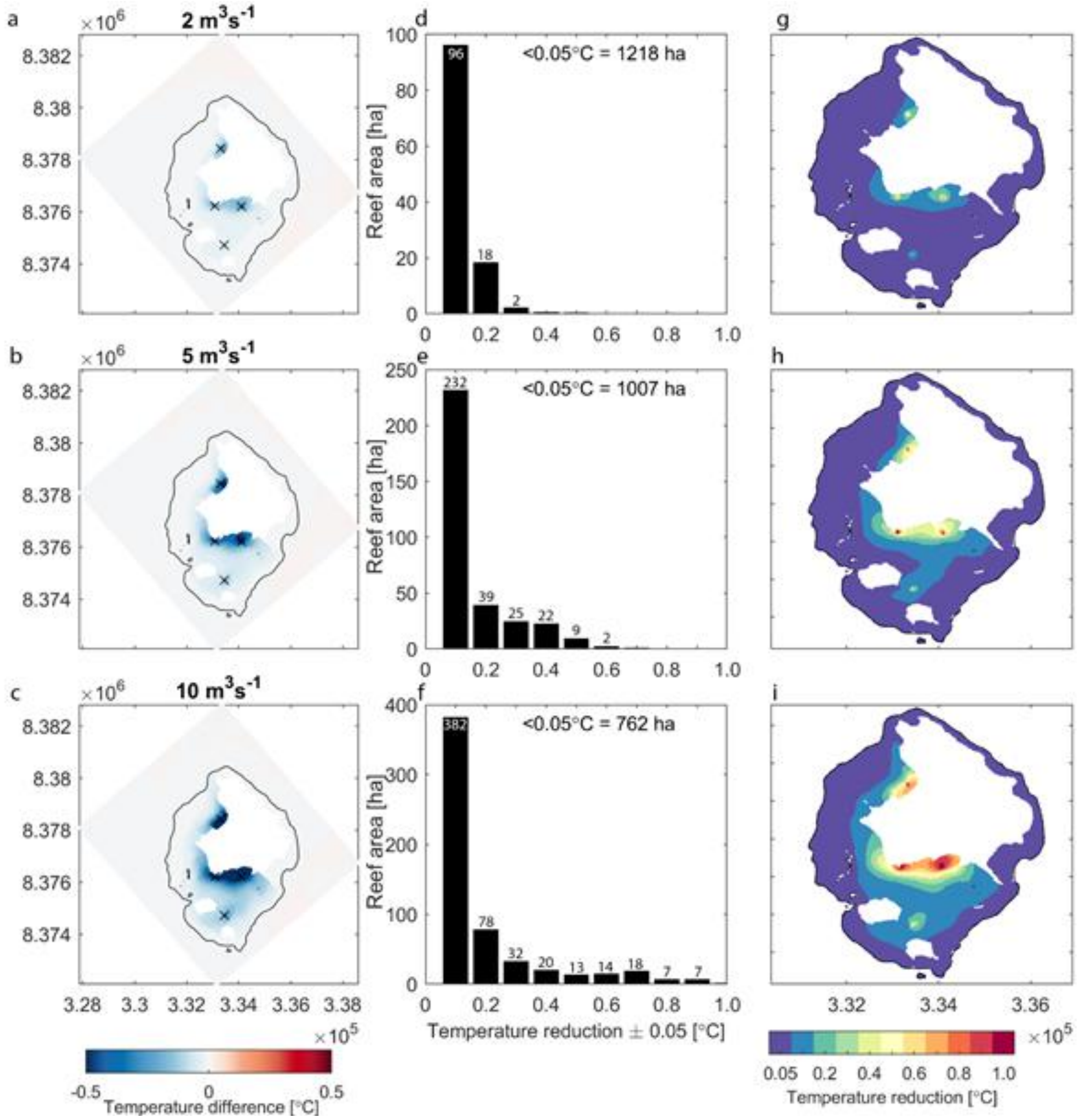

Figure 5: Mean seabed temperature reduction for 2, 5 and 10m^{3}s^{-1} injection of 27°C water averaged over water during half a tidal cycle (neap – spring) in January 2017. Left column: temperature change when pipes are included with continuous discharge Crosses denote location of the four source pipes. Middle column: total reef area subject to specific temperature. Note only values where area > 1ha are displayed. Right column: spatial distribution of temperature reduction over the reef for discharges. Rows indicate discharge rate: top 2m^{3}s^{-1} ; middle 5m^{3}s^{-1}, and bottom: 10m^{3}s^{-1}.

Calculation of energy costs of injections

The above simulations provide the temperature reduction of injecting 2, 5, and 10m^{3}s^{-1} of 27°C water at four sites on Lizard Island. This temperature water can be found at 40m depth, 3km to the east of the lagoon. Here we calculated the energy costs of these injections following the well-known Moody diagram style of calculations, as outline in Kays and Crawford (1993) and Incropera and de Witt (1990).

Assumptions:

1. Flow is constant through pipes with a roughness equivalent to rusted pipes extending 3km to site a 40m at which 27°C water is available. Greater roughness (i.e. barnacles) would increase energy costs and would be expensive to remove.
2. There is no energy loss due to bends in the pipe.
3. Pipe is submerged at both ends, so lift is based on reduced density, not the full mass.
4. Pipes are of equal dimensions and equal flow.

The input and output variables, and the equations used, are:

> V = volume transport per pipe [m^3/s]
> D = pipe diameter [m]
> n = number of pipes
> L = pipe length = 3000m
> h = depth of cool water = 40m
> ρ = density = 1022.72kg m^{-3} (density at 35 S, 27 C)
> μ = kinematic viscosity 1.08 x 10^{-3} kg/s/m
> A = π $(D/2)^2$ = cross-sectional area of pipe [m^2]
> U = V / A = flow rate through pipe
> ε = wall roughness = 0.025 (rusted steel pipe)
> Re = ρ D U / μ = Reynolds number (measure of turbulence, configured for a pipe)
> f = rough pipe friction factor = $1 / (-1.8 \log_{10}(((\varepsilon/D)/3.75)^{1.11} + 6.9/Re)$
> $\Delta p = f \rho U^2 L / (2D)$ = pressure drop along pipe L m long
> P_f = Power to overcome friction = Δp V [W]
> P_m = Power to accelerate flow = 0.5 ρ V U^2 [W]
> P_l = Power to lift from 40 m to reef seabed = 9.81 V $(\rho_{35,29} - \rho)$ h
> Ω - 1kWh = $A 1 (onshore industrial scale is much less for solar)

The energy costs required to pump water against friction (P_f) dominates over that for momentum (P_m) losses and to lift the water (P_l) (Table 1). These friction and momentum terms are proportion to U and U^2 respectively, which itself is inversely proportional to the pipe diameter. That is, reduce the pipe diameter and, for a given volumetric flow rate, the costs increase to an exponent greater than 1. Large diameter pipes are expensive and may affect the aesthetics of the reef and thus have social license issues. Thus, it is useful to calculate a range of pipe diameters for the different flow rates. A third variable is the number of pipes over which the flow is divided. Here we consider four pipes in parallel.

The pipe flow rate, the power to overcome friction, the momentum loss, and an approximate energy cost (colour shading) for a range of pipe diameters (x-axis) and volumetric flow rates (y-axis) are given in Figure 6. The top left panel is a simple calculation for a circular pipe to convert volumetric flow and pipe diameter into a velocity in the pipe – the key variable for power consumption calculations. In order to reduce friction losses we have kept pipe flow rate well below 1 m s^{-1} by using pipe diameters of 0.5, 1.25 and 2.5m (Figure 6, top left) for the 2, 5, and 10m^3s^{-1} cases respectively, and shown as by white squares, circles and diamonds. These symbols are repeated in the other three panels of Figure 6 for convenience.

Table 1: Calculated pipe flow, friction loss, momentum loss, lift loss and total cost per pipe for the three cases highlighted in Figure 5. To achieve the flows at each outlet location in the hydrodynamic simulations above requires four pipes.

Case Dia / Vol. Flow	Pipe flow U ($m\ s^{-1}$)	Friction loss, P_f (kW)	Momentum loss, P_m (kW)	Lift loss P_l (kW)	Total cost ($ per day per pipe)
1.0 m / 0.50 $m^3\ s^{-1}$	0.64	66	0.41	0.52	1610
1.5 m / 1.25 $m^3\ s^{-1}$	0.71	116	1.28	1.31	2856
2.0 m / 2.50 $m^3\ s^{-1}$	0.80	199	3.24	2.62	4920

The power consumption to overcome friction alone is 50-200kW (Figure 6, top right; 66, 116 and 199kW for the 2, 5, and $10m^3s^{-1}$ cases). Momentum and lift losses are smaller than the friction losses (Figure 6, bottom left; 1, 2, 6kW for the 2, 5, and $10m^3s^{-1}$ cases). See Table 1 for more details.

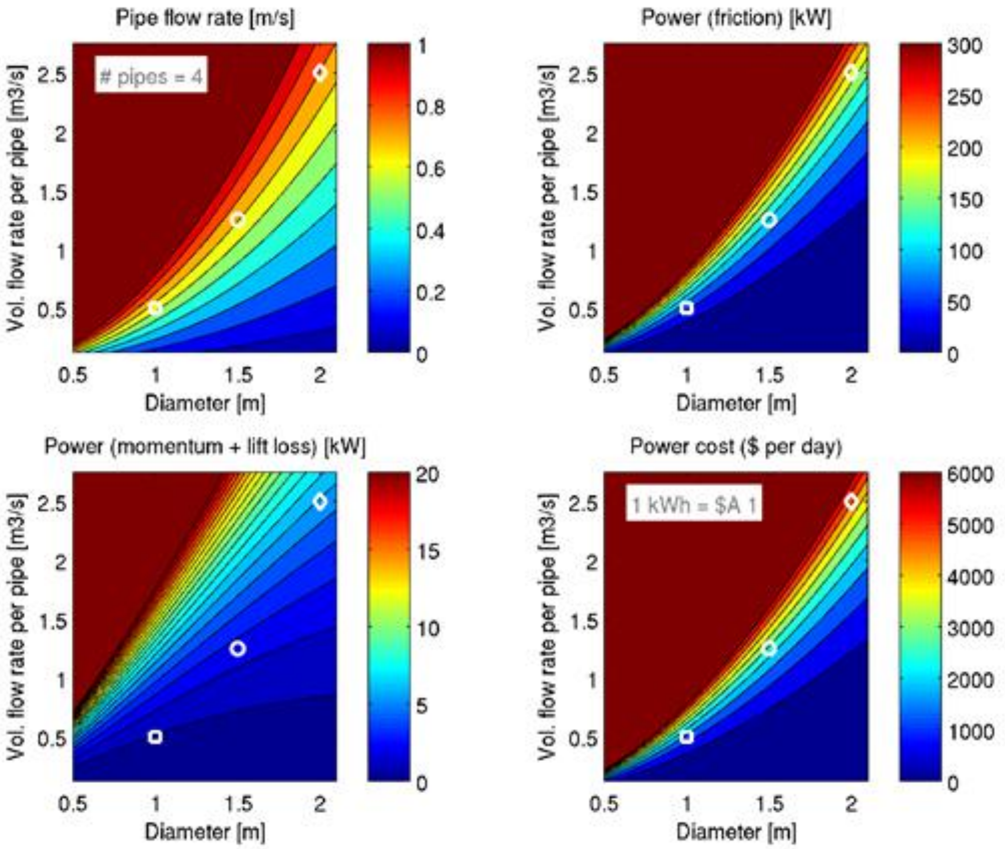

Figure 6: Pipe flow rate, power consumption and power cost for a range of flows for cold water injections onto Lizard Reef assuming access to water at 40m depth, 3km pipe from the injection site. Symbols show three examples of increasing volumetric flow and pipe diameter to complement earlier modelling.

The calculation of the cost of energy is difficult because of the quickly changing cost of producing energy at a remote site. While solar is easiest to price and has relatively small carbon emissions, the need for a constant cool water injection over a relatively short period of time (e.g. hottest five weeks of summer), but with no use for the rest of the year, does not suit solar energy generation. For simplicity we assume 1kWh = AUD$1.

Energy cost per site is around $2856 x 4 = $11,424 per day for the $5m^3/s$ case. With four sites, this rises to $45,696 per day. If this cooling is undertaken for five weeks, or 35 days the cost is $1,599,360. For this cost, the degree heating weeks is reduced by 1°C wk on all areas with 0.2°C cooling or more (Figure 4e, h), amounting to 97ha.

A more exhaustive analysis of pump operating costs would include considering variable pipe diameters, locations of pumping stations, variable pumping rates etc. In this report we have not considered the cost of installation of the pipes and pumping station equipment, which is likely to be in the tens of millions of dollars.

[1] Reef age, τ, is defined by:

$$\frac{\partial \tau}{\partial t} + \boldsymbol{u} \cdot \nabla \tau = \nabla \cdot (\nabla \mathrm{K})\tau + \emptyset, \emptyset = 1\ (\text{above reef}), \emptyset = 0\ (\text{open ocean})$$

where $\nabla = \partial/\partial x + \partial/\partial y + \partial/\partial z$ is the gradient operator, $\boldsymbol{u}$ is the velocity vector, K is the spatially and temporally- resolved diffusion coefficient, V is the volume of water in a model cell, A its area (thus V/A = layer thickness), and Φ is the source term is defined as 1 d d^{-1} above the reef and zero in the open ocean. We have defined the reef as areas with bottom depth less than 10m.

5. SUMMARY OF FINDINGS

The most straightforward means to reduce thermal-stress induced bleaching is to cool the water at the seabed above coral communities. The feasibility of reducing the seabed temperature through local interventions is considered first by analysing the feasibility of doing so on 20 reefs with differing physical environments using both simple, current-based estimates and residence time metrics. We then concentrate on Lizard Island, the most promising candidate of the 20 reefs, and develop a high-resolution hydrodynamic model to investigate the effect of the injection of cool water at differing volumetric rates. Injecting 27°C at a rate of $5m^3s^{-1}$ at four sites cooled 97ha of the reef by 0.15°C or more. As a first estimate of costs of injecting cool water on Lizard Island, we calculate the energy costs required for several simple pipe configurations accessing water from a nearby, 40m deep, channel. The energy costs alone of cooling 97ha of seabed surrounding Lizard Island in summer by one degree heating week (DHW) is $1.6M per year. A more precise costing will require further expert engineering design of the pumping equipment. As a result of less favourable hydrodynamic properties, cooling seabed temperatures on most of the reefs of the Great Barrier Reef will be more expensive per hectare than at Lizard Island.

Concluding thoughts

The process of mapping out the feasibility of an intervention across a large number of reefs, identifying a best candidate, and then simulating the effect of the intervention at a particular site, is a critical process in scoping out the best initial investments in reef adaptation/restoration. This process shows that even for the most favourable reefs, cool water injection is expensive, and that cool water injection could not be scaled up to any meaningful fraction of the 3100 reefs of the Great Barrier Reef.

Should value be seen in reducing thermal stress on one or a few individual reefs, the next process is to optimise the intervention at the chosen site. For example, we have not explored the best location of the outlet pipes, or operational strategies for calculating optimal flow rates. Further, while the modelling aimed to achieve temperature reductions, a more appropriate ecological target such as degree heating weeks, reduced oxygen stress, bleach mortality, or socio-economic values will provide policy makers with the most relevant information.

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APPENDIX A – RRAP DOCUMENT MAP

Reef Restoration and Adaptation Program

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GBRrestoration.org

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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