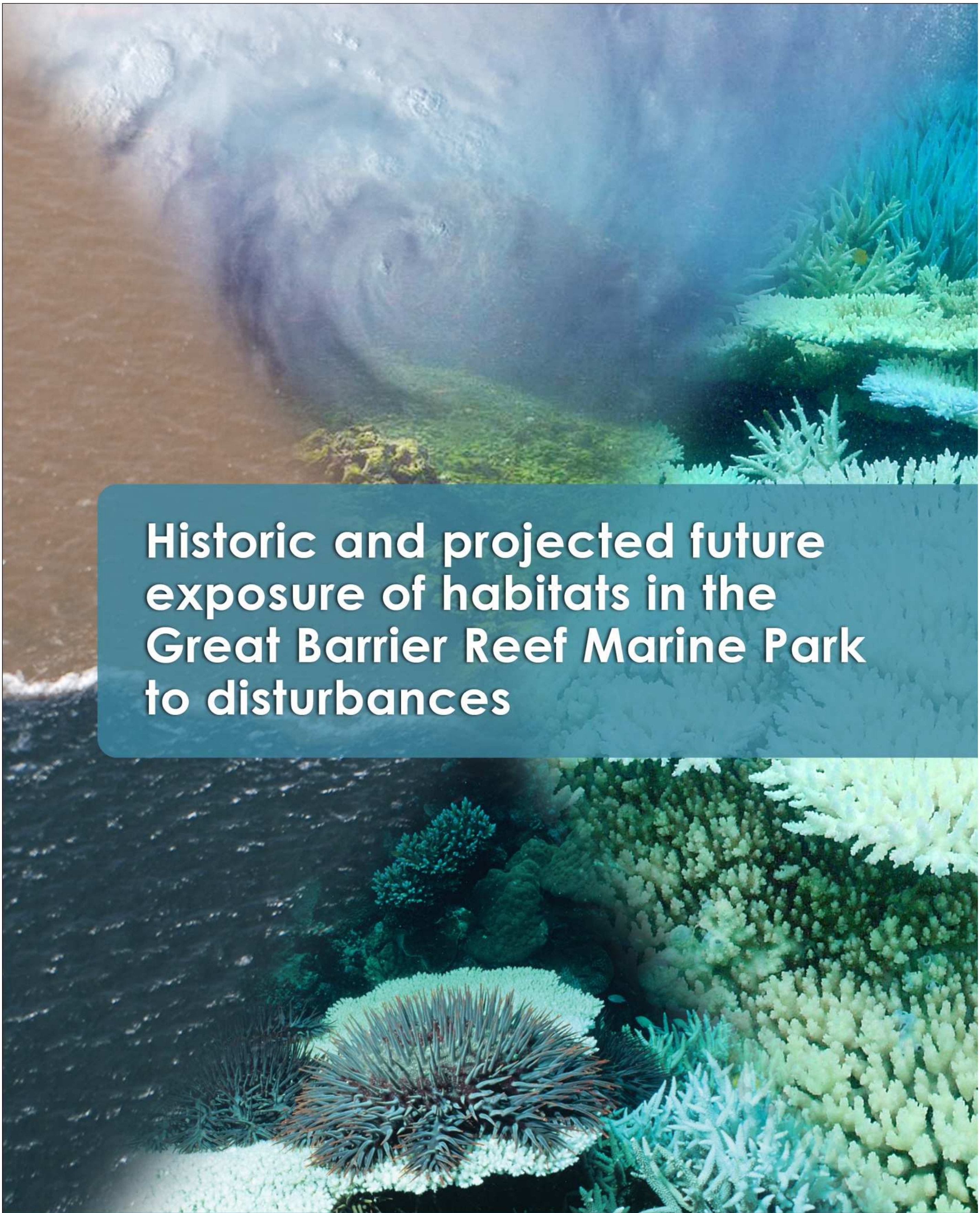

Historic and projected future exposure of habitats in the Great Barrier Reef Marine Park to disturbances

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Report prepared for the Climate Change Group at the Great Barrier Reef Marine Park Authority

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1. Executive Summary

In the vulnerability assessment framework used by the Intergovernmental Panel on Climate Change (IPCC) exposure and sensitivity combine to produce a potential impact that with adaptive capacity determines the vulnerability of a habitat, ecosystem, or social sector. For large-scale ecosystems comprised of widespread habitats like the Great Barrier Reef it is prohibitively resource-intensive to monitor more than even 10% of the ecosystem. Managers thus cannot regularly acquire reliable information from all locations on factors contributing to sensitivity, like condition. For this reason, information relating to exposure to disturbance is hugely valuable, especially as adaptive capacity of habitats in an era of climate change will be largely determined by the return period between disturbances. Mapping exposure to disturbances provides insight into how forces like tropical cyclones shape ecosystem condition. Further, spatial variability in exposure to disturbances can identify both the frequently disturbed sites where supporting recovery processes is critical, and the relative ‘refugia’ that may have the best chance of coping with climate change.

This project aims to document the exposure of the Great Barrier Reef Marine Park and key habitats (coral reefs, seagrass, and other non-reef areas) to disturbances between 2001 and 2011. We identify the spatial patterns of exposure to damaging waves from tropical cyclones, freshwater inundation, thermal stress and coral bleaching, and crown-of-thorns starfish outbreaks. We also identify spatial patterns in cumulative exposure for both reef and non-reef areas. These two areas correspond generally to the 30 reef bioregions and 40 non-reef bioregions from the Great Barrier Reef Representative Areas Program. In this report, we also share results from tests of whether the current Great Barrier Reef Marine Park Zoning Plan (2003) protects representative percentages of reef areas with relatively high and low exposure to disturbances within the Marine National Park (green) zones.

For bleaching and thermal stress, damaging waves from cyclones, and crown-of-thorns starfish outbreaks exposure is relatively high in the central Great Barrier Reef between Port Douglas and Bowen, and in parts of the Swains Reefs and Capricorn-Bunkers. Exposure to freshwater inundation is highest nearshore and affects a small percentage of reefs overall but a very high percentage of the reefs visited by reef stakeholders and recreational users. Patterns in cumulative exposure match those for the individual disturbances with exposure highest in the central Great Barrier Reef and lowest in the GBRMPA Far Northern Marine Management Area.

Many of the low (the relative refugia) and high exposure reef and non-reef areas identified are within Marine National Park zones. For coral reef areas, low and high exposure areas not currently within Marine National Park zones are identified for all of the GBRMPA Marine Management Areas.

Climate change projections using ensembles of IPCC climate models forced with a fossil-fuel aggressive scenario characteristic of current conditions suggests all reefs within the Marine Park could experience coral bleaching annually by 2050. In contrast, bleaching projections based on emissions scenarios that include pre-2100 emissions stabilisation and near-term emissions reductions suggest reefs will experience bleaching stress annually far later in the century. In contrast to rising sea temperatures, scientists are much less certain about whether tropical cyclones will either become more frequent in the Great Barrier Reef or more severe. A review of the available literature suggests: the number of tropical cyclones per year will stay roughly the same or even slightly decrease, more storms may occur in the southern areas of the Marine Park than has been typical of the past, and that more highly intense storms may occur. Projections for rainfall in the Great Barrier Reef are that there will be slight increases in average rainfall and more extreme rainfall. This will translate into altered river flow patterns, with more flood events predicted due to the increase in intense rainfall. Inshore habitats in the Great Barrier Reef that are currently affected by flood plumes will continue to be exposed to freshwater and associated pollutants, likely on a more frequent basis. The implications of increased future flooding for crown-of-thorns outbreaks and spatial patterns therein are unknown.

The research outcomes presented here now need to be combined with the concurrent work on resilience-based decision making (the RSP5 project) as well as the future vulnerability mapping under the NERP program. In combination, these research efforts and the Reef Health and Impact Survey monitoring program can inform management decision-making by providing a dynamic assessment of the current and projected future condition of the habitats within the Great Barrier Reef Marine Park.

2. Introduction and Objectives

The 50 per cent decline in coral cover in the Great Barrier Reef documented over the past three decades (De'ath et al. 2012) highlights that multiple disturbances are impacting on Great Barrier Reef habitats. Information is needed to understand how these stressors interact and whether they will exceed the capacity for habitat recovery in the future. The cluster of severe tropical cyclones and wet seasons on the Great Barrier Reef since 2009 has raised the question of whether more severe disturbances combined with deteriorating conditions for recovery will become the norm, leading to further ecosystem-wide decline. While inherently stochastic, many of these disturbances have co-occurred in recent years with resultant declines in the condition of Great Barrier Reef habitats like coral reefs and seagrass meadows. This project aims to document the exposure of the Great Barrier Reef Marine Park and key habitats (coral reefs and seagrass) to disturbances between 2001 and 2011. Recent years (since 2009) have included many La Niña events whereas El Niño events were more common earlier in the study period. The rationale for the 2001–2011 period for evaluating cumulative impacts is to standardise to the decade for which remote sensing data are available for all variables (freshwater data are only available from 2001–2011) and to cover a full range of ENSO extremes.

We identify the spatial patterns of exposure to damaging waves from tropical cyclones, freshwater inundation, thermal stress, and crown-of-thorns starfish outbreaks, as well as spatial patterns in cumulative exposure for both reef and non-reef areas (Fig. 1). These two areas correspond generally to the 30 reef bioregions and 40 non-reef bioregions from the Great Barrier Reef Representative Areas Program. We also test whether the current Great Barrier Reef Marine Park Zoning Plan (2003) protects representative percentages of reef areas with relatively high and low exposure to disturbances for the entire time period for which data are available for each disturbance. Lastly, we present the most up-to-date understanding of what projections of global and regional climatic conditions mean for the frequency and severity coral bleaching, tropical cyclones, and freshwater inundation from flooding in the future.

The project had three objectives related to historic exposure, two related to testing the representativeness of low and high exposure areas in Marine National Park (green) zones, and one objective relating to projected future exposure. These six project objectives are as follows.

Historic Exposure

1. **Exposure to disturbance.** Assess exposure between 2001 and 2011 of habitats in the Great Barrier Reef Marine Park to: (a) damaging waves from tropical cyclones, (b) anomalously warm summer sea surface temperatures (as thermal stress severe enough to cause bleaching for reef areas and as anomalies for non-reef areas), (c) freshwater inundation from flood plumes, and, for coral reefs, (d) crown-of-thorns starfish outbreaks.

2. **Cumulative exposure.** Assess cumulative exposure between 2001 and 2011 to all four disturbances (see a–d in objective 1) for coral reef areas and non-reef areas in the Great Barrier Reef Marine Park.

3. **Maps and visual outputs.** Visualise outputs from objectives (1) and (2) as maps for coral reef areas (30 reef bioregions from the Representative Areas Program), non-reef areas (40 non-reef bioregions), and for seagrass meadows (sub-set of non-reef areas).

Low and high exposure areas and Marine National Park zones

4. **Representativeness of Marine National Park zoning.** We examine whether reef areas with relatively low and high exposure are well represented within Marine National Park (green) zones in two ways. 1) We test whether a representative percentage (±5 per cent) of these reef areas are included, and also for non-reef areas. 2) We also test whether at least 20 per cent of low and high relative exposure reef areas are included since this was the goal percentage of each reef bioregion to be included during the re-zoning of the Great Barrier Reef Marine Park in 2003.

Future exposure

5. Project future exposure to thermal stress events severe enough to cause coral bleaching using ensembles of General Circulation Models from Intergovernmental Panel on Climate Change (IPCC) fifth phase of the Coupled Model Intercomparison Project (CMIP5 – towards the IPCC's 5th Assessment Report) forced with the new Representative Concentration Pathway (RCP) experiments/emissions scenarios.

6. Write brief reviews of the literature describing the state-of-science regarding future exposure of Great Barrier Reef habitats to tropical cyclones, and freshwater inundation from flooding.

Figure 1 Landscape and macro photographs of the impacts caused by four key disturbances on habitats within the Great Barrier Reef Marine Park; coral bleaching (a), damaging waves from cyclones (b), crown-of-thorns starfish outbreaks (c) and freshwater inundation from flooding (d). Photos copyright the Great Barrier Reef Marine Park Authority.

Methods used to meet the objectives, as well as the project outputs and results are presented in the following order: Historic exposure to disturbances (objectives 1, 2, 3); Cumulative exposure to disturbances (objectives 2, 3); Zoning and cumulative exposure (objective 4); and Projected exposure of coral reefs to bleaching conditions (objectives 5 and 6).

3. Methods

3.1 Historic exposure to disturbances

This project produced data for four different types of disturbances that can impact on habitats in the Great Barrier Reef Marine Park (the Marine Park). Thermal stress is separated for coral reef and non-reef areas into accumulated heat stress severe enough to cause bleaching and sea surface temperature anomalies, respectively. Habitats are broadly classified here as coral reef and non-reef areas, and results for these two classifications are contained within the body of the report. Maps for seagrass meadows are shown in Appendix 2 for all of the stressors related to non-reef areas; these are simply the non-reef area data cut with a spatial data layer (a raster) outlining the boundaries of seagrass meadows (data from McKenzie and Grech at JCU).

Methods to compile or generate data for two of the disturbances – damaging waves from cyclones and freshwater – are the same for coral reef and non-reef areas. The methods for these are described first. Methods for sea surface temperature anomalies for non-reef areas are described next; this disturbance is broadly characterised as 'thermal stress'. Then, methods are described for disturbances specific to coral reef areas: (i) thermal stress events severe enough to cause coral bleaching, and (ii) crown-of thorns starfish outbreaks.

Damaging waves from tropical cyclones

Direct measurements of tropical cyclone wave energy are rarely possible. Here, well-documented empirical relationships between wind speed, duration of gales, fetch and wave heights (US Army Coastal Engineering Research Center 1977, see Table 1) were used to assess whether wave heights $\geq$ 4 m were possible during each tropical cyclone that entered the Marine Park between 1985–2011. Waves greater than 4 m can cause catastrophic physical damage to coral reefs[1]. For each pixel, each time a 4 m wave could have been generated counts as an event and we calculate frequency of exposure by dividing the number of years that included 4 m wave events by the 11 years in the time period (then normalised to a scale between 0 and 1 by anchoring to the maximum value). Methods used to calculate wind speeds, the duration of gales, fetch and Poisson probability formulas to assess 4 m wave generation are below.

Wind speeds were hindcast hourly as 10-minute maximum winds using a parametric model (Holland 2010) anchored in the outer radii of gale force winds (as per Puotinen 2007). This is adapted for use in GIS and mapped at a 4-km resolution. An asymmetry correction (McConochie et al. 2004) was applied and the resulting wind speeds were scaled to fit within the tropical cyclone gale radii. Missing radius data were calculated based on Moyer et al. (2007) and regionally adjusted (Chavas and Emanuel 2010). The hourly duration of wind speeds every

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[1] A related project by these same authors and also funded and managed by the Climate Change Group at the Great Barrier Reef Marine Park Authority is empirically deriving the relationships between variables describing storm characteristics and their interaction (e.g., wind speeds, duration of gales, and generation of 4 m waves) and spatial variation in damage severity during tropical cyclones Ingrid, Larry and Yasi. This will result in an improved capacity to predict spatial variation in damage when tropical cyclones occur and enter the Great Barrier Reef Marine Park. These maps can then be produced for past and future storms through collaboration with this author team (not from within Great Barrier Reef Marine Park Authority). A process has been developed and described within a mini-report that explains how data from the Australian Bureau of Meteorology can be used to run the model and produce the damage predictions should the Great Barrier Reef Marine Park Authority be interested in doing so (i.e., if triggers in the Tropical Cyclone Response Plan are met).

1m/s from 17 to 33 m/s were counted at each reef pixel. Using this, a 4 m wave was deemed possible at a pixel that sustained sufficient hours of wind at any of the relevant speeds. This was then adjusted at sites that lacked sufficient fetch for 4 m waves to form. Fetch is measured as maximum distance to the nearest wave-blocking obstacle every 7.5 degrees – as per Pepper and Puotinen (2009). See this link for another simpler explanation of fetch (http://en.wikipedia.org/wiki/Fetropical cycloneh_per cent28geographyper cent29). Finally, the Poisson probability of a 4 m wave occurring at each cell in a given year was calculated using the formula:

$$\Pr(X \geq 1) = 1 - e^{-\lambda} \qquad (1)$$

Where λ is the yearly average number of events (Tartaglione et al. 2003; Klotzbach 2011). Applying equation (1) resulted in a value for each Great Barrier Reef pixel indicating the probability that a 4 m wave could have formed for at least an hour in a given year. To find the yearly average number of events, the total number of years where a tropical cyclone was sufficient to generate a 4 m wave was divided by the number of years in the study period. The resultant probability values were scaled into 11 classes of probability from 0 to 1 by anchoring to the maximum probability found in the data field, for both coral reef and non-reef area pixels.

Table 1 Pioneering research by the US Army Coastal Engineering Research Center (1977) showing that significant wave height (≥4 m waves) can be estimated based on modelled wind speeds, duration of those winds in hours and the fetch in km.

4 m waves		
Wind Speed (m/s)	Duration (hr)	Fetch (km)
17	12	220
18	10	175
19	8	145
20	7	120
21	6	95
22	5	77
23	5	71
24	4	66
25	4	59
26	3	57
27	3	49
28	3	43
29	2	38
30	2	36
31	2	33
32	2	29
33	2	28

Freshwater inundation

Freshwater inundation was assessed based on satellite measurements of Colour Dissolved Organic Matter (CDOM, 1-km resolution) processed according to Brando et al. (2012). A CDOM value greater than 0.14 is associated with salinity values of less than 30 parts per thousand (ppt) and is consistent with a freshwater influence like a terrestrial flood plume. Reef and non-reef area pixels are considered here to have been exposed to freshwater during a given year if CDOM levels exceed 0.14 at least once in that year. The CDOM data are post-processed as

CDOM is difficult to reliably detect in very shallow clear waters on and around reefs and because CDOM readings on the outer-shelf of the Great Barrier Reef can be caused by processes unrelated to flooding. Post-processing included four steps: 1) spatially interpolating across reefs based on reliable data, 2) setting CDOM values exceeding 0.14 to zero if outside the area of known maximum flood plume extent from Devlin et al. (2012), 3) manually error-checking outer-shelf areas using expert judgment to zero out any remaining high CDOM values extremely unlikely to be attributed to terrestrial flooding, and 4) re-sampling from 1 (raw CSIRO data) to 4-km using weighted averaging to standardise the data grid for this to that of the other disturbances. Final values are frequencies for the period between 2001 and 2011, then normalised to a scale between 0 and 1 by anchoring to the maximum value.

Thermal stress in non-reef areas

Observed sea surface temperature data for the period 1982–2011 (4-km resolution) was obtained from NOAA Pathfinder Version 5.2 (Casey et al. 2010). The data was quality screened and only data with a quality flag of 4 or greater was used, which is standard for use of this dataset. From this data a monthly climatology was constructed for the period 1982–2000. Positive anomalies (above the monthly average) in the summer period of 1 December to 28 February were summed for each year between December 2000 and February 2001 (the 2001 summer) to December 2010 and February 2011 (the 2011 summer). These 11 values were then averaged to produce a value for summer thermal stress for all non-reef areas. The resultant values for summer thermal stress were scaled into 11 classes from 0 to 1 by anchoring to the maximum value found in the data field.

Disturbances specific to coral reefs

Thermal stress events severe enough to cause coral bleaching

The same data described in the section just above for summer thermal stress in non-reef areas was used to evaluate thermal stress in coral reef areas during the 2001–2011 study period. The 1982–2000 monthly climatology was used and the total accumulated heat stress each summer (1 December – 28 February, as in section above) was calculated using degree heating weeks (DHWs). One DHW is equivalent to one week of temperatures being 1 ^{o}C above the long-term monthly average (from the 1982–2000 climatology). Thermal stress was considered here to be severe enough to cause bleaching if a total of eight DHWS[2] accumulate in a summer. In the analysis this was considered a 'bleaching event'. The total number of bleaching events was counted for all reef areas. The resultant values for numbers of bleaching events were scaled into 11 classes from 0 to 1 by anchoring to the maximum value found in the data field.

Crown-of-thorns starfish outbreaks

The Great Barrier Reef Long-term Monitoring Program (LTMP) has surveyed 482 reefs for crown-of-thorns starfish since 1986 using the manta-tow method (AIMS Standard Operational Procedures; Miller et al. 2009) where an observer makes a visual assessment of the number of crown-of-thorns starfish seen during each manta tow (2 minutes duration) around the entire reef perimeter. Crown-of-thorns starfish populations are described as outbreaks when they reach densities such that the starfish are consuming coral tissue faster than corals can grow. There are various ways of estimating this level but when populations detected on a reef using manta tow surveys average one crown-of-thorns starfish per tow the coral cover will certainly be reduced; this is referred to as an active outbreak. When manta tow surveys detect 0.22 crown-of-thorns starfish /tow this is essentially detecting intermediate to adult sizes when they are present at near or actual outbreak levels, and referred to as an incipient outbreak.

The estimated density of crown-of-thorns starfish for the period 2001 to 2011 was modelled from LTMP survey data. The number of crown-of-thorns starfish observed per manta tow was averaged per reef and interpolated over the entire Marine Park (reef and non-reef areas) using the approach described in Fabricius and De'ath (2001).This modelled raster was produced using the following process:

1. Raw data was extracted directly from the AIMS LTMP database maintained by the LTMP team and the AIMS data centre.

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2 The threshold 8 DHWs has been used here rather than the more commonly used threshold of 6 DHWs to reduce the number of 'false positive' events predicted whereby bleaching is predicted to occur but is unlikely to have. Our use of this approach is due to the relationships between thermal stress and bleaching being unknown for the Far Northern. Moderate to severe bleaching is likely once 8 DHWs have accumulated (see Strong et al. 2006, van Hooidonk and Huber 2009) but setting the threshold to 6 DHWs resulted in a prediction of bleaching for almost all of the Far Northern during many summers in the study period and these are believed to be false positives. 8 DHWs as a threshold is thus a compromise slightly under-estimating the frequency of bleaching events in the central and southern, while avoiding extreme over-estimates of bleaching event frequency in the Far Northern and allowing for the use of a single threshold Great Barrier Reef-wide. Many in this field now agree that operational tools that predict the severity of bleaching responses during the summer season would benefit from the use of regional rather than Great Barrier Reef-wide bleaching thresholds, once those can be developed (i.e., once we have more survey data following future bleaching events).

2. From the complete database, surveys results between 1 January 2001 and 31 December 2011 were selected. All reefs that were surveyed in this period were included in the analysis, including those that were surveyed only once.
3. The crown-of-thorns starfish counts observed per manta tow were averaged over each reef for each survey to give an estimated density. Reefs with multiple surveys were passed to the statistical model as multiple observations and not averaged prior to modelling. This was done to allow the modelling to effectively perform the averaging, allowing data from reefs with only one survey to be combined with reefs with multiple surveys.
4. Where densities exceeded the outbreak level of 1 crown-of-thorns starfish per manta tow the level was clipped to 1 individual per manta tow.
5. A statistical model (Generalised Additive Model) was then used to create a modelled surface that best describes the spatial distribution of the data using cross validation. A quasibinomial transform was used to ensure that the modelled values were limited between 0–1.
6. This model was then used to predict all points on the Marine Park, including reef and non-reef areas.
7. The extent of the model was trimmed to areas taken to be reasonably reliable using the modelled estimated standard error.

The interpolation for this project mapped crown-of-thorn starfish density as observed in the manta tow data, up to a maximum of 1, corresponding to the active outbreak level. This step was done to ensure the model focused on fitting a surface for levels below or approaching outbreak levels rather than trying to model peak crown-of-thorn starfish density values, which tend to be infrequent but with very high peaks. The clipped density values correspond very closely with the probability of an active outbreak due to the temporal averaging performed by the modelling process, the clipping of the maximum density and the coincidence of the active outbreak level equalling 1, resulting in no re-scaling of the result to get a probability of 1.

An example modelled value of 0.2 would correspond to an incipient outbreak level occurring over nearly the entire period of interest or an active outbreak occurring once every 5 years. To improve the modelling, the 'locations' of the sites were translated into a coordinate space defined by relative distance across and along the Great Barrier Reef (Fabricius and De’ath 2001). Distance across was set to the value 0 on the coast and 1 on the outermost edge of the continental shelf (80 m isobath), and distance along the shelf takes the value 0 on the southern boundary of the Great Barrier Reef Marine Park and 1 on the northern boundary.

3.2 Cumulative exposure

Three different analyses of cumulative exposure were undertaken based on combinations of the historic exposure data generated for: (i) damaging waves from tropical cyclones, (ii) freshwater inundation, (iii) thermal stress in non-reef areas, and (iv) disturbances specific to coral reefs. For coral reef areas, thermal stress events severe enough to cause coral bleaching, damaging waves from tropical cyclones, freshwater inundation and crown-of-thorns starfish outbreaks were combined. Another analysis for coral reef areas included bleaching, cyclones and crown-of-thorns starfish outbreaks but excluded freshwater as very few reefs are affected by freshwater inundation (see results). For non-reef areas, damaging waves from tropical cyclones, freshwater inundation, and average summer sea surface temperature anomalies totals ('thermal stress') were combined.

For each of these three analyses the mathematical process had the same two steps. First, the anchored and normalised values were summed for each 4 km pixel for each disturbance used in the analysis[3].This creates a new range of values in the data field (4 km resolution) that are then anchored to the highest value (step two) and normalised to a scale of 0–1, consistent with the normalisation process for the original disturbance data. Anchoring and normalising the data expresses the cumulative exposure of each pixel to the disturbances relative to the pixel considered to be the 'worst affected'. In this case, 'worst affected' is based on a core assumption for this analysis that the disturbances are all considered equal. Exploring other scenarios whereby the disturbances are scaled – weighted as being more or less important in terms of ecological impacts – was not possible within the scope and resources of this project. The data provided make it possible for the Great Barrier Reef Marine Park Authority Spatial Data Centre to explore all potential approaches to scaling the disturbances based on their perceived relative importance.

As with each individual disturbance, the cumulative exposure analyses produced a data field that is categorised into 11 classes for the purpose of visualising the data into maps. These

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[3] Both averaging the values and summing the values produces the same final results when the data are anchored to the maximum value and normalized to the scale of 0 to 1. This is an artefact of the math used to express values relative to one another.

classes include ‘zero’ and then ~ 0.1 intervals from 0.01–0.09, 0.10–0.19 onwards up to 0.90–1.0. The classes are equivalent to 10 per cent bins.

3.3 Zoning and cumulative exposure

The total reef and non-reef area was calculated based on the standard 4-km grid used. The estimate is therefore an over-estimate for both reef and non-reef areas, albeit a highly consistent one across the Marine Park, due to the mismatch between the 4-km grid and reef and coastline polygon raster outlines used for the Great Barrier Reef Marine Park Authority published area estimates[4]. The area within Marine National Park no-take (green) Zones was calculated for the entire Marine Park and for all four of the Marine Management Areas; Far Northern, Cairns-Cooktown, Townsville-Whitsunday, Mackay-Capricorn (Fig. 2) .

For this analysis, the methods for assessing frequency of exposure to disturbances on reefs are different to what is described in the sections above. We use the entire time period for which data on the disturbances is available for reef areas in this analysis. This ensures that frequency of exposure estimates for each disturbance are as representative as possible of the recent past rather than just this last decade. As examples, crown-of-thorns starfish outbreaks were more common in the 1990’s than the 2000’s but the opposite is true of tropical cyclones. The timeframes used for this analysis for exposure to disturbance in reef areas are: coral bleaching (1983–2011), damaging waves from cyclones (1985–2011), crown-of-thorns starfish outbreaks (1986–2011), and freshwater inundation remains as 2001–2011. The timeframes used for disturbances for non-reef areas remain as 2001-2011. This analysis forms the focus of Maynard et al. (in review); the methods section for that manuscript can be found in Appendix 3.

Total area (in km^2) within each of the 11 exposure classes was calculated and compared to the area within Marine National Park Zones made up by reefs and non-reef areas within each of the exposure classes. This comparison tests representativeness of each exposure class within Marine National Park Zones. We consider each exposure class to be well-represented if there is less than a 2 per cent difference between: a) the reef and non-reef area within each exposure class expressed as a percentage of the total reef area, and b) the reef area within each exposure class expressed as a percentage of the reef area in Marine National Park Zones. We also tested whether at least 20 per cent of the reef area within the lower and higher relative

[4] The most recent published area estimates are here: http://www.environment.gov.au/heritage/places/world/great-barrier-reef/pubs/gbr-factsheet.pdf

exposure classes is within Marine National Park Zones. The area of reef in low and high relative exposure classes that is within and outside of Marine National Park Zones in each Marine Management Area is shown in tables and maps.

The results section of this report contains the abstract for a manuscript currently in review for the reef areas, the results from the same manuscript, and the results for non-reef areas. As above, the methods for the manuscript currently in review can be found in Appendix 3.

Figure 2 Map of the Great Barrier Reef Marine Park showing the four Marine Management Areas of the Great Barrier Reef Marine Park Authority.

3.4 Projected exposure of coral reefs to bleaching conditions

The methods for calculating the projected exposure of coral reefs to bleaching conditions are as per van Hooidonk et al. (2013). Therefore, the methods presented here are abbreviated and full details can be found in that paper. Monthly SST temperature data were retrieved for each available General Circulation Model (GCMs; see Appendix 1 for complete list) from the World Climate Research Programme's CMIP5 data set (Taylor et al. 2012) – for four IPCC Representative Concentration Pathway (RCP) experiments (RCP2. 5, n=15; RCP4.5, n=11; RCP6.0, n=10; RCP8.5, n=16[5]). The new RCPs are comparable to the previously used SRES scenarios, but with considerable refinements, such as a strong reduction in aerosol emissions. For a detailed description of the RCPs and how they differ see van Duren et al. (2012)[6].

Although the spatial resolution in the new generation of GCMs has increased, the current resolution still does not represent small-scale processes that influence local conditions, such as upwelling or diurnal heating on reef flats. Dynamical and statistical downscaling approaches could resolve these issues but are either computationally expensive or introduce additional assumptions and therefore are not applicable to assessments like those presented here, which are a subset of a global analysis. Statistical downscaling where satellite data is used to project temperatures for reef environments is possible (e.g. Donner et al. 2005) but even those techniques are limited by the spatial and temporal resolutions of the satellite data. Moreover, these statistical approaches train the downscaling model with observed data, data that can be dominated by short-term variability (such as diurnal or intra-seasonal). The long-term variability is most important for projections of climate change impacts (Huth et al. 2004).The approach used here is robust for the purpose of characterising projected differences in the rates of SST increase in different parts of the Great Barrier Reef.

To match the start of each model with an observed climatology, the models' mean SST were corrected using observational data from the NOAA Optimal Interpolated SST V2 (see Reynolds et al. 2002) obtained from NOAA/OAR/ESRL PSD, Boulder, Colorado, USA[7]. Model means were corrected at each location by subtracting the 2006–2011 mean of each model and adding the mean of the OISST 1982–2005 climatology to the entire time series. To prevent incorrect

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[5]Where n here refers to the numbers of models used in the ensemble (data from http://www.esg.llnl.gov; see also Appendix 1).
[6] A detailed description of the RCP process can also be found at: http://judithcurry.com/2011/08/11/representative-concentration-pathways/
[7]http://www.esrl.noaa.gov/psd/

projections of thermal stress, annual cycles were replaced with those from the observed climatology (van Hooidonk and Huber 2012). Missing values such as near-coast pixels were filled in using an interpolation routine that solves Poisson's equation via relaxation. This function uses the non-missing data as boundaries and interpolates in the zonal direction (east to west).

From the 1982–2005 climatology[8], the warmest month was selected at each location as the maximum monthly mean. Here, Degree Heating Weeks (DHWs) start to accumulate when projected SSTs exceed the maximum monthly mean; not the maximum monthly mean+1ºC as in Gleeson et al. (1995). The positive anomalies for three months were added to get Degree Heating Months and then converted to DHWs by multiplying by 4.34. This conversion from Degree Heating Months to DHW is necessary to compare model DHWs with a previously established optimal global bleaching threshold of 6 DHWs (van Hooidonk and Huber 2009). For each cell (1º x 1º), we project the year in which a decade starts with 10 years of projected 'bleaching conditions', that is, bleaching conditions (>6 DHWs) occur annually. For all RCP experiments, projections were made for each separate model and the median (a year) of all models was derived for each cell. For each RCP experiment, maps were produced using the National Center for Atmospheric Research (NCAR) Command Language (NCL version 6.0.0). Tables were also produced showing the percentage of the Great Barrier Reef Marine Park and of total coral reef area projected to start experiencing annual bleaching conditions during all of the 5-yr periods between 2020 and 2070, and for 2070 onwards.

4. Results and Discussion

4.1 Historic exposure to disturbances

Damaging waves from tropical cyclones

For reef and non-reef areas the highest probabilities of damaging waves from cyclones are in three main areas:(1) the central Great Barrier Reef offshore from Townsville, (2) the mid- and outer-shelf reefs offshore from Proserpine and Mackay, and (3) the centre of the Far Northern section (see Fig. 2 for a map of the Great Barrier Reef Marine Park and locations of the Marine Management Areas). The maximum value for the probability of a damaging wave (4 m) from

[8] The OISST climatology at 1º resolution is different (data source, resolution, and timeframe) than the 1985-2000 climatology used to assess sea surface temperature anomalies and bleaching conditions in the historical exposure analysis.

cyclones was 26.81 per cent for the period 2001–2011.This indicates that the cell most frequently exposed to damaging waves is predicted (by the model) to have experienced a damaging wave roughly one out of every four years. These cells are given the maximum value of 1; all other values are normalised to a 0–1 scale by dividing by the maximum value. To aid with interpretation, this means that cells with values of 0.5 had half the probability of experiencing a damaging wave from a tropical cyclone during 2001–2011 as compared to the sites with the maximum value of 26.81 per cent.

The results are similar for reef and non-reef areas (Fig. 3). Approximately 17 per cent of reef and non-reef areas experienced no damaging waves from tropical cyclone during the study period (Fig. 3).The non-reef areas that didn't experience damaging waves from tropical cyclones are: (1) in the Far Northern Marine Management Area, close inshore from Cooktown south to Cairns, (2) inshore just north of Bowen, and (3) inshore from Mackay to the southern Marine Park boundary (Fig. 4). Nearly all of the reef areas that didn't experience damaging waves from tropical cyclone are in the Far Northern Marine Management Area (Fig. 4).

Slightly more than 5 per cent of reefs (6.98 per cent for non-reefs) are in the highest exposure class (0.9–1) and all of these reefs are in the central Great Barrier Reef offshore from Townsville (Fig. 5). Almost 25 per cent of reef area is in the 0.7–0.79 exposure class (22.47per cent for non-reefs), and 52.90 per cent of reefs are in the 0.3–0.39 exposure class (53.46 per cent for non-reefs, see Fig. 3).

Exposure class	% of Total Reef Area	% of Total Non-reef Area
None	16.97	17.08
0.01 - 0.09	0.00	0.00
0.1 - 0.19	0.00	0.00
0.2 - 0.29	0.00	0.00
0.3 - 0.39	52.90	53.46
0.4 - 0.49	0.00	0.00
0.5 - 0.59	0.00	0.00
0.6 - 0.69	0.00	0.00
0.7 - 0.79	24.82	22.47
0.8 - 0.89	0.00	0.00
0.9 - 1	5.30	6.98

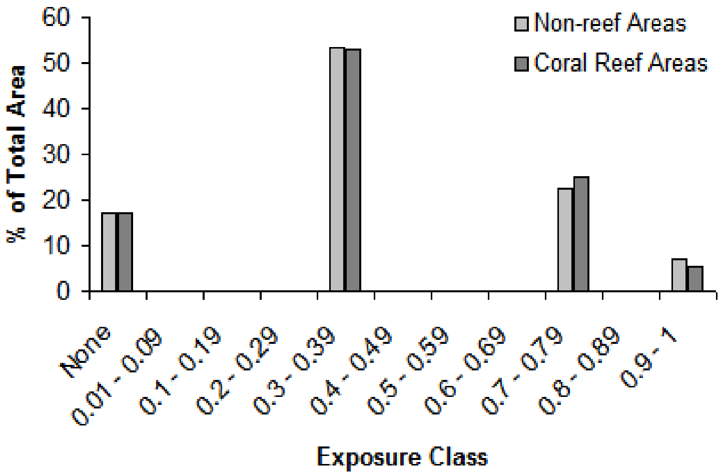

Figure 3 The percentage of total reef and non-reef area within each of the 11 exposure classes for damaging waves from cyclones.

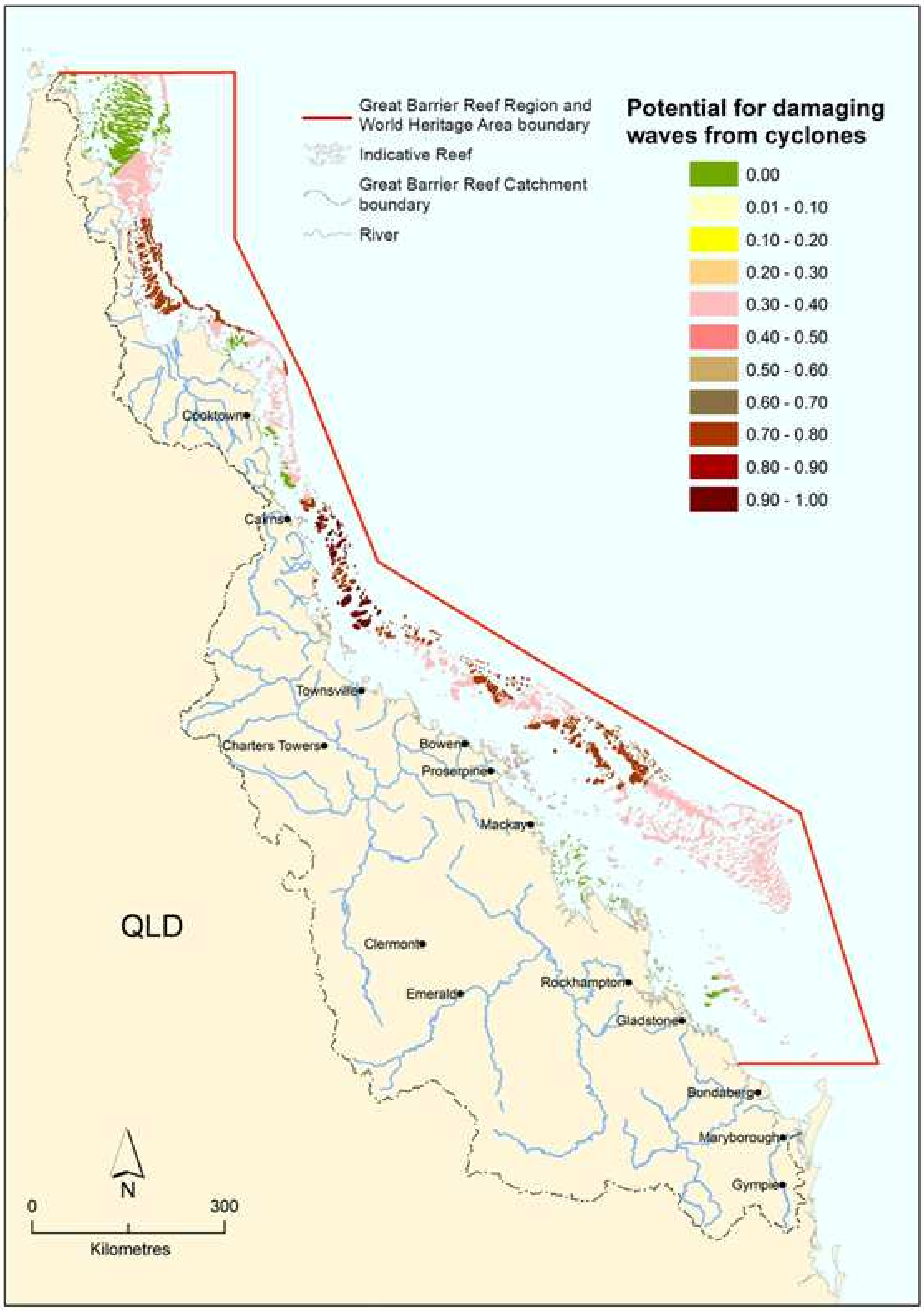

Figure 4 Annual probability in reef areas of exposure to at least one hour of 4 metre waves from tropical cyclones that caused gale force (>17 m/s) winds during the 2001–2011 period. Data are scaled from 0 to 1 based on a maximum value of 26.81 per cent.

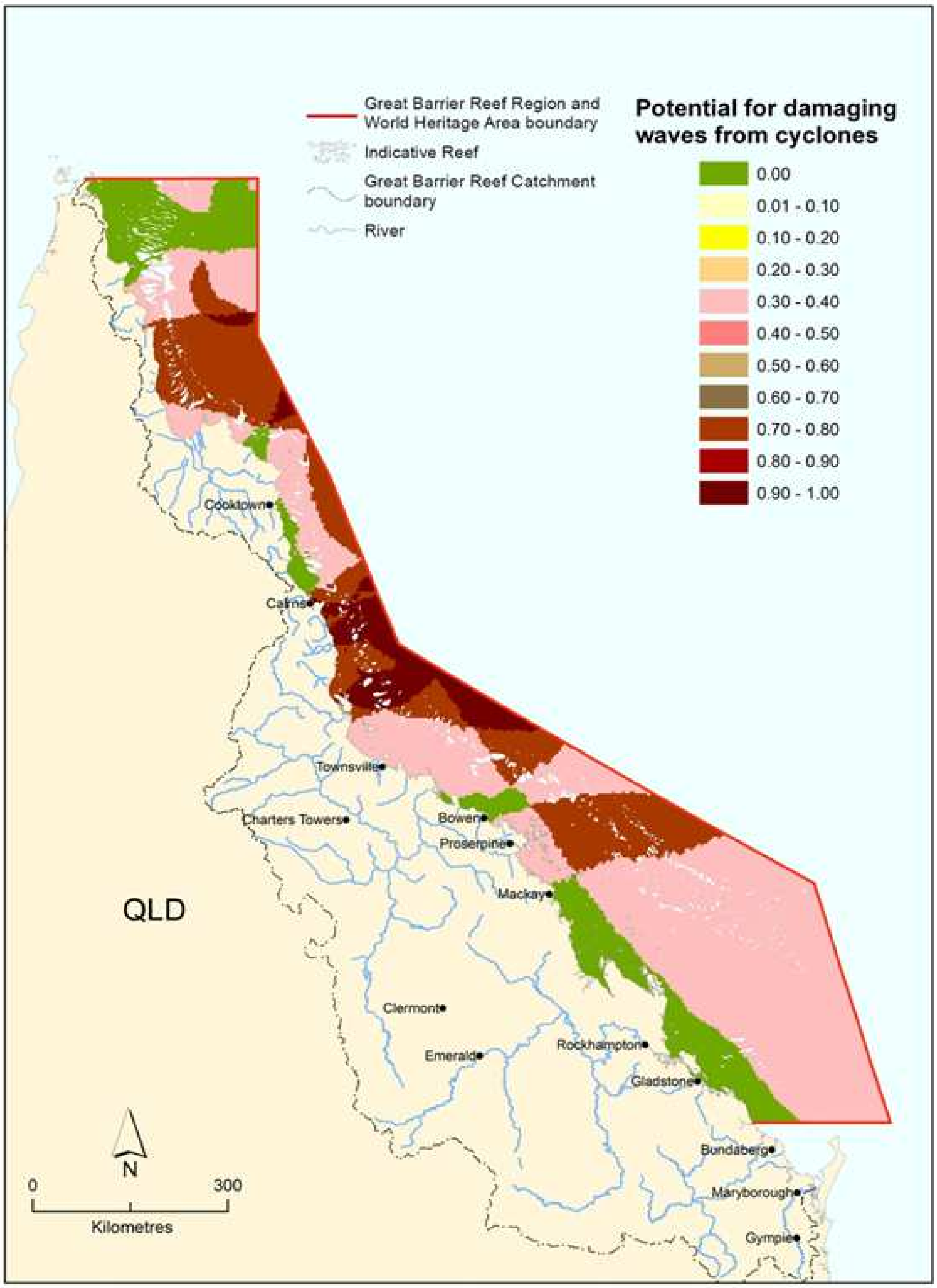

Figure 5 Annual probability of exposure in non-reef areas to at least one hour of 4 metre waves from tropical cylones that caused gale force (>17 m/s) winds during the 2001-2011 period. Data are scaled from 0 to 1 based on a maximum value of 26.81per cent. These data are presented again in Appendix 2 to show seagrass habitat.

Freshwater inundation

The general pattern of freshwater exposure during the period 2001–2011 shows a strong shelf gradient with areas most frequently exposed being exclusively inshore (see Figs. 7 and 8).The maximum value for freshwater exposure for the study period is 10, indicating that some cells were exposed to freshwater 10 out of the 11 years in the study period (Fig. 6). These cells are given the maximum value of 1; all other values are normalised to a 0–1 scale by dividing by the maximum value. To aid with interpretation, this means that cells with values of 0.5 were exposed to freshwater 5 out of 10 years during the study period (Fig. 6).

Nearly all mid-shelf and outer-shelf areas either had no freshwater exposure during the study period within known potential plume extents, or are beyond known plume extents (both count as 'none' in Fig. 6, see also Fig. 8). For coral reefs, nearly 2 per cent (of total coral reef area) is in the highest exposure class (0.9–1) and these are mostly inshore in the Far Northern Marine Management Area or in Shoalwater Bay (Fig. 7). More than 96 per cent of the total coral reef area had no freshwater exposure between 2001 and 2011 according to this analysis; all other exposure categories have less than 1 per cent of the total coral reef area (see Fig. 6). More than 85 per cent of the total non-reef area had no freshwater exposure during the study period according to the analysis. Approximately 5 per cent of the non-reef area is in the highest exposure class; all other exposure classes have ~1 per cent or less except 0.2–0.29 (2.02 per cent) and 0.1–0.19 (3.25 per cent; see Fig. 6).

Exposure class	% of Total Reef Area	% of Total Non-reef Area
None	96.17	85.57
0.01 - 0.09	0.00	0.00
0.1 - 0.19	0.69	3.25
0.2 - 0.29	0.19	2.02
0.3 - 0.39	0.19	1.10
0.4 - 0.49	0.27	0.91
0.5 - 0.59	0.12	0.79
0.6 - 0.69	0.20	0.64
0.7 - 0.79	0.09	0.53
0.8 - 0.89	0.20	0.53
0.9 - 1	1.87	4.66

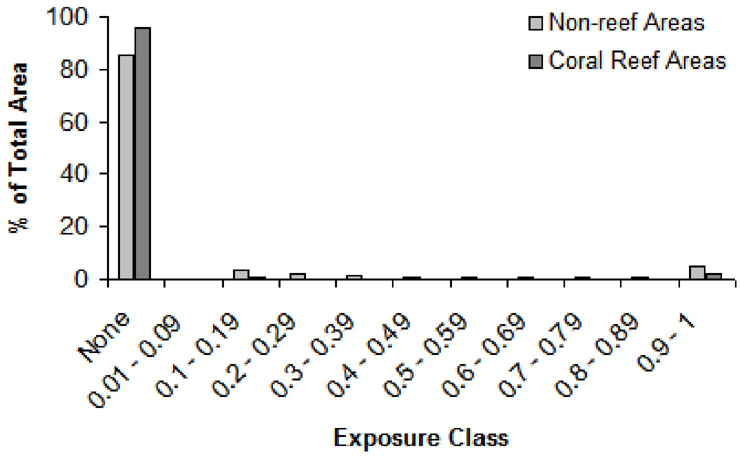

Figure 6 The percentage of total reef and non-reef area within each of the 11 exposure classes for freshwater exposure.

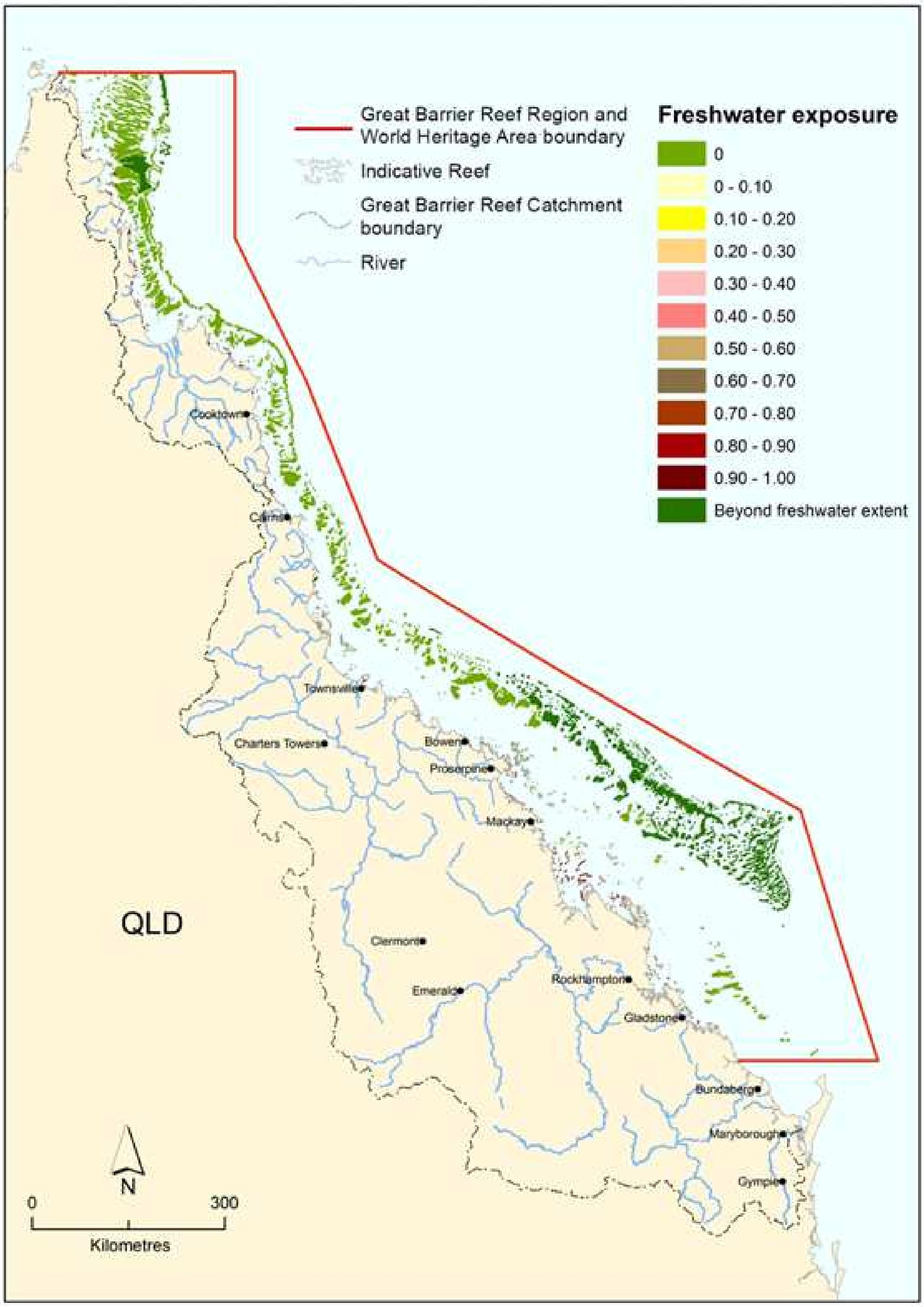

Figure 7 Observed frequency in reef areas of freshwater plumes between 2001 and 2011 based on remotely sensed CDOM data provided by CSIRO Land and Water. Data are based on mapped plume extent resulting in a display of both true zeros and 'beyond plume extent'. Data are scaled from 0 to 1 based on a maximum value of 10.

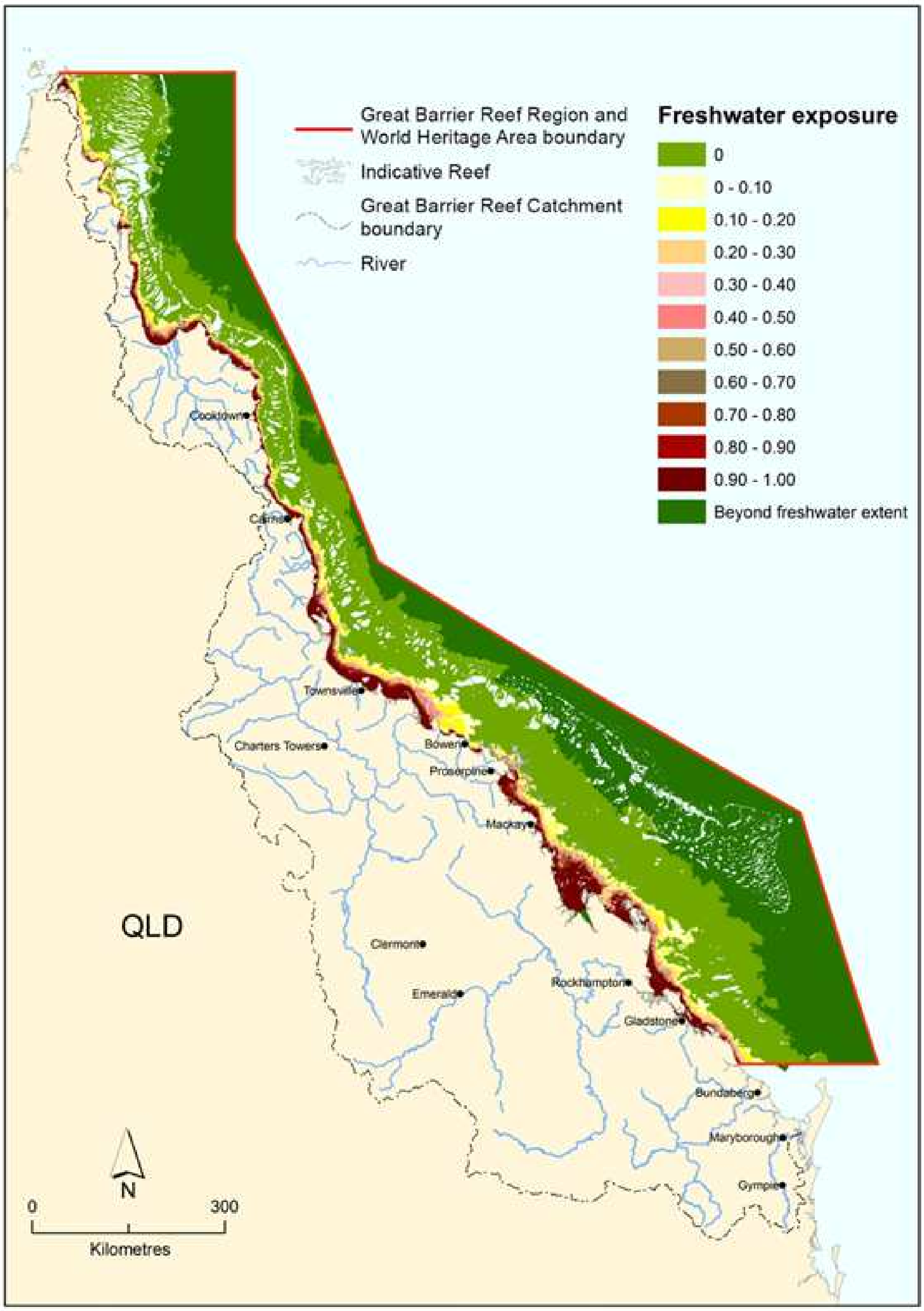

Figure 8 Observed frequency in non-reef areas of freshwater plumes between 2001 and 2011 based on remotely sensed CDOM data provided by CSIRO Land and Water. Data are based on mapped plume extent resulting in a display of both true zeros and 'beyond plume extent'. Data are scaled from 0 to 1 based on a maximum value of 10.These data are presented again in Appendix 2 to show seagrass habitat.

Summer thermal stress in non-reef areas

Average summer thermal stress in non-reef areas during the period 2001–2011 was much higher in the southern Marine Park than anywhere else (see Fig. 9).The maximum value for summer thermal stress in non-reef areas was 68.79 (Fig. 9). As a sum of all positive anomalous SST this is equivalent to 68.79 days with the SST being 1 degree above the monthly averages; or 68.79 ‘degree heating days’. These values are an average of the degree heating day counts during the study period, with year as the sampling unit (i.e. some years may have more, and some less). Cells with 68.79 for an average are given the maximum value of 1; all other values are normalised to a 0–1 scale by dividing by this maximum value. To aid with interpretation, this means that cells with values of 0.5 had an average degree heating day count of ~34 or half that of the maximum value calculated.

There is not a single 4 km cell north of Mackay in any of the exposure classes above 0.5. This indicates that north of this point non-reef areas were exposed to half or less the average summer thermal stress experienced in the southern Great Barrier Reef from 2001-2011. The data are roughly normally distributed among the exposure classes with ~65 per cent of the area within the 0.2–0.29, 0.3–0.39, and 0.4–0.49 exposure classes. Less than 5 per cent of non-reef area is in the low-exposure classes (0, 0.01–0.9, and 0.10–0.19, and less than 5 per cent are in the highest exposure classes (0.7–0.1). The areas with the lowest average summer thermal stress are in the Far Northern Marine Management Area and in some parts of the central Great Barrier Reef offshore from Townsville (see Fig. 10).

There is no evidence to suggest that these average summer positive anomaly counts or ‘degree heating days’ have an ecological consequence in non-reef areas. Rather, the map in Figure 10 simply visualises relative differences in exposure to summer thermal stress during the study period. This is distinct from the thermal stress calculations used to predict coral bleaching described in the next section; those relate to an empirically derived relationship between the temperature stress and the bleaching response in corals.

Exposure class	% of Total Non-reef Area
None	0.00
0.01 - 0.09	0.05
0.1 - 0.19	3.59
0.2 - 0.29	19.44
0.3 - 0.39	23.84
0.4 - 0.49	21.69
0.5 - 0.59	16.81
0.6 - 0.69	9.92
0.7 - 0.79	3.54
0.8 - 0.89	1.07
0.9 - 1	0.06

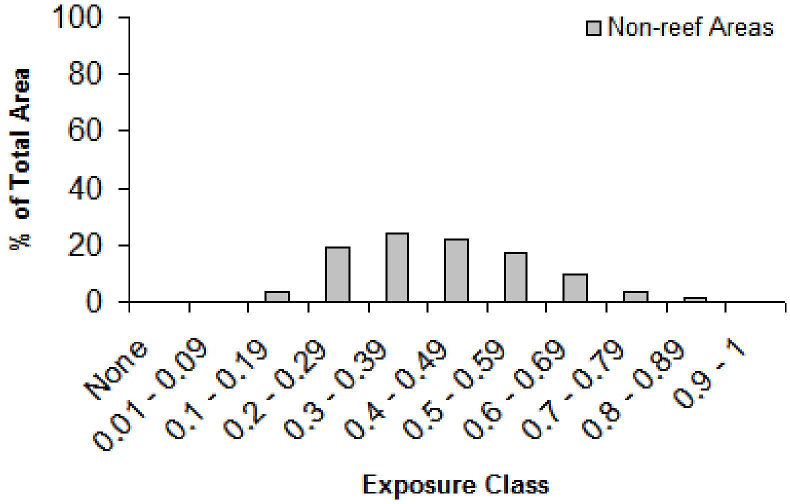

Figure 9 The percentage of total non-reef area within each of the 11 exposure classes for summer thermal stress.

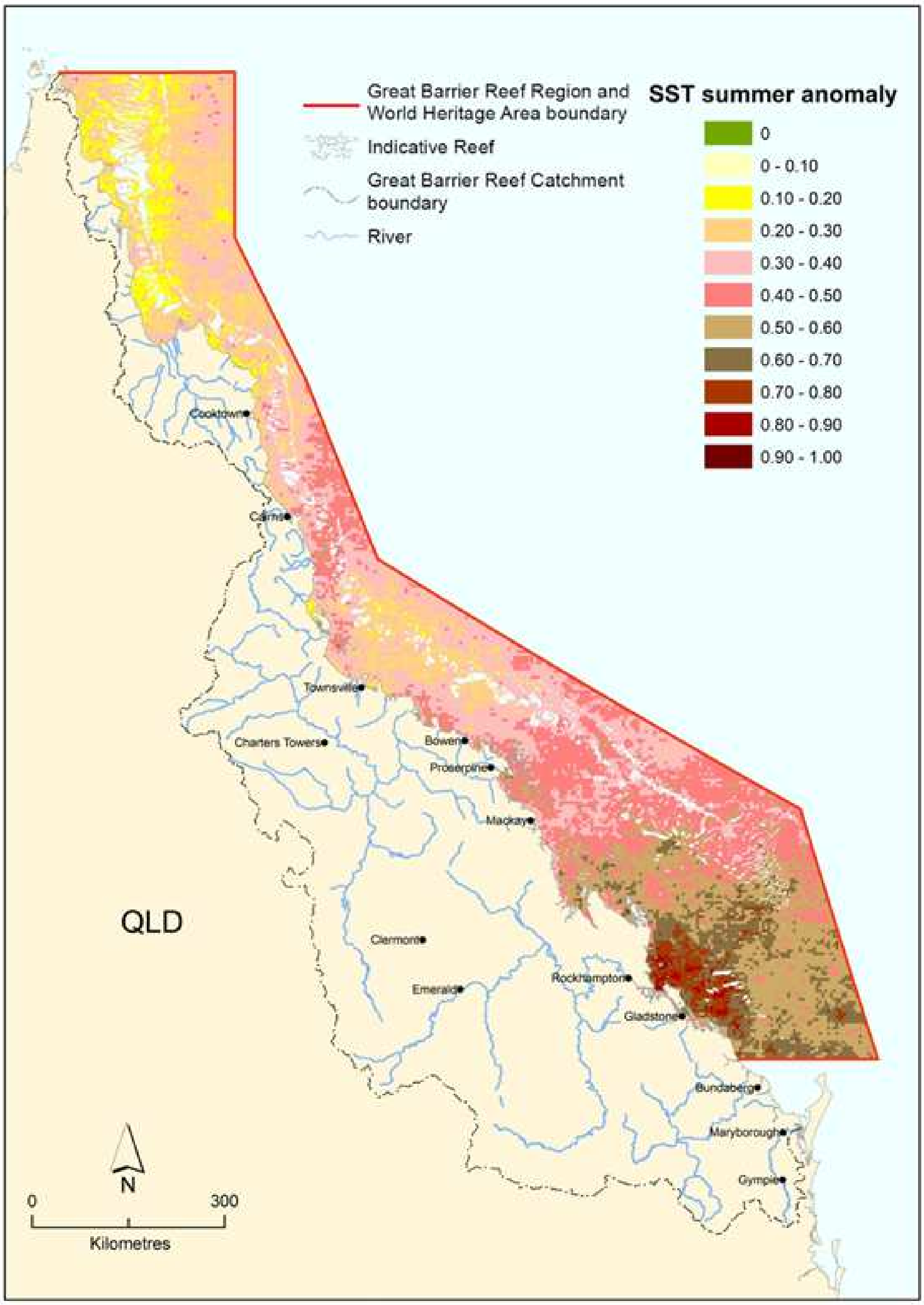

Figure 10 Average summer (December to February) sea surface temperature (SST) anomalies (sums) from 2001–2011 for non-reef areas, scaled to the maximum value (68.79).These data are presented again in Appendix 2 to show seagrass habitat.

Thermal stress events severe enough to cause coral bleaching

Very few thermal stress events severe enough to cause coral bleaching occurred between 2001 and 2011.These are not confirmed bleaching events *per se* (i.e. ground-truthed through *in situ* monitoring) but for simplicity we call these bleaching events from this point forward. The most well-known bleaching events in the Great Barrier Reef occurred in 1998 and 2002 (reef-wide), and in the southern Great Barrier Reef in 2006, and to a lesser extent (with regards to severity and spatial coverage) in 2008.The maximum value for bleaching events was five, indicating that some cells experienced eight Degree Heating Weeks (DHWs) five different times during the study period. These cells are given the maximum value of 1; all other values are normalised to a 0–1 scale by dividing by this maximum value. To aid with interpretation, this means that cells with values of, for example, 0.4 experienced eight DHWs twice during the study period.

Less than 1 per cent of the total reef area experienced five bleaching events during the study period, corresponding to the highest exposure class of 0.9–1 (see Fig. 11). All of the reefs in the highest exposure class are in the Keppel Bay area offshore from Yeppoon (see inset box, Fig. 12).The majority of reef areas (75.42 per cent) did not experience any bleaching events during the study period (Fig. 12). These reefs run from the northern Marine Park boundary to the reefs in the Central Section offshore from Mackay but do not include the reefs offshore from Cairns to Ingham (Fig. 12). Approximately 15 per cent of total reef area was exposed to one bleaching event (exposure class 0.2–0.29), 7.49 per cent was exposed to two events (0.4–0.49), 1.2 per cent exposed to three events (0.60–0.69), and less than 1 per cent (in total) was exposed to four events (0.80–0.89, see Fig. 11). Reefs exposed to 2, 3 and 4 bleaching events during the study period are almost exclusively in: (1) the area offshore from Cairns to Ingham, (2) the Swains and Capricorn-Bunkers, and (3) the inshore far southern Great Barrier Reef near Keppel Bay (Fig. 12).

Exposure class	% of Total Reef Area
None	75.42
0.01 - 0.09	0.00
0.1 - 0.19	0.00
0.2 - 0.29	15.85
0.3 - 0.39	0.00
0.4 - 0.49	7.49
0.5 - 0.59	0.00
0.6 - 0.69	1.20
0.7 - 0.79	0.00
0.8 - 0.89	0.04
0.9 - 1	0.00

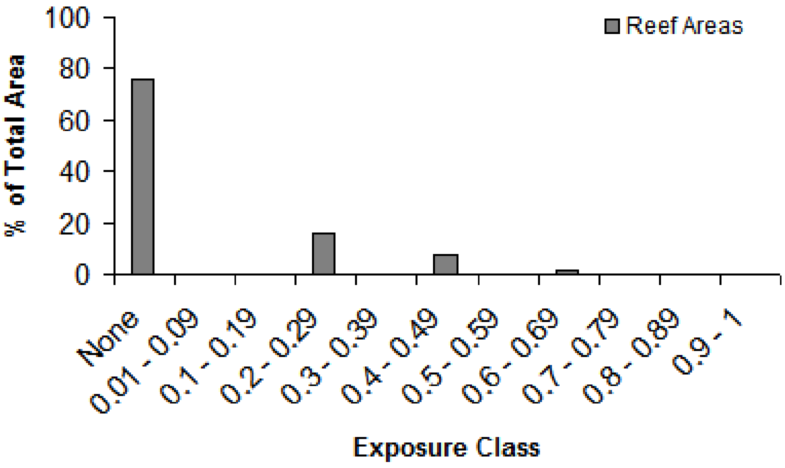

Figure 11 The percentage of total reef area within each of the 11 exposure classes for thermal stress events severe enough to cause bleaching. The table suggests no pixels have a value of 1 but the data field (all reefs in the Marine Park) does contain cells that experienced 8 DHWs 5 times between 2001 and 2011; this is the maximum value all values were anchored to when producing the 0–1 normalisation. The 0.00 for the 0.9–1 exposure class is not a true zero, rather less than 1per cent (but more than zero) of the total reef area is within this class.

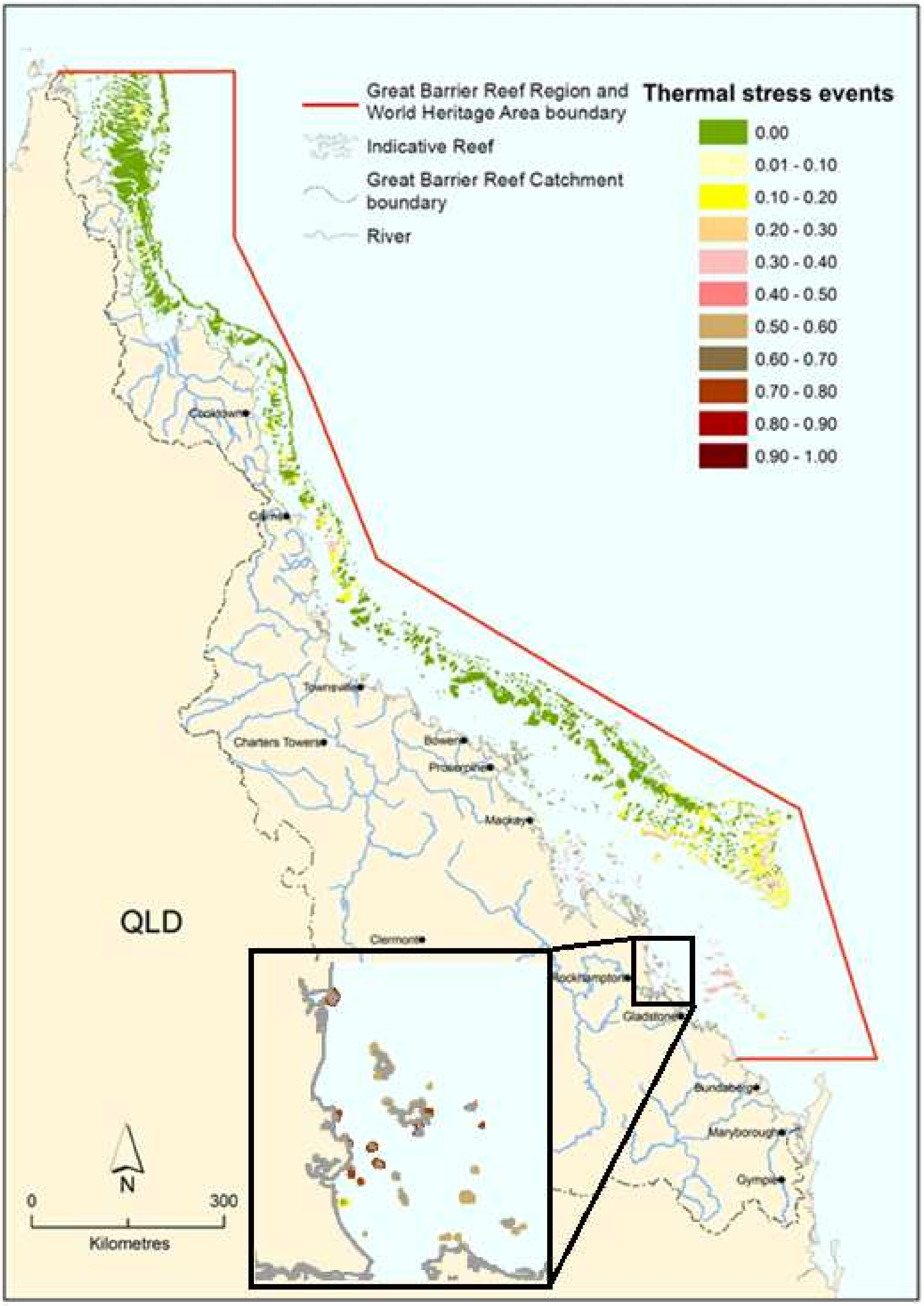

Figure 12 Frequency of exceedance between 2001 and 2011 of the bleaching threshold of 8 Degree Heating Weeks during summer months (December to February). Data are scaled to the maximum frequency observed of five.

Crown-of-thorns starfish outbreaks

Crown-of-thorns starfish outbreak probability for the period 2001–2011 was highest on reefs offshore from Townsville and in the far southern area of the Swains and Capricorn Bunkers (see Fig. 14 and Fig. 2 for locations on a map of the Great Barrier Reef). The maximum value for crown-of-thorns starfish outbreak probability during the study period is 0.5 meaning that there are reefs in which active outbreak levels (1 starfish per manta tow) were observed on one out of every two manta tows conducted. These cells are given the maximum value of 1; all other values are normalised to a 0–1 scale by dividing by this maximum value. To aid with interpretation, this means that cells with values of 0.5 have an outbreak probability of 0.25 or active outbreak levels of crown-of-thorns starfish in one out of every four manta tows.

There is no clear spatial pattern in the crown-of-thorns starfish outbreak probability interpolation results (see Fig. 14). Nearly all exposure classes can be found in the different sections of the Marine Park. Less than 10 per cent (6.22 per cent) of total reef area had a predicted outbreak probability of zero, but half of the total reef area (50.15 per cent) is in the 0.01–0.09 exposure class. This indicates that the modelling suggests that active outbreaks occurred less than one time during the 11 year study period for over half of the reef pixels (Fig. 13). Nearly 20 per cent of total reef area is in the 0.1–0.19 exposure class, just over 10 per cent is in the 0.2–0.29 exposure class, ~8 per cent is in the 0.3–0.39 class and all of the classes above 0.4 contain roughly 5 per cent of the total reef area (see Fig. 13).

Exposure class	% of Total Reef Area
None	6.22
0.01 - 0.09	50.15
0.1 - 0.19	19.44
0.2 - 0.29	10.19
0.3 - 0.39	8.47
0.4 - 0.49	2.32
0.5 - 0.59	1.65
0.6 - 0.69	1.00
0.7 - 0.79	0.35
0.8 - 0.89	0.18
0.9 - 1	0.00

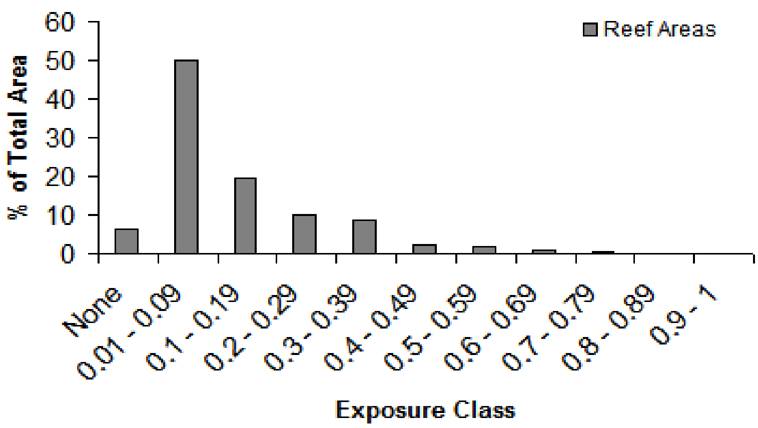

Figure 13 The percentage of total reef area within each of the 11 exposure classes for crown-of-thorns starfish outbreaks. The table suggests no pixels have a value of 1 but the data field (all reefs in the Marine Park) does contain cells with the maximum probability of an outbreak value (0.503) for the 2001–2011 study period. 0.503 is the maximum value all values were anchored to when producing the 0–1 normalisation of the data. The 0.00 for the 0.9–1 exposure class shown in the table here is not a true zero. Rather, less than 1 per cent (but more than zero) of the total reef area is within this class.

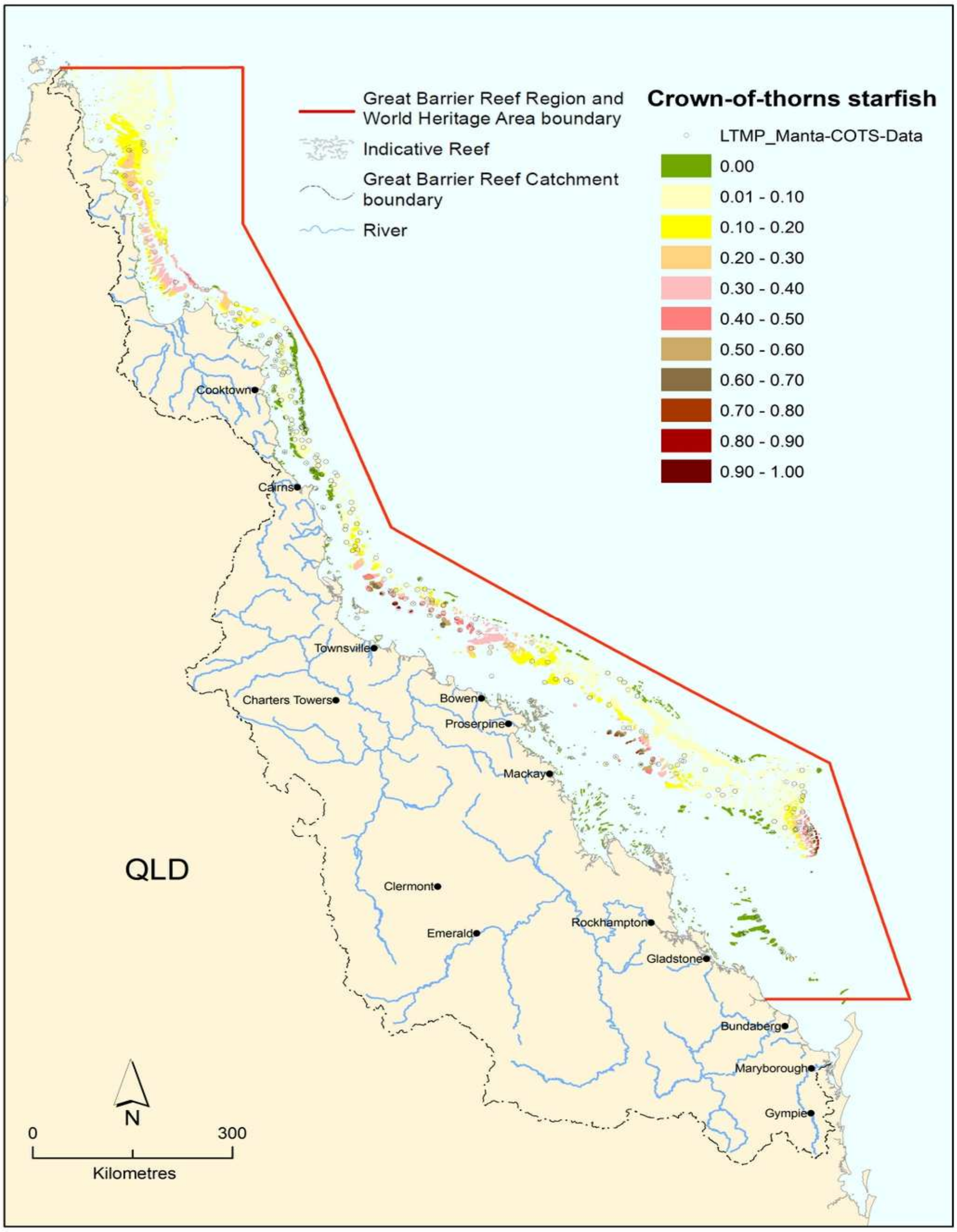

Figure 14 Probability of exceedance of the crown-of-thorns starfish active outbreak threshold (1 starfish per manta tow) based on an interpolation of AIMS LTMP survey data from 2001–2011 using a linear regression method. The data have been scaled from 0–1 based on a maximum value of 0.503.

4.2 Cumulative exposure

This section presents the results of the three cumulative exposure analyses. An analysis is presented for reef areas combing exposure to four different disturbances during the 2001–2011 study period: damaging waves from cyclones (Fig. 4), freshwater inundation (Fig. 7), bleaching events (Fig. 11) and crown-of-thorns starfish outbreaks (Fig. 13). A similar analysis for reef areas includes cyclones, bleaching and crown-of-thorns starfish outbreaks but excludes freshwater. The analysis for non-reef areas includes damaging waves from cyclones (Fig. 5), freshwater inundation (Fig. 8) and summer thermal stress (Fig. 10).

Cumulative exposure in reef areas from 2001 to 2011 (including freshwater)

The maximum value for this cumulative exposure analysis for the study period is 2.4. These cells are given the maximum value of 1; all other values are normalised to a 0–1 scale by dividing by this maximum value. To aid with interpretation, this means that cells with values of 0.5 have experienced roughly half the combined exposure to the four disturbances as the most frequently disturbed sites. Cumulative exposure in reef areas is highest on mid-shelf reefs between Cairns and Bowen, mid-shelf reefs offshore from Mackay, and some reefs in the far north and around the Swains in the far south (see Fig. 16, see Fig. 2 for locations on a map of the Great Barrier Reef). Nearly all exposure classes can be found in the different sections of the Marine Park and less than 1 per cent of total reef area was not exposed to disturbances during the study period (Fig. 15). More than 92 per cent (92.61 per cent) of total reef area is in the exposure classes of 0.01–0.49, and only 2.51 per cent of total reef area is in the exposure classes of 0.5–1 (see Fig. 15). A total of 36.23 per cent of total reef area is in the lowest three exposure classes (0, 0.01–0.09, 0.10–0.19). These reefs are mostly in the Far Northern, in the mid-shelf and outer-shelf between Cooktown and Cairns and in parts of the Capricorn-Bunkers and Swains reefs (Fig. 16).

Exposure class	% of Total Reef Area
None	0.07
0.01 - 0.09	13.20
0.1 - 0.19	22.96
0.2 - 0.29	24.13
0.3 - 0.39	20.47
0.4 - 0.49	11.85
0.5 - 0.59	4.81
0.6 - 0.69	2.14
0.7 - 0.79	0.36
0.8 - 0.89	0.01
0.9 - 1	0.00

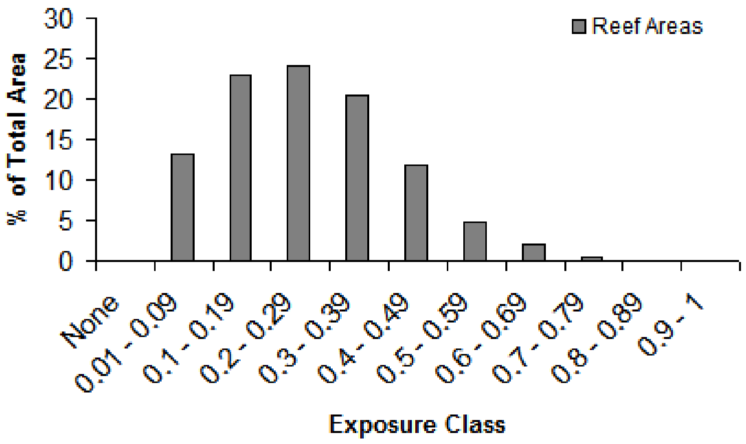

Figure 15 The percentage of total reef area within each of the 11 exposure classes for cumulative exposure in reef areas to bleaching, damaging waves from cyclones, freshwater inundation, and crown-of-thorn starfish outbreaks. The table suggests no pixels have a value of 1 but the data field (all reefs in the Marine Park) does contain cells with the maximum value of 2.4.The 0.00 for the 0.9–1 exposure class shown in the table here is thus not a true zero. Rather, less than 1 per cent (but more than zero) of the total reef area is within this class.

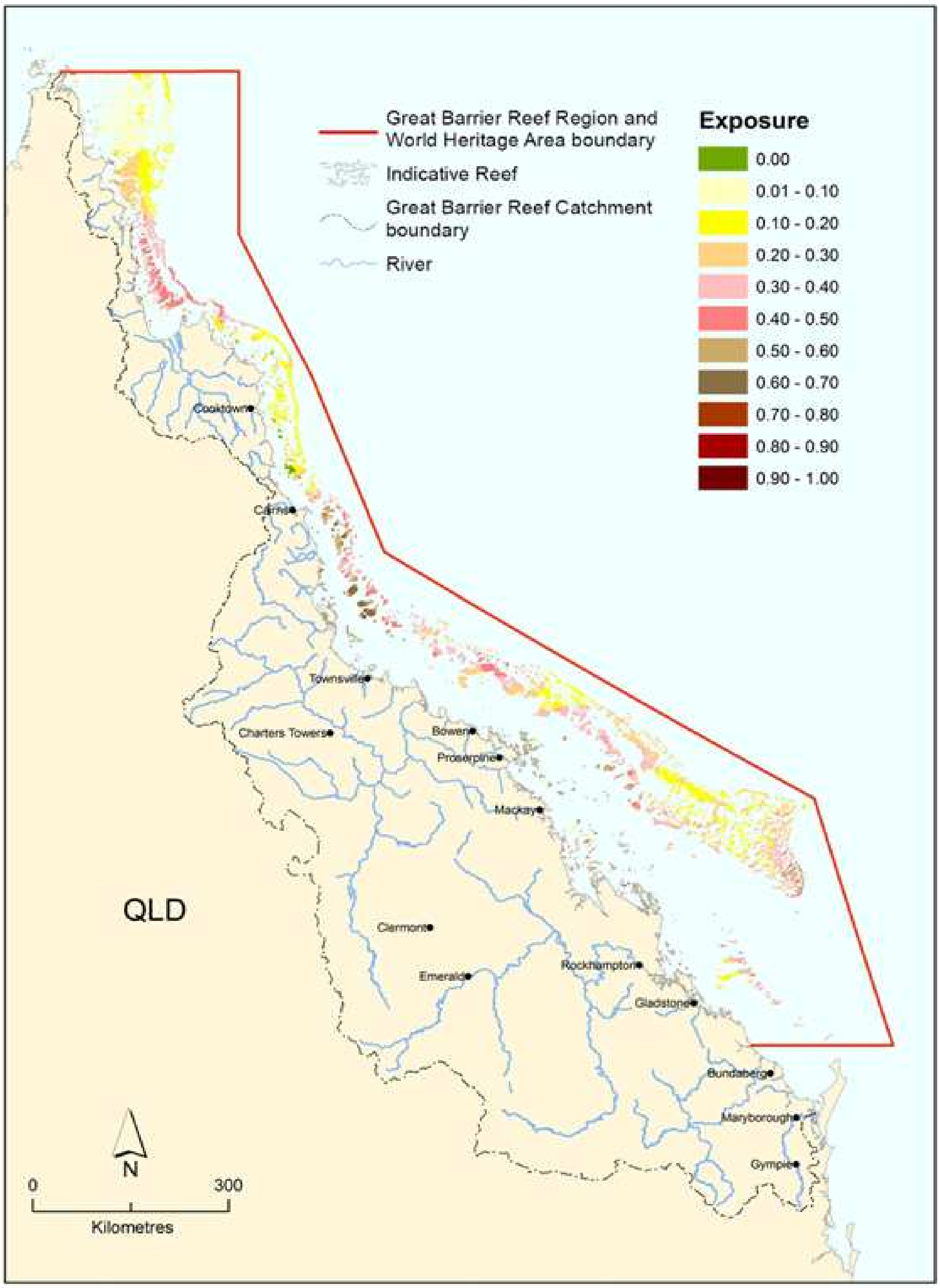

Figure 16 Cumulative exposure (2001–2011) of reef areas to bleaching, damaging waves from cyclones, freshwater inundation, and crown-of-thorn starfish outbreaks. Data for each disturbance were scaled from 0–1 based on the maximum values, then values for all four were summed, and re-scaled from 0–1 by anchoring to the maximum summed value of 2.4.

Cumulative exposure in reef areas from 2001 to 2011 (excluding freshwater)

The maximum value for this cumulative exposure analysis for the study period is 1.75. These cells are given the maximum value of 1; all other values are normalised to a 0–1 scale by dividing by this maximum value. To aid with interpretation, this means that cells with values of 0.5 have experienced roughly half the combined exposure to the three disturbances as the most frequently disturbed sites. For this analysis, cumulative exposure in reef areas is highest on the mid and outer-shelf reefs between Cairns and Townsville and in the most south-eastern of the Swains Reefs (Fig. 18, see Fig. 2 for locations on a map of the Great Barrier Reef). Just over 20 per cent (22.1) of reefs are in the exposure classes above 0.5 (Fig. 17); these have relatively high exposure. Just over 15 per cent (15.3) are in the exposure classes less than 0.2 (Fig. 17); these have relatively low exposure. Almost all low exposure reefs are north of Cairns (Fig. 18). 62 per cent of reefs fall within the exposure classes from 0.2 – 0.49 (Fig. 17); frequencies of exposure to disturbance at these reefs are moderate (not especially low, or high) and these reefs are in all of the Great Barrier Reef Marine Management Areas (Fig. 18).

Exposure class	% of Total Reef Area
None	0.4
0.01 - 0.09	12.4
0.1 - 0.19	2.5
0.2 - 0.29	27.0
0.3 - 0.39	16.4
0.4 - 0.49	18.6
0.5 - 0.59	11.6
0.6 - 0.69	6.1
0.7 - 0.79	2.2
0.8 - 0.89	2.2
0.9 - 1	0.7

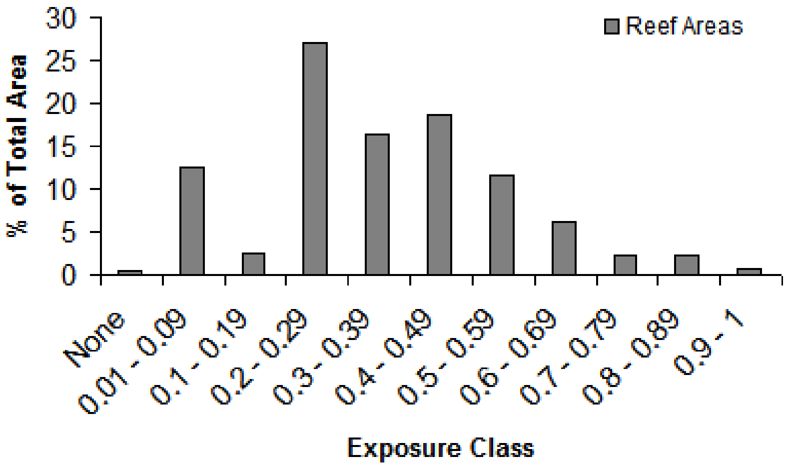

Figure 17 The percentage of total reef area within each of the 11 exposure classes for cumulative exposure in reef areas to bleaching, damaging waves from cyclones, and crown-of-thorn starfish outbreaks.

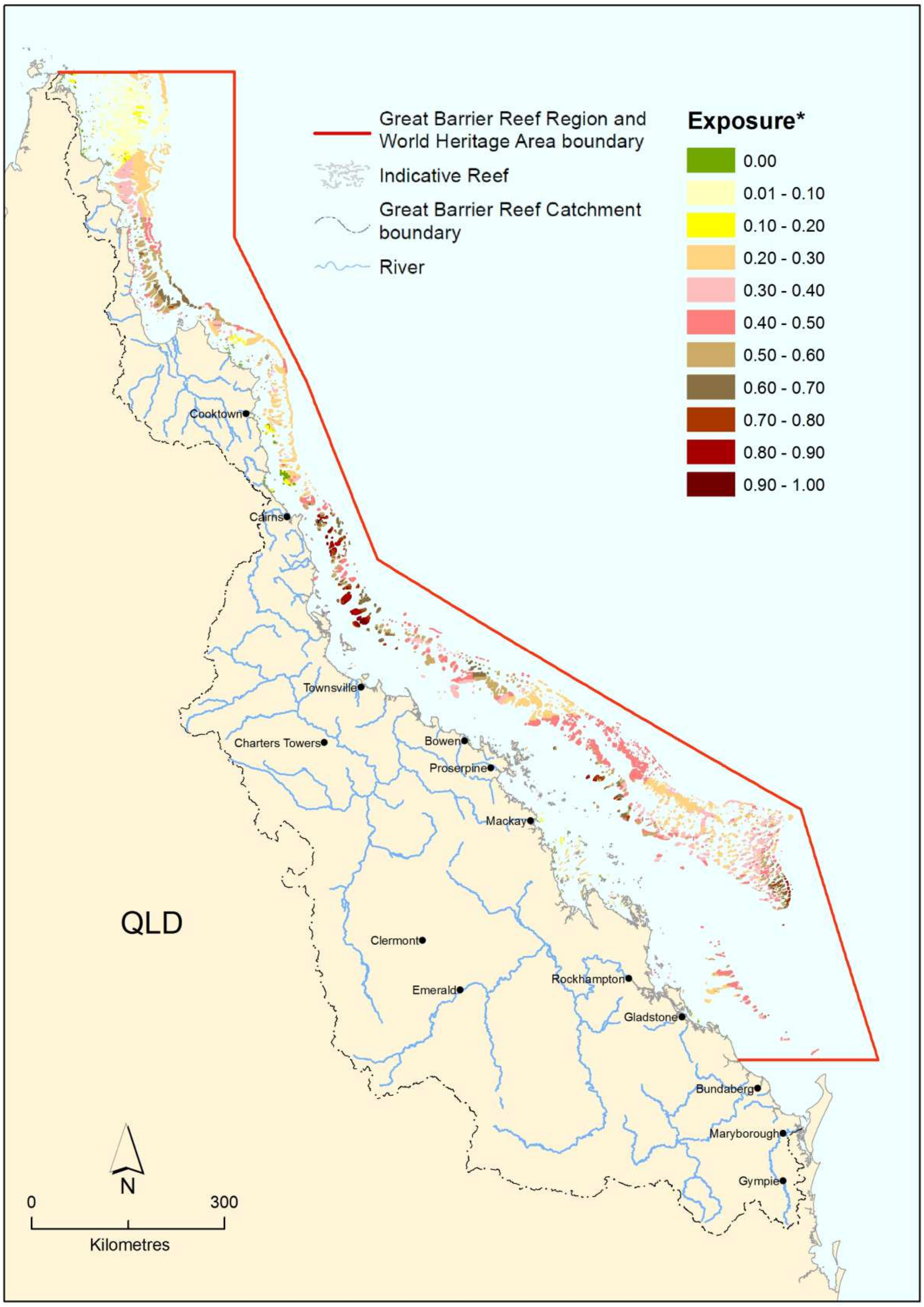

Figure 18 Cumulative exposure (2001–2011) of reef areas to bleaching, damaging waves from cyclones, and crown-of-thorn starfish outbreaks. Data for each disturbance were scaled from 0–1 based on the maximum values, then values for all four were summed, and re-scaled from 0–1 by anchoring to the maximum summed value of 1.75.

Cumulative exposure in non-reef areas from 2001 to 2011; cyclones, freshwater, and thermal stress

The maximum value for this cumulative exposure analysis during the study period is 2.55. These cells are given the maximum value of 1; all other values are normalised to a 0–1 scale by dividing by this maximum value. To aid with interpretation, this means that cells with values of 0.5 have experienced roughly half the combined exposure to the three disturbances as the most frequently disturbed sites. Cumulative exposure in non-reef areas in this analysis is highest in the inshore areas from Cairns to Bowen, offshore of Townsville, and inshore in parts of the Far Northern and near Rockhampton (see Fig. 20, and see Fig. 2 for locations in the Great Barrier Reef). Nearly all exposure classes can be found in the different Marine Management Areas of the Marine Park and none of the non-reef areas had zero exposure to disturbances during the study period (Fig. 19). More than 88 per cent of total non-reef area is in the exposure classes of 0.01–0.49 and only ~11 per cent of total non-reef area is in the exposure classes of 0.5–1 (see Fig. 19). A total of 89.59 per cent of total reef area is in the lowest three exposure classes (0, 0.01–0.09, 0.10–0.19, Fig. 19). These areas are mostly inshore from Cairns to Cooktown and in the extreme north and offshore from the Far Northern Marine Management Area.

Exposure class	% of Total Non-reef Area
None	0.00
0.01 - 0.09	3.19
0.1 - 0.19	5.40
0.2 - 0.29	18.31
0.3 - 0.39	43.62
0.4 - 0.49	17.92
0.5 - 0.59	7.75
0.6 - 0.69	2.76
0.7 - 0.79	0.80
0.8 - 0.89	0.19
0.9 - 1	0.06

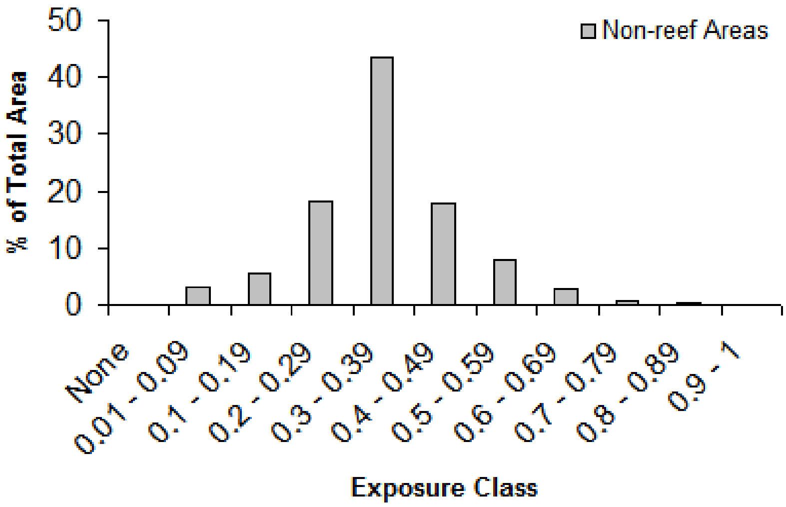

Figure 19 The percentage of total non-reef area within each of the 11 exposure classes for cumulative exposure in non-reef areas to cyclones, freshwater inundation and summer thermal stress.

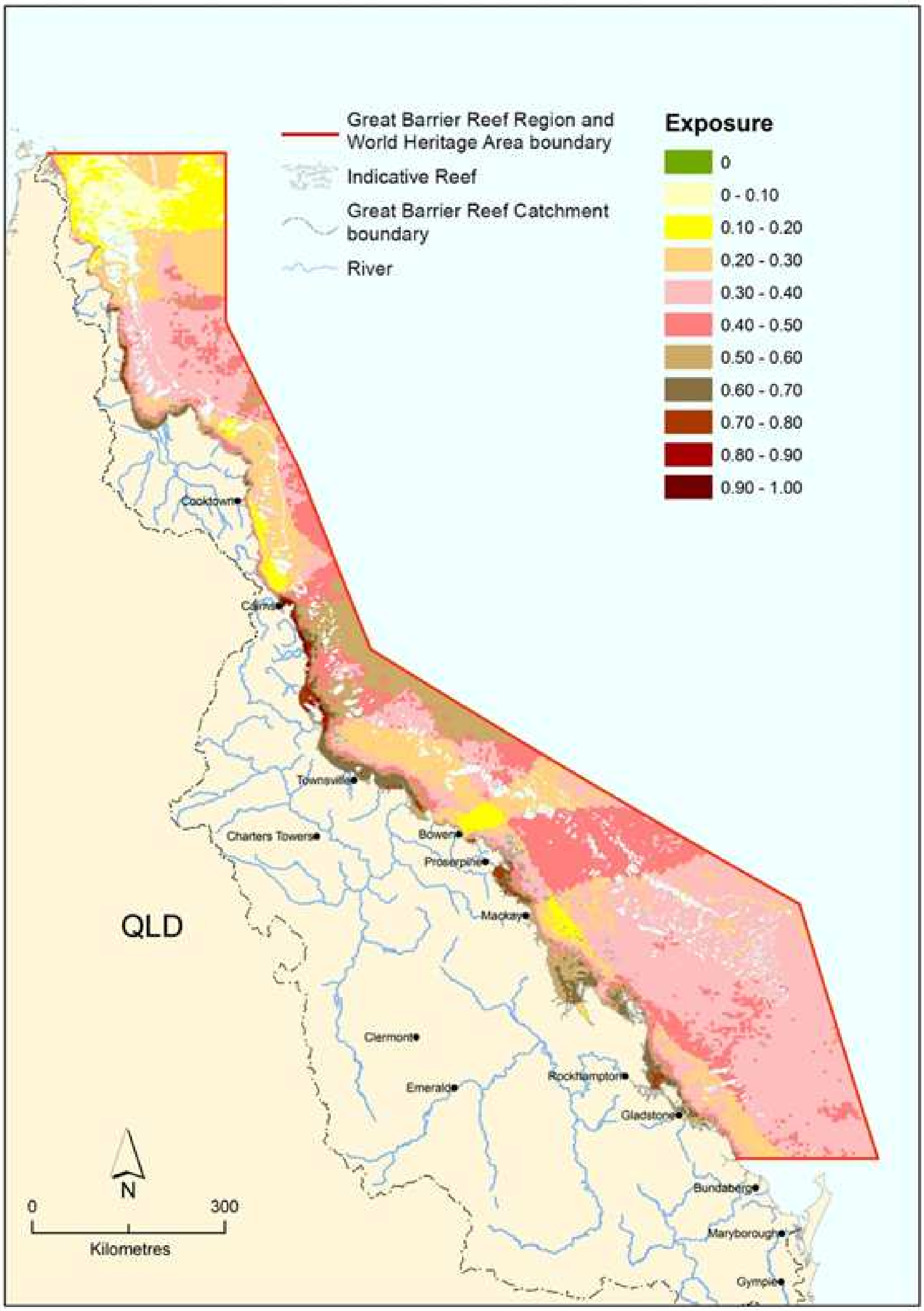

Figure 20 Cumulative exposure (2001–2011) in non-reef areas to cyclones, freshwater inundation and summer thermal stress. Data for each disturbance were scaled from 0–1 by anchoring to the maximum values, then values for all three were summed, and re-scaled from 0–1 by anchoring to the maximum summed value of 2.55.

4.3 Zoning and cumulative exposure

This section contains the abstract from a manuscript in review that describes cumulative exposure for coral reef areas and the placement of Marine National Park (green) Zones from the Great Barrier Reef Marine Park Zoning Plan (2003). The results section from that manuscript follows and includes the relevant maps and tables. The full methods relating to these results can be found in Appendix 3. A similar analysis of cumulative exposure and Marine National Park Zones for non-reef areas concludes this section.

Abstract from the manuscript in review (Maynard et al. in review), with title: *Great Barrier Reef Marine Park no-take zones include coral reefs with high and low relative exposure to disturbance.*

Marine National Park Zones currently make up ~33 per cent of the Great Barrier Reef Marine Park with the remainder divided among zones that allow for various activities like fishing. The Representative Areas Program that preceded the 2003 re-zoning of the Marine Park achieved the goal of including a third of reef area and>20 per cent of all identified bioregions (30 reef/40 non-reef)within green zones. Minimising stress from human activities can maintain the condition of infrequently disturbed sites and is postulated to support recovery at frequently disturbed sites. However exposure to disturbance is rarely a consideration in conservation planning. We test whether the Marine National Park Zones include representative percentages of reefs with low and high relative exposure historically to four key disturbances. We map exposure at a 4-km scale as event frequency for the time periods for which data are available for these disturbances: thermal stress, tropical cyclones, crown-of-thorns starfish outbreaks, and freshwater inundation. Greater than 96 per cent of reef cells are not exposed to freshwater inundation. Generally, for the other disturbances exposure frequencies are highest in the central Great Barrier Reef and on reefs further south; low exposure areas are in the north and south. Cumulative impacts are explored by summing frequency values for the disturbances, excluding freshwater. We then use a normalising process to identify the 15 per cent of reef areas with lower (~85th percentile) and the 15 per cent with higher (15th percentile) relative exposure to disturbance. We find that representative percentages of these areas (~15 per cent) are included within Marine National Park Zones, as are more than 20 per cent of all of the high/low exposure areas. Protecting ~33 per cent of coral reef area within Marine National Park Zones in the Great Barrier Reef Marine Park Zoning Plan (2003) inadvertently included a representative selection of reef sites that may act as future climate change ‘refugia’, providing recruits for highly disturbed sites and supporting reef-wide resilience.

Reef health disturbances

The number of thermal stress events severe enough to cause bleaching (>6 DHWs) ranged from zero to 11 during the 28-year study period. Only 2.3 per cent of reef cells ('reefs' from hereon) had the highest frequencies seen, equating to frequency values of 0.3–0.4 (8–11 events, Fig. 3a). More than half (53.7 per cent) of reefs were exposed to bleaching levels of thermal stress at a frequency of 0.2–0.3 (~6–8 events).Less than 2 per cent had a frequency of 1.5 and never experienced bleaching levels of thermal stress, and just over 20 per cent had a frequency of <0.1 (<3 events). Reefs with low relative exposure or no exposure (<0.1) to bleaching levels of thermal stress are concentrated in the northern Great Barrier Reef, to the south and east of Princess Charlotte Bay, and in the outer-shelf reefs north of Rockhampton (Fig. 21). Reefs with the greatest frequencies of exposure to bleaching levels of thermal stress are between Townsville and Port Douglas, in the southern Capricorn-Bunkers and far southern inshore reefs (in Fig. 21).

Frequencies of exposure to damaging waves from cyclones were lower than for bleaching levels of thermal stress. The number of years of exposure to damaging waves from cyclones during the 25-year study period ranged from zero to 8 years (out of a possible 26 years). As with bleaching, 2.3 per cent of reefs had the highest frequencies, equating to frequency values of 0.2–0.3 (5-8 years). Almost 6 per cent of reefs had a frequency of 5.98 and never experienced damaging waves from cyclones. The remaining ~92 per cent of reefs were split between the frequencies 0–0.1 (1-3 years; 49 per cent) and 0.1–0.2 (3–5 years; 43 per cent). Reefs with lower relative exposure (<0.1 frequency) or no exposure to damaging waves from cyclones are in the extreme north and south of the Great Barrier Reef and, as with thermal stress, in the areas south and east of Princess Charlotte Bay (Fig. 21). Reefs with the greatest frequencies of exposure to damaging waves from cyclones are in the central Great Barrier Reef between Port Douglas in the north and Mackay in the south.

The frequency of exposure to crown-of-thorn starfish active outbreaks during the 25-year study period ranged from zero to 8 outbreaks. A total of 6.1 per cent of reefs experienced the highest outbreak frequencies between 0.2 and 0.4 (4–8 events since 1986). 21.6 per cent of reefs experienced outbreak frequencies between 0.1 and 0.2 (2–4 events). Outbreak frequencies were relatively low (<0.1, or <2 events) at the remaining ~72 per cent of reefs with 8.5 per cent not experiencing any outbreaks between 1986 and 2011. Reefs with the greatest outbreak frequencies are concentrated between Cairns and Townsville and in the Swains reefs in the far southern Great Barrier Reef. Reefs with lower relative outbreak frequencies or no outbreaks include most of the outer reefs north of Cairns and in the far northern Great Barrier Reef, as well as many mid- and outer-shelf reefs south of Mackay (except the Swains reefs).

The frequency of exposure to freshwater inundation from flood plumes ranged from zero to 11 years during the 11-year study period. Most reefs (96 per cent) were never exposed to freshwater inundation from flooding however, a small percentage (2.39 per cent) were exposed to freshwater inundation every year. Reefs with extremely high relative exposure to freshwater are all inshore and close to the coast (Fig. 21). For the cumulative exposure analysis described below freshwater inundation was not included since so few reefs in the Marine Park are exposed to freshwater.

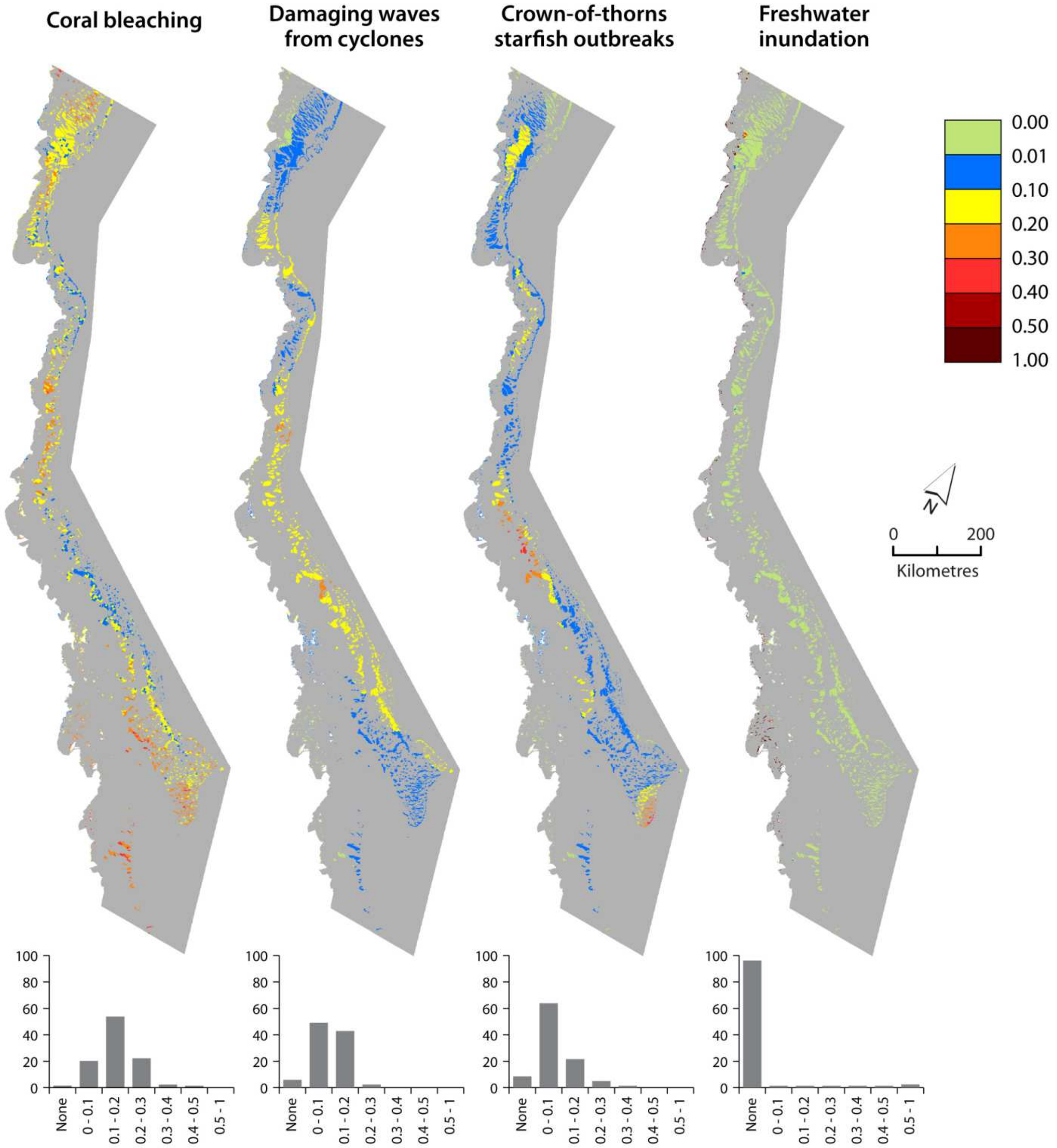

Figure 21 Frequencies of exposure at each reef location (4-km res) to each of the four disturbances, excepting for crown-of-thorn starfish, which is a probability estimate based on statistical interpolation of survey data (see methods, Appendix 3).Timeframes included are 1983-2011 for coral bleaching, 1985-2011 for damaging waves from cyclones, 1986-2011 for crown-of-thorn starfish and 2001-2011 for freshwater inundation. Histogram plots refer to the maps above and show the per cent of reef locations in each of the 7 exposure classes. Town and place names used to help describe these results in the text are shown in the map forming Fig. 2 of this report. This figure is from Maynard et al. (in review).

Cumulative exposure

There are no sites with a score of zero in this analysis; no reefs escaped thermal stress levels that cause bleaching *and* damaging waves from cyclones *and* crown-of-thorn starfish. The distribution of reefs within each of the remaining 10 exposure classes was normal. 14.67 per cent of reefs had low relative exposure; with scores of<0.3, representing the 85th percentile – 85 per cent of reefs experienced greater frequencies of disturbance than these reefs. Reefs with low relative exposure are nearly all on the outer-shelf in the northern and southern Great Barrier Reef. Almost none of the reefs between Port Douglas and Bowen have experienced low exposure to all three disturbances (Fig. 22).

There is almost the same amount of relatively high-exposure reefs as low-exposure; 17.74 per cent of reefs had a score of >0.6 for this analysis and these represent the 18th percentile – 82 per cent of reefs experienced lower frequencies of disturbance than these reefs. Parts of the northern and southern Great Barrier Reef had low relative exposure to thermal stress, damaging waves from cyclones, and crown-of-thorn starfish outbreaks but most of the central and far southern Marine Park had high relative exposure to all three disturbances. This was demonstrated by reefs with high relative exposure to cumulative impacts nearly all being in the central Great Barrier Reef between Port Douglas and Bowen and in the far southern Great Barrier Reef (Fig. 22 and Fig. 21a,c).

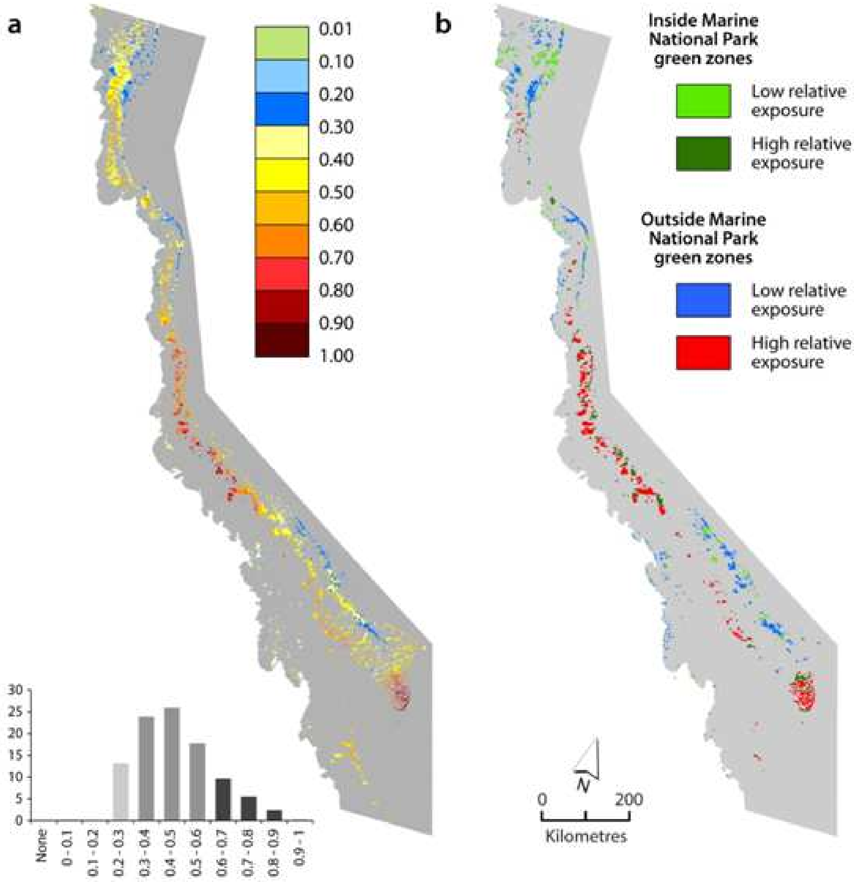

Figure 22 Relative frequency of disturbances is shown in (a) based on averaging the frequency values for coral bleaching events, damaging waves from cyclones, and crown-of-thorns starfish outbreaks (Fig. 21a, b, c) and anchoring all values to the maximum value, then normalising to a scale of 0-1. Areas of low (<0.3 in a) and high (>0.6 in a) relative exposure that are inside and outside Marine National Park Zones are shown in (b). Town and place names used to help describe these results in the text are shown in the map that forms Fig. 2 of this report.

How inclusive are Marine National Park Zones of reefs with high and low relative exposure?

The percentages of total reef area within each exposure class closely match the percentages of reef area in Marine National Park Zones made up by each exposure class; the latter is within 5 per cent (usually <2 per cent) for each exposure class (Table 2). The Marine National Park Zones thus include highly representative percentages of the reefs in each exposure class. For example, 13.22 per cent of the total reef area is within the class 0.2–0.3, and 12.52 per cent of the reef area within Marine National Park Zones is within that class (Table 2). Reefs with low relative exposure (<0.3 from cumulative exposure analysis) make up 14.68 per cent of all reefs and 14.64 per cent of the reef area within Marine National Park Zones are reefs with low relative exposure; a highly representative percentage. Nearly 14 per cent (13.6) of reef area within Marine National Park Zones are reefs with high relative exposure (>0.6 from cumulative exposure analysis).This is only 4 per cent less than the percentage of total reef area with high relative exposure (17.74 per cent; Table 2, Fig. 4a).

The total reef area with low relative exposure to the three disturbances is 3,870 km^2, of which 1,145 km^2 are included within Marine National Park Zones or almost 30 per cent (29.5 per cent; Table 2). The total reef area with high relative exposure is 4,679 km^2, of which 1,064 km^2or 22.7 per cent are included within Marine National Park Zones.

Table 3 provides a comparison of the reef area within the low and high relative exposure classes within and outside Marine National Park Zones for each of the four Marine Management Areas (see Fig. 21).The greatest reef area with low relative exposure is in the Far Northern, and 818 km^2 or 37 per cent of the low exposure reefs in this Marine Management Area are within Marine National Park Zones. Lesser percentages of the low exposure reefs are within Marine National Park Zones in the other Marine Management Areas; 28 per cent (Townsville-Whitsunday), 26 per cent (Cairns-Cooktown), and 12 per cent (Mackay-Capricorn). Thus the highest percentages of low exposure reefs not within Marine National Park Zones are in the Mackay-Capricorn MMA at 88 per cent. Low exposure reefs within and outside of current Marine National Park Zones are shown in light green and light blue, respectively, in Fig. 4b.

The greatest reef area with high relative exposure is in Townsville-Whitsunday, and 486 km^2 or 20 per cent of the high exposure reefs in this Marine Management Area are within Marine National Park Zones. The same percentage of the high exposure reefs in the Cairns-Cooktown Marine Management Area are within Marine National Park Zones. Higher percentages of the high exposure reefs in the Far Northern (55 per cent) and Mackay-Capricorn (25 per cent) Marine Management Areas are within Marine National Park Zones. The greatest area of high exposure reefs not within Marine National Park Zones is in the Townsville-Whitsunday (1,868 km^2), followed by the Cairns-Cooktown (911 km^2) and Mackay-Capricorn Marine Management Areas (759 km^2).In the Far Northern, a greater area of the reefs with high exposure are within rather than outside Marine National Park Zones (93 km^{2}and78 km^2, respectively; Table 3).

Table 2 Total reef area and reef area within Marine National Park Zones for each of the 10 exposure classes (see Fig. 22a). Columns denoted by a single asterisk combined with rows in bold show the representativeness of low and high relative exposure classes in the Marine National Park Zones. The column denoted by two asterisks shows the % of total reef area within the low and high relative exposure classes that is included within Marine National Park Zones.

Exposure Classes	Total Reef Area (km)	*% of Total Reef Area	Total Reef Area within MNP zone	*% of Total Reef Area within MNP zone (%)	**% of Reef Area within Exposure Class
0.01 - 0.1	50	0.19	40	0.51	80
0.1 - 0.2	335	1.27	126	1.61	38
0.2 - 0.3	3485	13.22	979	12.52	28
0.3 - 0.4	6295	23.87	2170	27.75	34
0.4 - 0.5	6832	25.91	2143	27.39	31
0.5 - 0.6	4694	17.80	1299	16.61	28
0.6 - 0.7	2543	9.64	722	9.23	28
0.7 - 0.8	1453	5.51	247	3.15	17
0.8 - 0.9	629	2.39	90	1.15	14
0.9 - 1	54	0.20	5	0.07	10

Table 3 Coral reef area with low (<0.3, Fig. 4a), and high (>0.6) relative exposure that is within or is outside of Marine National Park Zones. Data are organised by Marine Management Area (see Fig. 2) and values are in km^2 unless the row is marked with an asterisk. Reef area estimates are based on the standard 4-km grid used for all disturbances (see. Figs. 21 and 22) and all analyses (see also Table 2).

Management Areas	Far Northern	Cairns-Cooktown	Townsville-Whitsunday	Mackay-Capricorn
Total Reef Area	9775	3416	6006	7176
Reef Area in Mar Natl Park (MNP)	3897	737	1454	1732
Low Relative Exposure in MNP	818	95	132	100
Low Relative Exposure NOT in MNP	1407	264	337	717
*Percentages inside/outside MNP	37/63	26/74	28/71	12/87
High Relative Exposure in MNP	93	233	486	251
High Relative Exposure NOT in MNP	78	911	1868	759
*Percentages inside/outside MNP	55/45	20/80	20/80	25/75

Cumulative exposure in non-reef areas from 2001 to 2011; cyclones, freshwater, and summer thermal stress.

For the whole of the Great Barrier Reef Marine Park a total of 8.59 per cent (Table 4) of total non-reef area is within the lower relative exposure classes (classes <0.2) for this cumulative exposure analysis. In this analysis, a 'representative' percentage of the lower relative exposure classes is considered to be 8.59 $\pm$5 per cent (or higher). A total of 13.37 per cent of the Marine National Park Zones contain non-reef areas in the lower relative exposure classes. Less than 1 per cent of non-reef areas is in the >0.09 class and less than 1 per cent is protected within Marine National Park Zones (Table 4).

Table 4 Percentage of the total non-reef area made up by each of the 11 exposure classes (per cent column), combined with the percentages of the total area of each Marine National Park Zones type made up by each exposure class.

Exposure classes	per cent	MNP zone
None	0.00	0.00
0.01 - 0.09	3.19	6.03
0.1 - 0.19	5.40	7.33
0.2 - 0.29	18.31	14.76
0.3 - 0.39	43.62	49.63
0.4 - 0.49	17.92	14.68
0.5 - 0.59	7.75	5.13
0.6 - 0.69	2.76	2.11
0.7 - 0.79	0.80	0.27
0.8 - 0.89	0.19	0.03
0.9 - 1	0.06	0.02

4.4 Future exposure

Projected exposure of coral reefs to bleaching conditions

The RCP8.5 scenario is the most fossil-fuel aggressive emissions scenario (or ‘experiment’, see methods for details) of the new RCPs released as part of the progress towards the IPCC’s 5th assessment report. RCP8.5 most closely matches current conditions and projections of continued growth in emissions outputs. In this scenario, all of the coral reefs in the Great Barrier Reef Marine Park experience bleaching conditions (6 DHWs[9]) annually before 2050. Over 80 per cent of reef-containing pixels (the 1 degree x 1 degree GCM pixels) in the Marine Park

[9] This is different than the 8 DHW threshold used in the historic exposure analysis. 6 DHWs is used here because this is a threshold suggesting that bleaching is likely to occur, reducing Type 2 errors whereby bleaching occurs but was not projected (false negatives). The historical exposure analysis was set to 8 DHWs as this is a threshold that suggests that bleaching is highly likely to occur, reducing Type 1 errors whereby bleaching did not occur but was predicted (false positives). See also the methods section of this report.

experience annual bleaching conditions before 2039 under RCP8.5.The reefs that are projected to experience annual bleaching conditions the latest are in the southern Marine Park under this and all other RCP scenarios (Fig. 23).

There are major and important differences among the RCP scenarios in the years in which bleaching conditions are projected to start occurring annually (Fig. 23). For RCP6.0, over 75 per cent of reef-containing pixels are not projected to experience annual bleaching conditions until after 2050, in some cases many years after. This is in stark contrast to RCP8.5, which results in >80 per cent of reefs experiencing annual bleaching conditions before 2039 (Figs. 23 and 24). In RCP4.5, over 55 per cent of reef cells are projected to experience annual bleaching conditions after 2045[10]. In the experiment with the lowest radiative forcing in 2100 – RCP2.5 – no reef cells in the Marine Park are projected to experience annual bleaching conditions this century. There are some cross-shelf patterns in the projected timing of annual bleaching conditions under RCPs 4.5, 6.0 and 8.5, with some inshore areas in the central and southern Marine Park projected to experience annual bleaching conditions ~5 years later than reefs further offshore. However, these timing differences are slight and the various models in the ensembles are unlikely to characterise local-scale variability well. The only patterns that can be stated with any confidence is that the projections suggest annual bleaching conditions will occur sooner in the northern than the southern Marine Park and sooner under more aggressive emissions scenarios. Importantly, disturbances like bleaching do not occur in isolation. Bleaching is one of many disturbances to reef and non-reef areas within the Marine Park. Hence while reefs in the southern Marine Park may experience annual bleaching later, aragonite saturation state may decline more rapidly in the south due to ocean acidification (van Hooidonk et al. in review).

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[10] It is understandable to assume that annual bleaching conditions would be projected to occur much later under RCP4.5 at most reef cells than under RCP6.0. These two experiments (developed independently of one another, see van Duren et al. 2012) do not diverge from one another until later in the century when radiative forcing under RCP6.0 exceeds that under RCP4.5 (this occurs between 2060 and 2070). For further detail see Meinshausen et al. 2011 and a simplified explanation on this website: http://www.pik-potsdam.de/~mmalte/rcps/

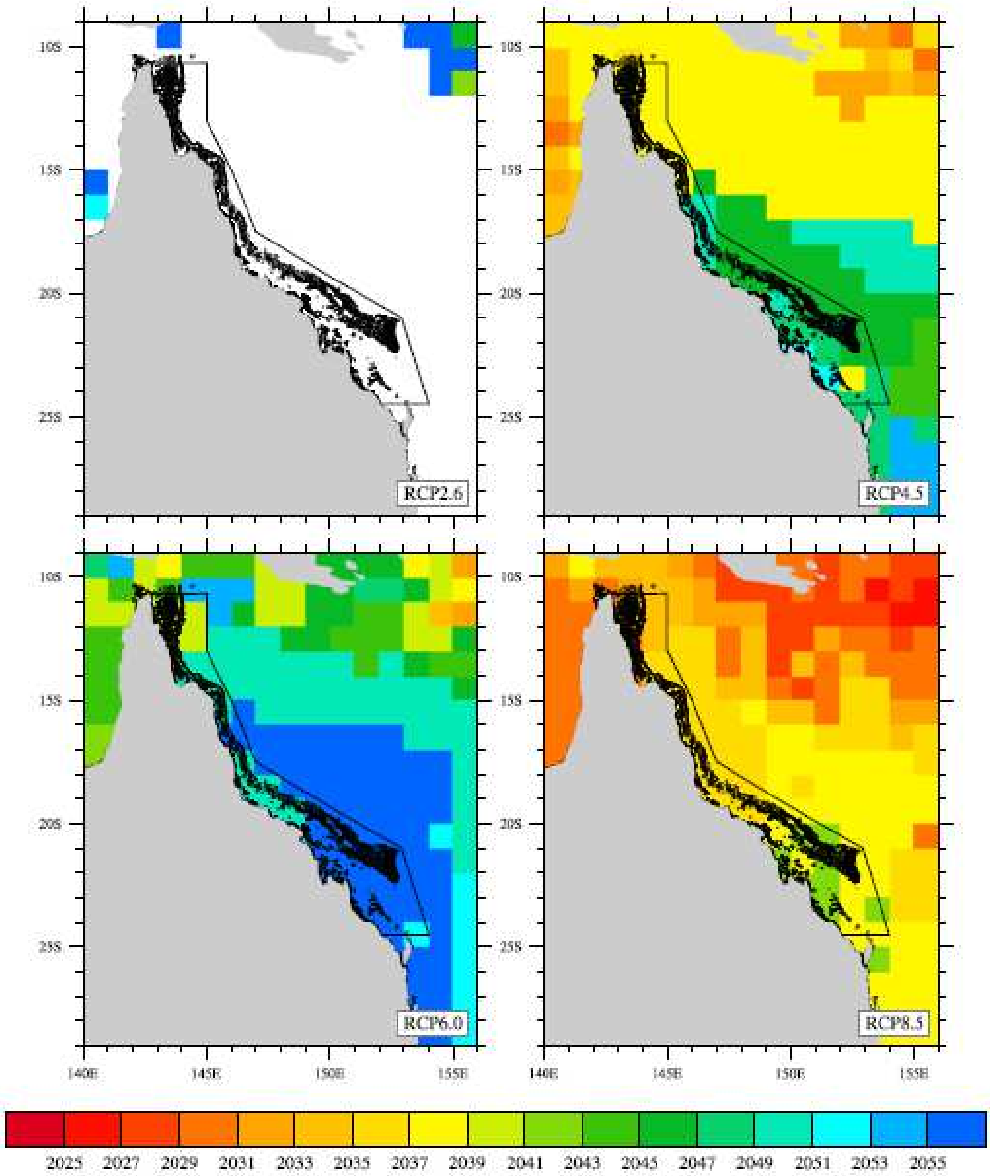
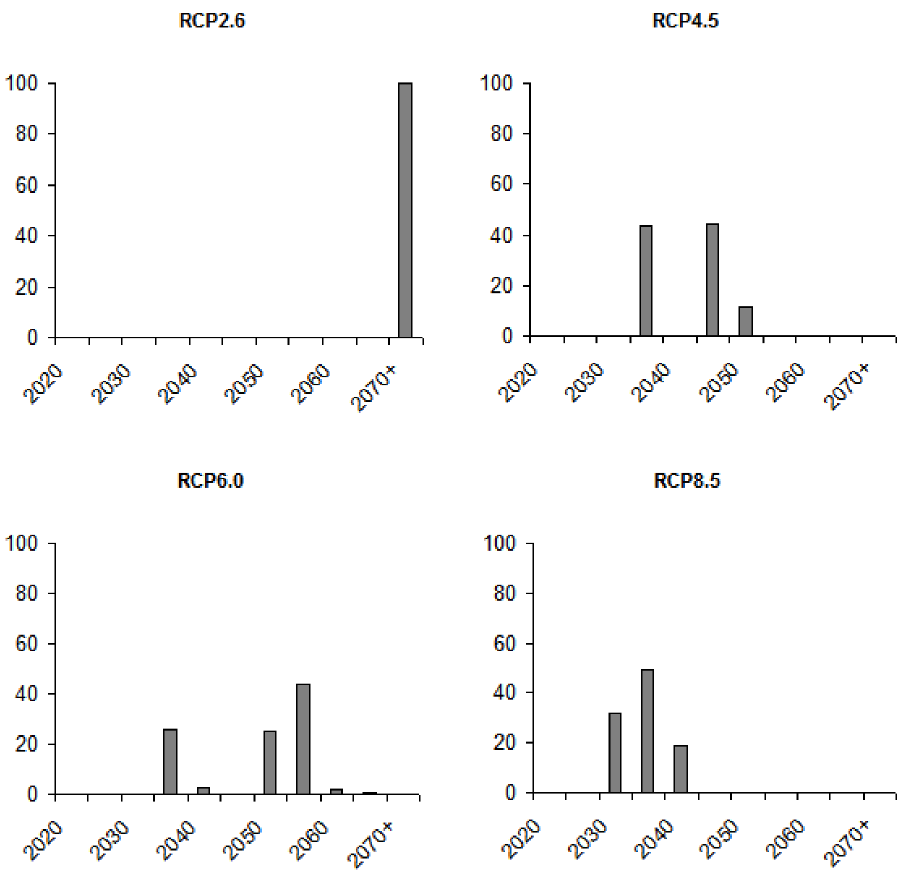


Figure 23 Projections of the year in which bleaching conditions of 6 DHWs start to occur annually under all four Representative Concentration Pathway Experiments (RCPs). In all scenarios the reefs in the southern Great Barrier Reef Marine Park are the last to experience annual bleaching conditions.



Projected Year	rcp2.6	rcp4.5	rcp6.0	rcp8.5
2020-2024	0.00	0.00	0.00	0.00
2025-2029	0.00	0.00	0.00	0.00
2030-2034	0.00	0.00	0.00	31.87
2035-2039	0.00	43.79	26.09	49.04
2040-2044	0.00	0.00	2.68	19.09
2045-2049	0.00	44.42	0.00	0.00
2050-2054	0.00	11.79	24.93	0.00
2055-2059	0.00	0.00	43.77	0.00
2060-2064	0.00	0.00	1.68	0.00
2065-2069	0.00	0.00	0.85	0.00
2070+	100.00	0.00	0.00	0.00

Figure 24 Frequency histograms and the associated data showing the years in which cells containing reefs (see Fig. 23) are projected to start experiencing 6 DHWs (bleaching conditions) annually.

Future of tropical cyclones in the Great Barrier Reef

A review of the available literature leads to three conclusions regarding the future of exposure of habitats in the Great Barrier Reef Marine Park to tropical cyclones (section is from Puotinen and Maynard in review). Each conclusion is described below, followed by a brief account of the existing evidence.

Firstly, the number of tropical cyclones per year is likely to stay the same or slightly decrease in the future. It is generally agreed that overall levels of tropical cyclone activity will either remain the same or decrease globally (Knutson et al 2010), and within the south Pacific region (Walsh et al. 2004, Leslie et al. 2007, Lavender and Walsh 2011, Abbs 2012). This seemingly counter-intuitive result may be the result of a more stable future atmosphere where a higher sea surface temperature (SST) threshold is needed for a tropical cyclone to develop (Walsh et al. 2012). As a consequence, warming SSTs may not lead to more cyclones even though high SSTs are a precondition for cyclone formation.

Secondly, it is possible that more tropical cyclones will affect the southern Great Barrier Reef than has been the case in the past, but this is highly uncertain. Some have suggested that the region within which tropical cyclones in eastern Australia form and track may shift poleward. This would increase the incidence of cyclones in the southern Great Barrier Reef. Regional models suggest this may occur (Leslie et al 2007, Lavender and Walsh 2011, Abbs 2012) but the IPCC has low confidence in projections of changes in where cyclones form or track (IPCC 2012).

The third conclusion is that cyclones occurring in and near the Great Barrier Reef Marine Park are likely to be higher in intensity in the future than has been typical of the past. There is widespread consensus among scientists that average maximum TC wind speeds are likely to rise under future climates globally (Knutson et al 2010). Regional projections for eastern Australia support this (Walsh et al. 2004; Leslie et al. 2007; Abbs 2012, Walsh et al. 2012). This translates to a greater proportion of storms near the Great Barrier Reef being high intensity. The recent spate of severe tropical cyclones crossing the Great Barrier Reef (Ingrid, 2005; Larry, 2005; Hamish, 2009; Yasi, 2011) has raised the question of whether rising SST has *already* led to an increased incidence of severe tropical cyclones in the region. Severe cyclones were certainly extremely rare over the recorded history for the region prior to 2005 (Lourenz 1981, Puotinen 2004). There is insufficient evidence though to support the assertion that severe cyclones have already become more frequent globally (IPCC 2012, Knutson et al 2010) or in the Great Barrier Reef Marine Park. Intensity was likely underestimated for many GBR cyclones prior to 1981 (Walsh et al 2012) so intense cyclones may have been more frequent in the GBR in the recent past than the data suggests.

Tropical cyclone activity in the Great Barrier Reef is generally higher during La Niña conditions (Kuleshov et al 2008). La Niña has dominated in recent years, but was suppressed for much of the last two decades, resulting in an unusually quiet period for cyclones on the Great Barrier Reef. Models disagree about how ENSO will respond to climate change (Collins et al 2010).

Future of flooding in the Great Barrier Reef

Since the late 19th century, average rainfall and its variability have significantly increased, with wet and dry extremes becoming more frequent than in earlier centuries. More variable tropical Queensland rainfall (and associated flooding) is likely the consequence of a warming global climate (Lough 2011, Climate Commission 2013). Recent observed climate in the Great Barrier Reef has documented consecutive extreme wet seasons with 2010/11 being the start of a La Niña phase that caused the largest floods on record in multiple rivers of the Great Barrier Reef catchment. Large-scale and in some cases severe flooding due to heightened tropical cyclone activity occurred from Brisbane to Cairns between 2009 and 2012. Extreme rainfall and flood events dominated the 2012/13 Queensland summer under a climate system that is warmer and moister (Trenberth 2012), demonstrating that climate change is already affecting Australia (Climate Commission 2013).

The changing climate as observed and predicted within the Great Barrier Reef region will increase the frequency with which coral reefs and seagrass meadows are being disturbed by extreme events such as floods, including flooding associated with tropical cyclones (Lough and Hobday 2011, Climate Commission 2013). Clear evidence is now emerging of a recent acceleration in the global hydrological cycle (Helm et al. 2010), and the projections for rainfall in the Great Barrier Reef are that there will be slight increases in average rainfall and more extreme rainfall (CSIRO and BoM 2007, Lough 2007). This will translate into altered river flow patterns, with more flood events predicted due to the increase in intense rainfall (Climate Commission 2013). Inshore habitats in the Great Barrier Reef that are currently affected by flood plumes will continue to be exposed to freshwater and associated pollutants, likely on a more frequent basis. The implications of increased future flooding for crown-of-thorns outbreaks and spatial patterns therein are unknown.

5. Conclusions and Future Work

The applied research presented within this report provides a glimpse of the importance of a dynamic understanding of exposure to disturbances from a management perspective. This has led to an analysis for coral reef areas presented in the results that shows the locations of coral reefs with relative low and high exposure to disturbances that are within and outside of Marine National Park Zones. This analysis may be informative in the future if decisions are ever made to further protect low or high exposure locations; these may represent the areas where mitigating stress from human activities can have the greatest impact on reef resilience. The research outcomes presented here now need to be combined with the concurrent work on resilience-based decision making (the RSP5 project) and future vulnerability mapping under the NERP program. In combination, these research efforts and the Reef Health and Impact Survey monitoring program can inform management decision-making by providing a dynamic assessment of current and projected future habitat condition. The research presented here also identifies where targeted local-scale actions to support recovery processes are most likely to be required; these are the reef and non-reef areas with the highest relative exposure. Lastly, the research outputs presented here may also aid in targeting long-term and responsive monitoring programs to include a suite of low, medium, and high relative exposure locations.

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Appendix 1. Models included in the ensembles used to produce the projections of coral bleaching conditions

The table below shows the formal abbreviated names of the CMIP5-generation IPCC models included in the ensembles used to develop the projections and analysis shown in section 4.4 of the main report.

	RCP26	RCP45	RCP60	RCP85
bcc-csm1-1	1			
CanESM2	1			1
CCSM4	1	1	1	1
CNRM-CM5	1			1
CSIRO-Mk3-6-0	1		1	1
GFDL-CM3	1	1	1	1
GFDL-ESM2G	1		1	1
GFDL-ESM2M	1	1	1	1
HadGEM2-CC		1		1
HadGEM2-ES	1	1	1	1
inmcm4		1		1
IPSL-CM5A-LR	1	1	1	1
IPSL-CM5A-MR	1	1		1
MIROC5	1	1	1	1
MPI-ESM-LR	1			1
MRI-CGCM3	1	1	1	1
NorESM1-M	1	1	1	1
Number of models	15	11	10	16

Appendix 2. Historical and cumulative exposure to disturbance in Seagrass areas

The spatial layer used to describe seagrass habitat comes from *in situ* surveys (ground-truthed habitat) and high probability ranges (0.5-1) of a deepwater seagrass habitat distribution model presented within Grech et al. (2010).The final version of these data was sourced from Len McKenzie at JCU, and this is the seagrass layer used in the Water Quality Risk Assessment Report being finalised right now (Brodie et al. in review). These are the non-reef area images (see Figs. 5, 8, 10, and 20 in the main body of report) cut with the seagrass data layer (raster). The map images show the data compiled and generated for: damaging waves from cyclones (Fig. Ap2.1), freshwater exposure (Fig. Ap2.2), summer thermal stress (Fig. Ap2.3), and the cumulative exposure analysis for non-reef areas (Fig. Ap2.4).

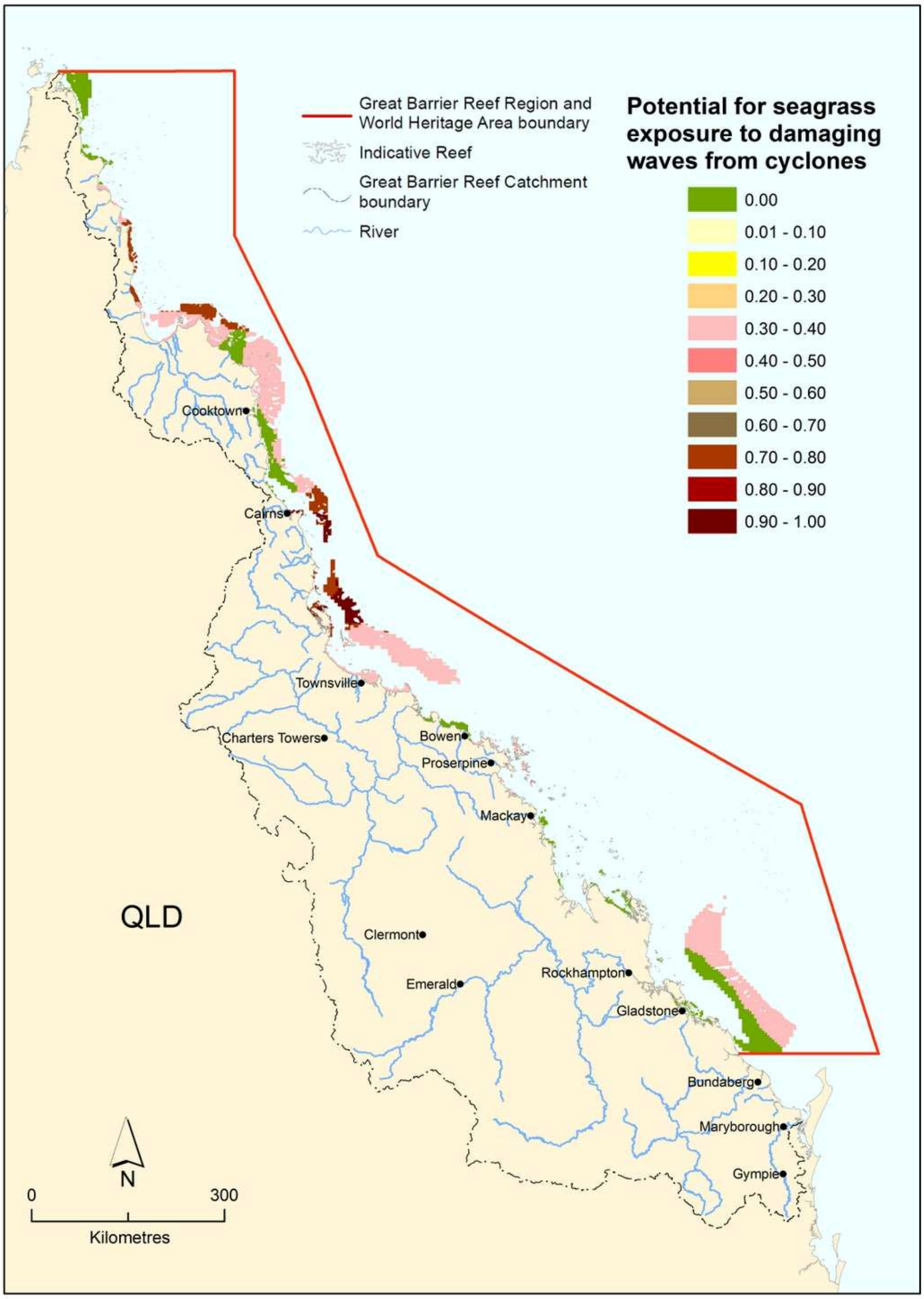

Fig. Ap2.1. Annual probability of exposure in seagrass areas to at least one hour of 4 metre waves from tropical cyclones that caused gale force (>17 m/s) winds during the 2001–2011 period. Data are scaled for non-reef areas (see Fig. 5) from 0 to 1 based on a maximum value of 26.81 per cent.

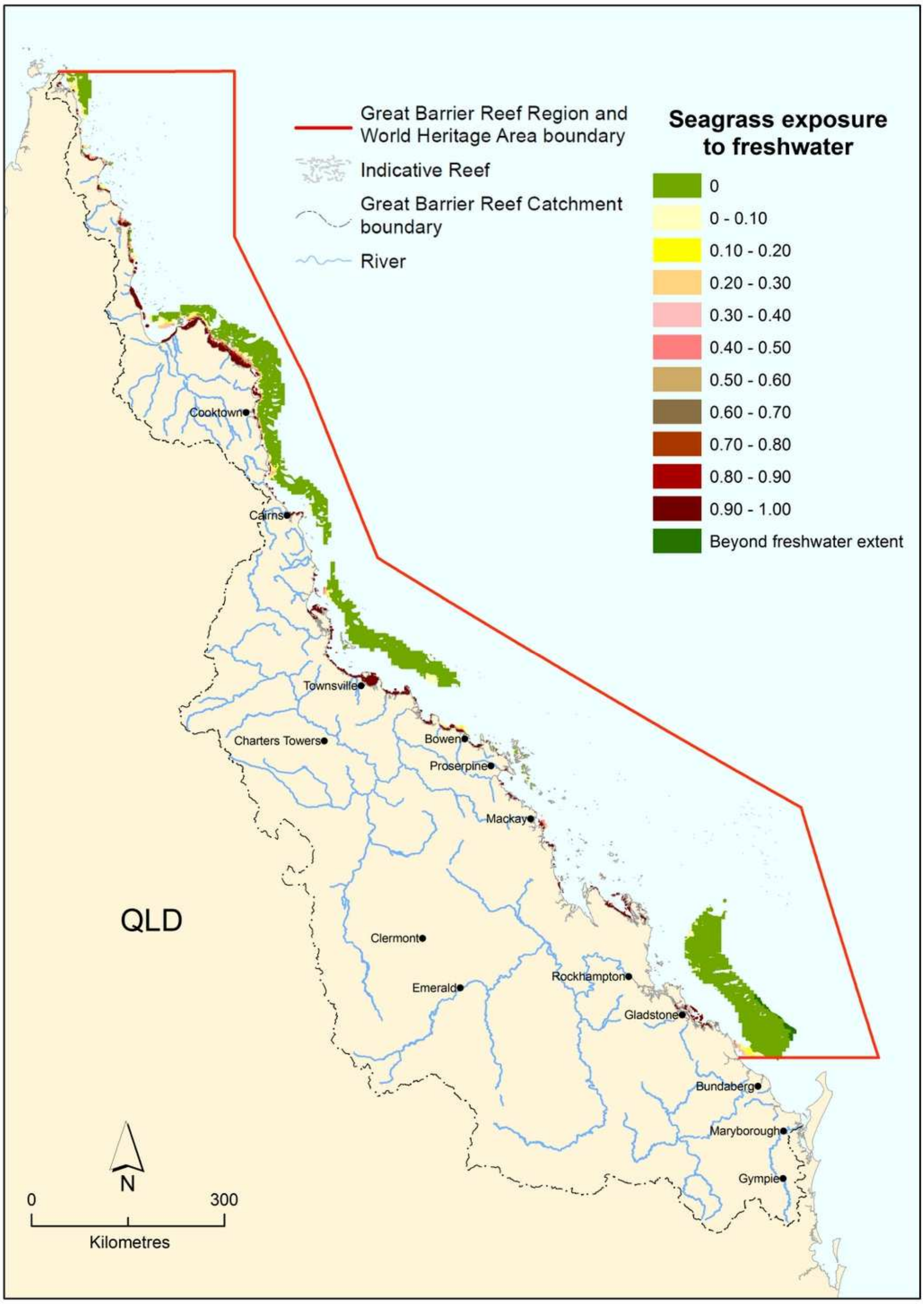

Fig. Ap2.2. Observed frequency in seagrass areas of freshwater plumes between 2001 and 2011 based on remotely sensed CDOM data provided by CSIRO Land and Water. Data are based on mapped plume extent resulting in a display of both true zeros and 'beyond plume extent'. Data are scaled for non-reef areas (see Fig. 8) from 0 to 1 based on a maximum value of 10.

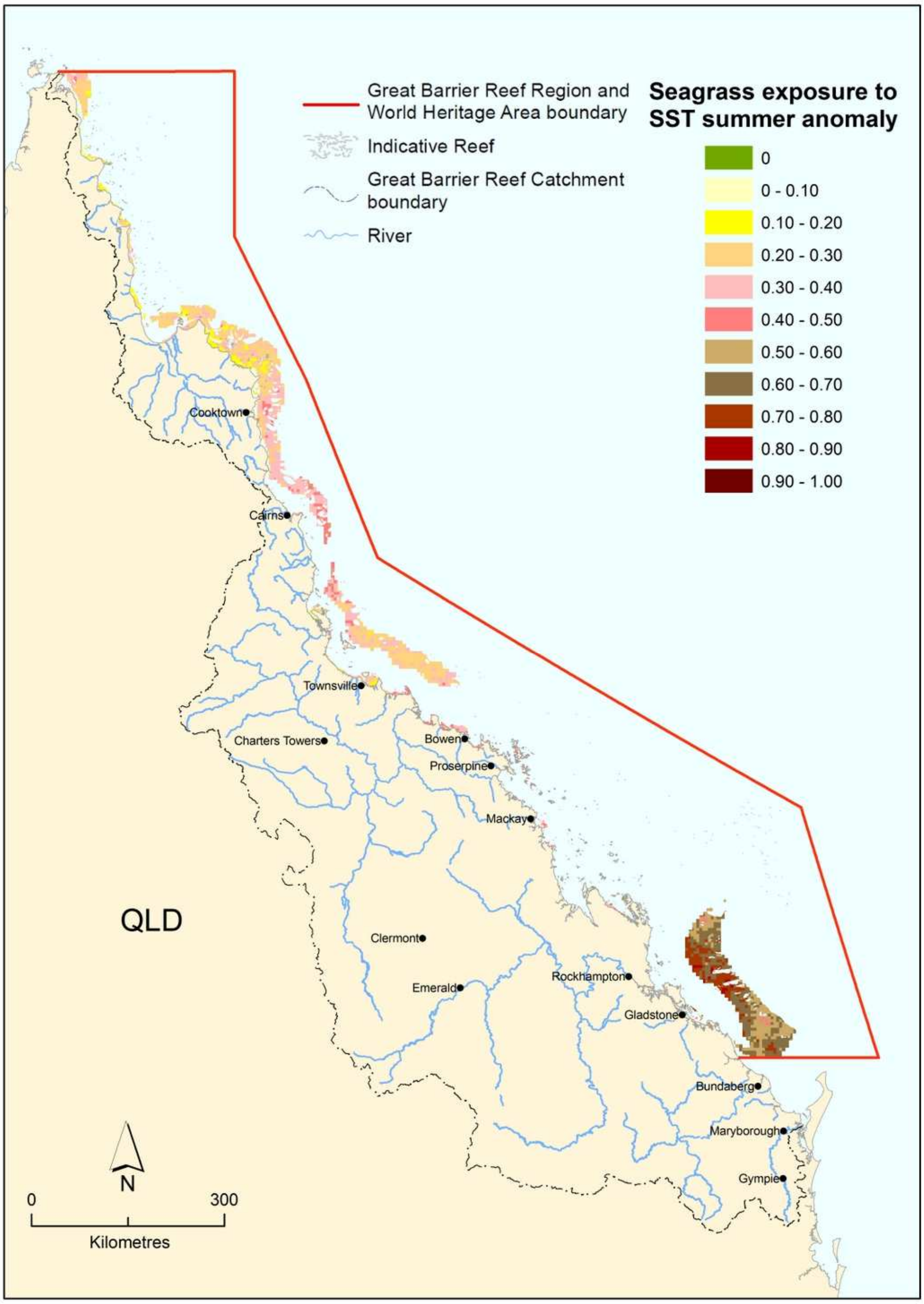

Fig. Ap2.3. Average summer (December to February) sea surface temperature (SST) anomalies (sums) in seagrass areas from 2001–2011, scaled to the maximum value in non-reef areas (see Fig. 10) of 68.79.

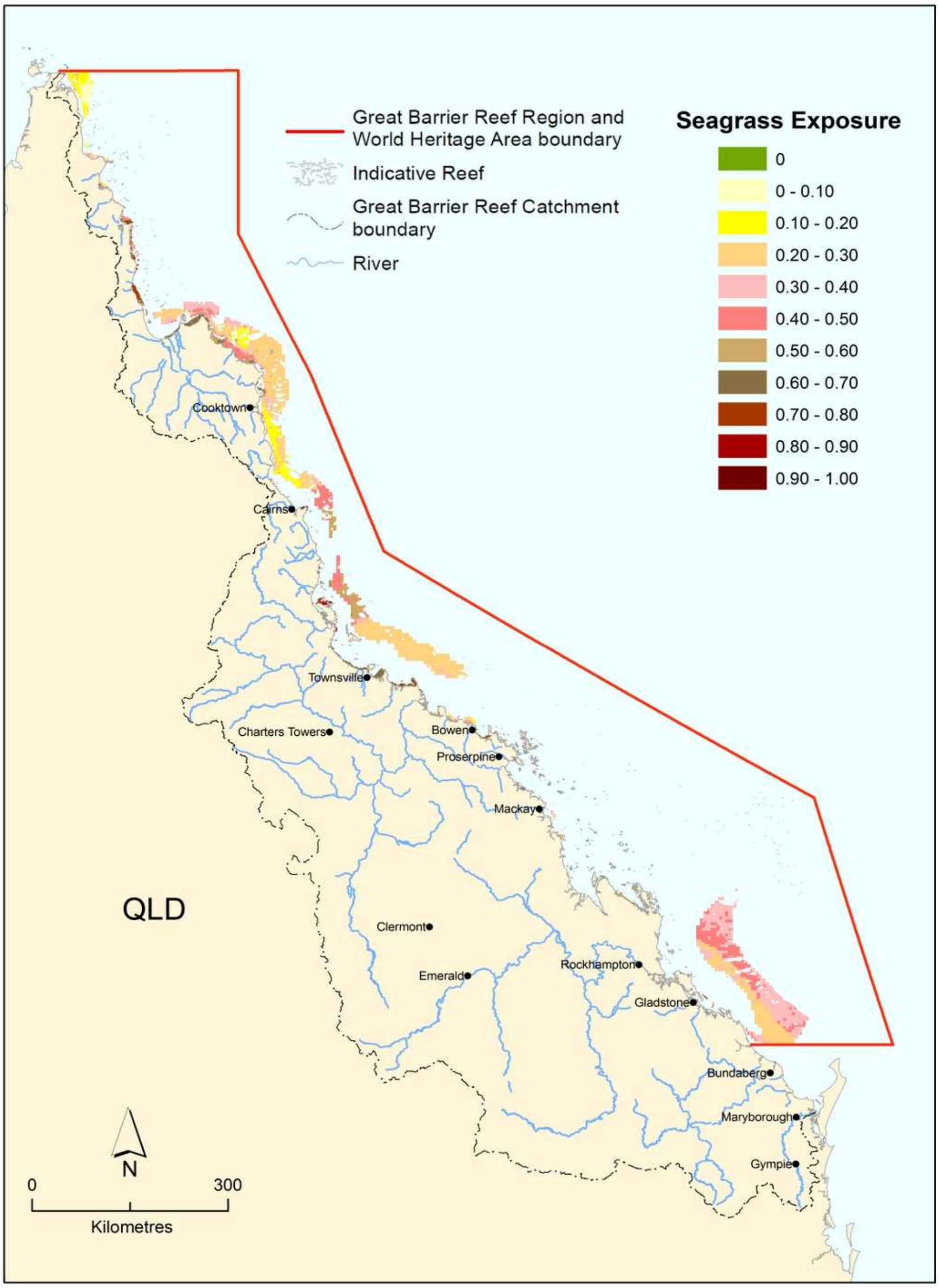

Fig. Ap2.4. Cumulative exposure (2001-2011) in seagrass areas of sea surface temperature anomalies, freshwater plumes, and damaging waves from cyclones. Data for each disturbance were scaled from 0–1 based on the maximum values for non-reef areas (see Figs. 5, 8, and 10), then values for all three disturbances were summed, and re-scaled from 0–1 based on the maximum summed value of 2.55 (see Fig. 20).

Appendix 3. Methods from Maynard et al. (in review)

Great Barrier Reef Marine Park no-take zones include coral reefs with high and low relative exposure to disturbance

Running Title: Great Barrier Reef no-take zones and exposure of reefs to disturbance

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Methods from the manuscript can be found below, followed by further supplementary methods material.

Methods

The methods and results sections present the four reef health disturbances first – thermal stress and coral bleaching, damaging waves from tropical cyclones, COTS outbreaks and freshwater inundation – followed by an analysis of cumulative exposure. The data time periods vary for each disturbance because the longest available time period of data was used for the analyses. Final data for each disturbance are standardised to enable comparison by calculating frequency values, and then normalising to a standard uni-directional scale. These two sections conclude with an assessment of the extent to which reef areas with low and high relative exposure are included within no-take zones.

Reef health disturbances

Thermal stress and coral bleaching

Observed sea surface temperature data for the period 1982–2011 (4-km resolution) were obtained from NOAA AVHRR Pathfinder Version 5.2 (Casey et al. 2010) to calculate exposure to thermal stress. The data were quality screened and only data with a quality flag of 4 or greater were used (standard for use of this dataset, see Casey et al. 2010). From this data a monthly climatology was constructed for 1982–2011. Total accumulated heat stress was calculated for each summer (1 December – 28 February) using degree heating weeks (DHWs). One DHW is equivalent to one week of temperatures being one ^{o}C above the long-term monthly average. Thermal stress was considered to be severe enough to cause bleaching if a total of six DHWs accumulate in a summer (per van Hooidonk and Huber 2009, van Hooidonk et al. 2013).For the purposes of the analysis, this was considered a 'bleaching event'. The total number of bleaching events was counted for all reef pixels and divided by the number of years in the time period (i.e. 28 years).Final values express exposure to thermal stress as the frequency of disturbancefrom1982–2011 (then normalised to a scale between 0 and 1 by anchoring to the maximum value).

Damaging waves from tropical cyclones

Direct measurements of tropical cyclone (TC)wave energy are rarely possible. Therefore this analysis used well-documented empirical relationships between wind speed, duration of gales, fetch and wave heights (US Army Coastal Engineering Research Center 1977) to assess whether wave heights $\geq$ 4m (known to cause catastrophic physical damage to corals) were likely during each TC that entered the Great Barrier Reef Marine Park between 1985–2011.For each pixel, every time a 4 m wave could have been generated counts as an event and we calculated frequency of exposure by dividing the number of years that included 4 m wave events by the 26 years in the time period (then normalised to a scale between 0 and 1 by anchoring to the maximum value).Methods used to calculate wind speeds, the duration of gales, fetch and Poisson probability formulas to assess 4 m wave generation are in the supplementary material.

Crown-of-thorns starfish outbreaks

The Great Barrier Reef AIMS Long-term Monitoring Program (LTMP) has surveyed 482 reefs for crown-of-thorns starfish (COTS) since 1986 using a manta-tow method (AIMS Standard

Operational Procedures; Miller et al. 2009). An observer makes a visual assessment of the number of COTS seen during each manta tow (2 minutes duration) around the entire reef perimeter. COTS populations are described as outbreaks when they reach densities such that the starfish are consuming coral tissue faster than corals are known to grow. When COTS populations detected on a reef average one per tow, coral cover will certainly be reduced and this is referred to as an ‘active outbreak’. The number of COTS observed per manta tow was averaged per reef and interpolated over the entire Great Barrier Reef Marine Park (reef and non-reef areas) using an interpolation approach described in Fabricius and De’ath (2001) and detailed for this study in the supplemental material. The standard 4-km grid used for bleaching and cyclones was also used. The resultant values that were mapped and used for the cumulative exposure analysis described below are the interpolated frequency values; the observed or modelled frequency of active outbreaks between 1986 and 2011(then normalised to a scale between 0 and 1 by anchoring to the maximum value).

Freshwater inundation from flooding

Freshwater inundation was assessed based on satellite measurements of Colour Dissolved Organic Matter (CDOM, 1-km resolution) processed according to Brando et al. (2012).A CDOM value greater than 0.14 is associated with salinity values of less than 30 parts per thousand(ppt) and is consistent with a freshwater influence such as a terrestrial flood plume. Reef pixels are considered to have been exposed to freshwater during a given year if CDOM levels exceeded 0.14 at least once in that year. The CDOM data were post-processed as CDOM is difficult to reliably detect in very shallow clear waters on and around reefs, and because CDOM readings on the outer-shelf of the Great Barrier Reef can be caused by processes unrelated to flooding. Post-processing included three steps: 1) spatially interpolating across reefs based on reliable data, 2) setting CDOM values exceeding 0.14 to zero if outside the area of known maximum flood plume extent from Devlin et al. (2012), and 3) manually error-checking outer-shelf areas using expert judgment to zero out any remaining high CDOM values extremely unlikely to be attributed to terrestrial flooding. Final values were frequencies for the period between 2001 and 2011, normalised to a scale between 0 and 1 by anchoring to the maximum value, and then interpolated to the standard 4-km grid using weighted averaging.

Cumulative exposure

A very large percentage of reefs are not exposed to freshwater (see results section) so we assessed cumulative exposure to thermal stress, damaging waves from cyclones and COTS outbreaks only. For all pixels, frequency values for each disturbance were averaged. These values were then anchored to the maximum value (by dividing) and thus normalised to a scale of 0 to 1.Cumulative exposure at all reef pixels was expressed relative to the highest frequency value averages; these raw values are not visualised because these frequencies are only based on observations each year at all sites for thermal stress and cyclones (COTS is modelled interpolated data from *in situ* surveys).Eleven exposure classes were set; none, and then at 0.10 intervals from 0.01 to 1.Exposure classes representing the ~85th percentile (85 per cent of reefs have higher scores) and ~15th percentile were considered to have low and high relative exposure, respectively.

Marine National Park Zones

The total reef area was calculated based on the standard 4-km grid. The estimate is therefore an over-estimate, albeit a highly consistent one across the Marine Park, due to the mismatch between the 4-km grid and reef polygon raster outlines used for the area estimate, as published by the Great Barrier Reef Marine Park Authority.The area within Marine National Park Zones was calculated for the entire Marine Park and for all four Marine Management Areas: Far Northern, Cairns-Cooktown, Townsville-Whitsunday, Mackay-Capricorn (Fig. 1). Total reef area (in km^2) within each of the 11 disturbance exposure classes was calculated and compared to the area within Marine National Park Zones made up by reefs within each of the exposure classes. This comparison tests representativeness of each exposure class within Marine National Park Zones. Each exposure class was considered to be well-represented if there was less than a 2 per cent difference between: a) the reef area within each exposure class expressed as a percentage of the total reef area, and b) the reef area within each exposure class expressed as a percentage of the reef area in Marine National Park Zones. We also tested whether at least 20 per cent of the reef area within the lower and higher relative exposure classes is within Marine National Park Zones. The area of reef in low and high relative exposure classes that is within and outside of Marine National Park Zones in each Marine Management Area is shown in tabular and mapped form.

Supplementary information

Damaging waves from cyclones (methods continued).

Wind speeds were hindcast hourly as 10 minute maximum winds using a parametric model (Holland et al. 2010) anchored in the outer radii of gale force winds (as per Puotinen 2007).This is adapted for use in GIS and mapped at the same 4-km resolution as bleaching and using the same grid . An asymmetry correction (McConochie et al. 2004) was applied and the resulting wind speeds were scaled to fit within the TC gale radii. Missing radius data were calculated based on Moyer et al. (2007) and regionally adjusted (Chavas and Emanuel 2010).The hourly duration of wind speeds every 1m/s from 17 to 33 m/s were counted at each reef pixel. Using this, a 4 m wave was deemed possible at a pixel that sustained sufficient hours of wind at any of the relevant speeds. This was then adjusted at sites that lacked sufficient fetch for 4 m waves to form. Fetch is measured as maximum distance to the nearest wave-blocking obstacle every 7.5 degrees – as per Pepper and Puotinen 2009).Finally, the Poisson probability of a 4 m wave occurring at each cell in a given year was calculated using the formula:

$$Pr(X \geq 1) = 1 - e^{-\lambda} \qquad (1)$$

where λ is the yearly average number of events (Tartaglione et al. 2003; Klotzbach 2011).

Crown-of-thorns starfish outbreaks (methods continued).

The estimated frequency of COTS outbreaks for the period 1986 to 2011 was modelled from the Australian Institute of Marine Science (AIMS) Long-term monitoring program (LTMP) survey data collected from 486 reefs.

The modelled raster file for use in GIS programs was produced using the following process:

1. Raw data was extracted directly from the AIMS LTMP database maintained by the LTMP team and the AIMS data centre.
2. From the complete database, surveys results between 1 January 2001 and 31 December 2011 were selected. All reefs that were surveyed in this period were included in the analysis, including those that were surveyed only once.
3. The COTS counts observed per manta tow were averaged over each reef for each survey to give an estimated COTS density. Reefs with multiple surveys were passed to the statistical model as multiple observations and not averaged prior to modelling. This

was done to allow the modelling to effectively perform the averaging, allowing data from reefs with only one survey to be combined with reefs with multiple surveys.

4. Where the COTS density exceeded the outbreak level of 1 COTS per manta tow the level was clipped to 1 COTS per manta tow.
5. A statistical model (Generalised Additive Model) was then used to create a modelled surface that best describes the spatial distribution of the data using cross validation. A quasibinomial transform was used to ensure that the modelled values were limited between 0–1.
6. This model was then used to predict all points on the Great Barrier Reef Marine Park, including reef and non-reef areas.
7. The extent of the model was trimmed to areas taken to be reasonably reliable using the modelled estimated standard error.

The interpolation for this project mapped the COTS density in COTS/manta tow, up to a maximum of 1, corresponding to the active outbreak level. This step was done to ensure the model focused on fitting a surface for levels below or approaching outbreak levels rather than trying to model peak COTS density values, which tend to be infrequent but with very high peaks. The clipped COTS density corresponds very closely with the probability of an active outbreak due to the temporal averaging performed by the modelling process. The clipping of the maximum density and the coincidence of the active outbreak level equalling 1, results in no re-scaling of the result to get a probability of 1.

An example modelled value of 0.2 would correspond to an incipient outbreak level occurring over nearly the entire period of interest or an active outbreak occurring once every 5 years. To improve the modelling, the 'locations' of the sites were translated into a coordinate space defined by relative distance across and along the Great Barrier Reef Marine Park (Fabricius and De’ath 2001). Distance across was set to the value 0 on the coast and 1 on the outermost edge of the continental shelf (80 m isobath), and distance along the shelf takes the value 0 on the southern edge of the Great Barrier Reef Marine Park and 1 on the northern edge.