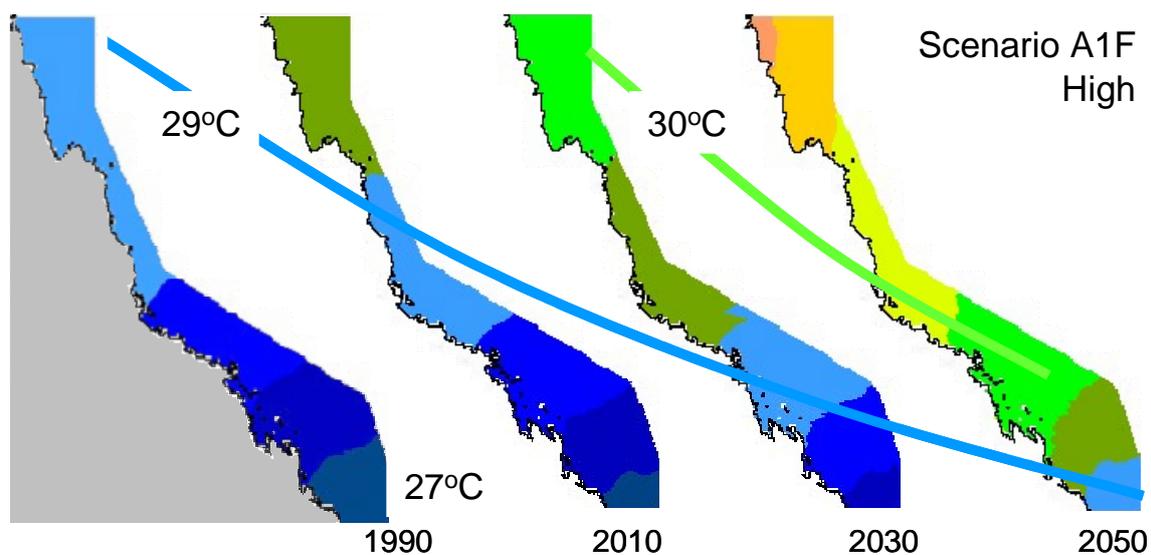


# Regional Scale Coral Bleaching Predictions for the Great Barrier Reef (1990-2050)

Milestone Report 2

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## Objective

To describe the downscaling methodology developed to enable GCM-scale scenarios of future SST to be interpreted as a regional-scale coral bleaching threat on the Great Barrier Reef, Australia.

## Introduction

It is now well established that anomalously warm sea surface temperatures (SSTs) are the primary triggering condition for *mass* coral bleaching events (Goreau and Hayes 1994; McWilliams et al. 2005). Indeed, coral bleaching has consistently occurred where normal summer sea temperatures have exceeded ambient by 1-2°C for more than a few days (Hoegh-Guldberg, 1999). This has meant an upper thermal bleaching threshold of around 30°C for most low-latitude ‘tropical’ reef systems.

Mass coral bleaching events over the past decade have been responsible for significant declines in reef communities around the world (Wilkinson 2000). Anthropogenic additions of CO<sub>2</sub> to the atmosphere (= ‘enhanced greenhouse effect’; Karl and Trenberth, 2003) has gained widespread acceptance as the underpinning driver of the present global trend towards warmer SSTs, and by inference, the increased threat of warm water coral bleaching impacts (Hoegh-Guldberg 1999; Wooldridge et al. 2005). Indeed, global climate models (GCMs) predict that the Earth’s climate could warm by 2 – 6°C by the year 2100, without a substantial effort to reduced greenhouse gas emissions far below current levels (IPCC, 2001).

The current generation of GCMs link the major components of the climate system – atmosphere, ocean, land surface, cryosphere and biosphere – to best capture the range of physical and biological feedbacks associated with climate variability and change. The forecast temperature of the water skin and the topmost ocean layer (10-20 m) is the most reliable information available for predicting the future thermal environment of coral reefs. However, the coarse spatial resolution of GCMs severely limits their ability to provide reliable representation of future reef climates. For example, most models employ a horizontal resolution of around 250 km that is better suited to representing the mean temperature of an area of ocean containing coral reefs than the temperature of an individual coral reef or an individual coral. Without representation of complex bathymetry and hydrodynamics of individual reefs, GCMs are unable to identify local areas that are consistently cooler or warmer than their averaged surrounds e.g. areas of upwelling of cooler deep waters or heating of shallow waters around the reef flat (Skirving et al. 2006; Wooldridge and Done, 2004). In an effort to better reconcile GCM-predicted SST with the thermal regime actually *experienced* by coral reefs, a downscaling methodology is needed that introduces local-scale dynamics and variability into the model predictions. In this report, I outline a downscaling methodology for the Great Barrier Reef (Australia) that takes GCM-scale predictions of SST and delivers regional-scale bleaching predictions. The methodology involves: (i) downscaling GCM model predictions into regional-scale (10 km) SST predictions, (ii) spatially disaggregate bleaching and mortality thresholds based on local acclimatisation regimes, and (iii) projecting the future exceedence of regional thresholds till 2050.

### **Regional-scale SST predictions:**

Previous computational analysis undertaken by CSIRO Atmospheric Research (Roger Jones and colleagues) has linked the GCM predictions of several modelling groups with the historical (average monthly) SST for the GBR. Table 1 displays the model information used. These monthly time series of SST have been converted into change per degree global warming patterns by linearly regressing the SST estimates against global average temperature and taking the slope of the relationship at each 10 km grid point as the estimated response. Figure 1 shows the sea surface temperature changes for the Great Barrier Reef Marine Park (GBRMP) expressed as change per degree of global warming for eight climate models for the December to March average. These changes show few consistent patterns between models that can be expressed in terms of model resolution or development. Most temperature increases are between 0.7 to 0.9°C per degree of global warming, or slightly less than the global average, but both CSIRO models are somewhat warmer. DARLAM, which was nested in CSIRO Mark2 and is largely regridded to the smaller grid (SST from the GCM is used to force DARLAM atmosphere, and although there is some feedback to alter ocean temperature this feedback is minor). The CSIRO Mark3 pattern shows the most structure, with a strong gradient of warming ranging from 0.4°C in the north to 1.5°C in the south. As there is no way to assess which changes are more likely, it must be considered that the range achieved for any location is representative of possible changes. For this reason, it was considered appropriate to treat the ensemble of model predictions as a distribution with specific mean and standard deviation. Although averaging across all models assumes that they are equally likely, this is favourable to selecting a single model considering the uncertainty attached to each.

The regional patterns of change allow for the projection of future warming scenarios:

$$\text{base climatology} + [\text{regional pattern} \times \text{global warming}] = \text{predicted SST} \quad 1.$$

Figure 2 displayed the future projected SST (2030, 2050) on the GBR given a global warming rate predicted by the A1T scenario (IPCC, 2001). The scenario assumes rapid economic growth and a global population that peaks in the middle of the 21<sup>st</sup> Century with the transition to non-fossil alternative energy sources over the coming century. As such, it is considered a 'mid-range' warming scenario, increasing globally averaged temperatures by 2 – 2.5°C by 2100. A dominant feature of the projected warming on the GBR is the proportionately higher rate of warming in the central-southern GBR.

### **Bleaching and mortality thresholds:**

The bleaching thresholds used here are taken from Berkelmans (2002) and are based on high resolution *in-situ* temperature records and historical observations of coral bleaching on the GBR (Fig. 3a). As the thermal tolerance of corals varies between locations, species and growth forms, Berkelmans' (2002) thresholds are calculated based on the dominant coral communities present at 13 different reefs spread out across the GBR. These thresholds have subsequently been regionalised for the entire GBR (see Wooldridge and Done 2004), based on the assumption that the prior (long-term) acclimatisation regime contributes to determining bleaching susceptibility (Coles and Brown 2003; Castillo et al. 2005). The bleaching thresholds for specific reefs were simply averaged for the particular thermal regions in which they were located, based on the results of Wooldridge and Done (2004). A major simplification of this study is that, although these thresholds vary spatially, they are assumed to remain temporally constant. In reality there may be potential for these thresholds to increase through adaptation, or fall through loss of resilience.

Mortality thresholds based on 50% mortality of thermally sensitive and locally abundant coral taxa have recently been proposed by Berkelmans (2007) (Fig. 3b). An analysis of these curves in relation to their bleaching thresholds indicates that at most of these sites thermally sensitive taxa die  $<1$  °C above their bleaching threshold and many  $<0.5$  °C above their bleaching threshold. For this study, a conservative threshold of 2°C above the bleaching threshold was adopted as a proxy for the probability of a reef being in a degraded state due to coral bleaching impacts. Tank tests indicate that temperatures two degrees above the threshold are likely to result in large-scale coral mortality (even for the thermally-tolerant *Porites* spp; Marshall and Baird 2000), regardless of exposure time (R. Berkelmans pers. com.), a catastrophic event for any reef.

### ***Projecting the likelihood of a degraded reef state***

Calculation of the exceedence probability of the 2°C (degraded reef state) threshold was achieved with a standard normal (z-score) methodology. In this case, at specific time intervals (1990, 2010, 2030, 2050), the downscaled SST projections from the 8 GCMs were used to develop a normal distribution of SST projections for each 10 km grid cell that constitutes the GBRMPA model domain. With the z-score approach, the likelihood of exceeding the spatially explicit threshold can be conceptualised as the area under the curve in excess of the threshold,  $z$  (Fig. 4). The standard deviation (SD) of this distribution for each grid cell was calculated based on a 15-year remotely-sensed climatology (AIMS SST web atlas) of maximum monthly SST during the Summer (Dec-Mar) period (Fig. 5). These SD estimates were temporally updated based on the assumption that the coefficient of variation of SST was stationary in time. Figure 6 displays the outworking of this methodology for (a) 1990, (b) 2010, (c) 2030, and (d) 2050 for the A1T warming scenario. Based on the analysis (and underpinning assumptions), the central-southern GBR appears to be at the greatest risk of reef degradation due to future bleaching impacts. By 2050, the predicted likelihood of catastrophic damage (20%) equates to a return interval of 5 years. It is difficult to reconcile such a short return interval with the continued existence of a viable (hard coral dominated) reef state; a similar conclusion reached by Wooldridge et al. 2005.

## Concluding comments:

The results of our most basic simulations to the year 2050 are consistent with those of previous studies (e.g. Hoegh-Guldberg 1999, Wooldridge et al. 2005) in demonstrating the potential for unprecedented levels of future coral reef decline on the GBR given even modest scenarios for future climate warming. Future refinement to the outlined methodology will focus on refining the dynamics of bleaching and mortality thresholds. In particular, the potential for other synergistic factors (e.g. water quality, light regimes etc) to interact with thermal stress to dynamically alter bleaching thresholds.

## **Acknowledgements:**

This study benefited from the GCM model data and analysis that was made available by Dr Roger Jones and colleagues at CSIRO Atmospheric Research.

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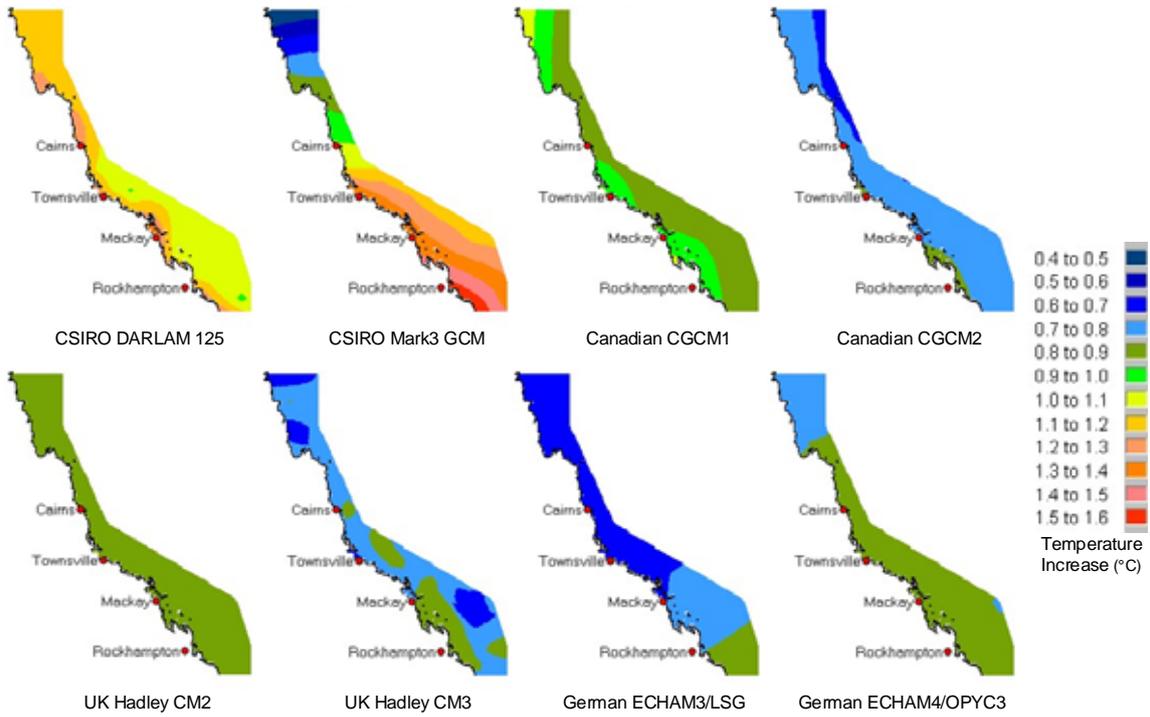
**Table 1.** Model runs used to produce SST change patterns

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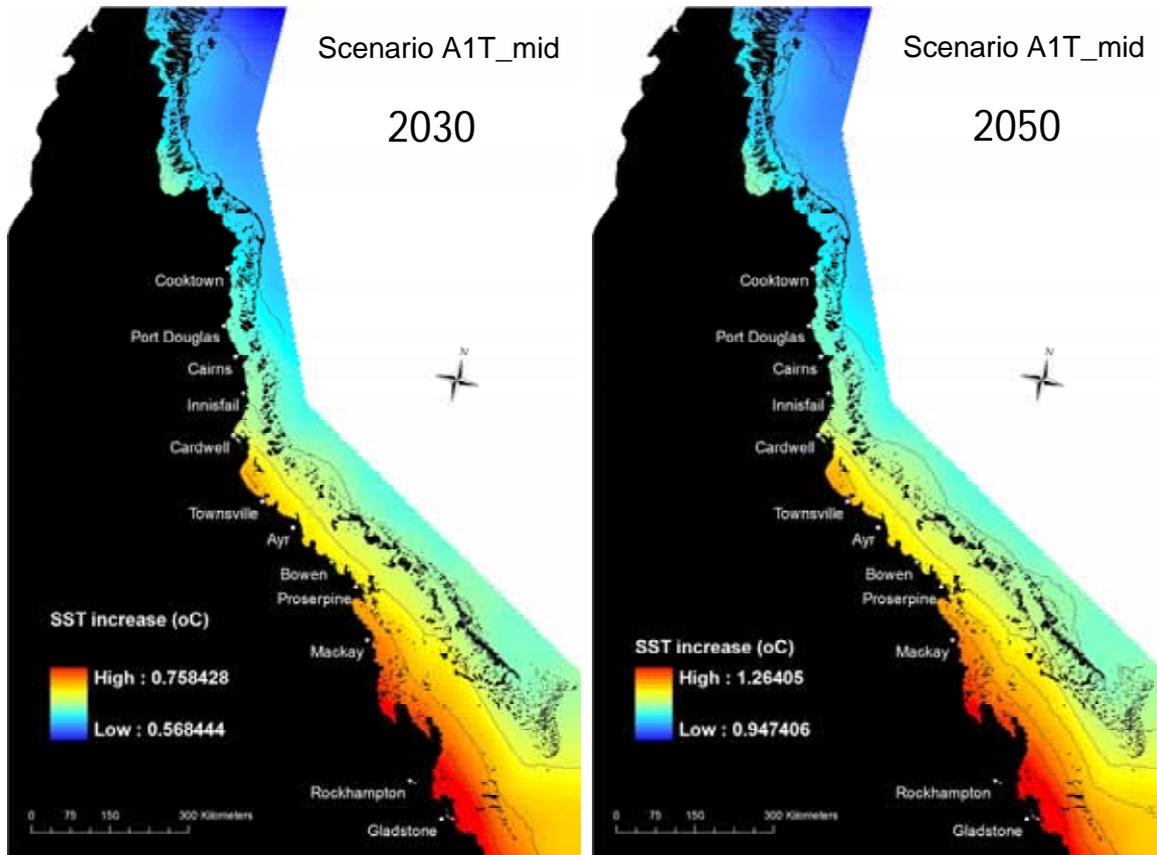
<b>Centre</b>	<b>Model</b>	<b>Emission Scenario</b>	<b>Features</b>	<b>Years</b>
CSIRO, Australia <sup>1</sup>	Mark3	SRES A2	SRES sulphates	1961–2100
CSIRO, Australia <sup>2</sup>	DARLAM 125 km	IS92a equivalent CO <sub>2</sub>	Nested in CSIRO Mk2	1961–2100
Canadian CCMA <sup>3</sup>	CGCM1	1% CO <sub>2</sub> pa	No sulphates	1900–2100
Canadian CCMA <sup>4</sup>	CGCM2	1% CO <sub>2</sub> pa	No sulphates	1900–2100
Hadley Centre, UK <sup>5</sup>	HADCM2	1% CO <sub>2</sub> pa	No sulphates	1861–2100
Hadley Centre, UK <sup>6</sup>	HADCM3	1% CO <sub>2</sub> pa	No sulphates	1861–2100
DKRZ/MPI, Germany <sup>7, 8</sup>	ECHAM4/OPYC3	IS92a	No sulphates	1860–2099
DKRZ/MPI, Germany <sup>7</sup>	ECHAM3/LSG	IS92a	No sulphates	1880–2085

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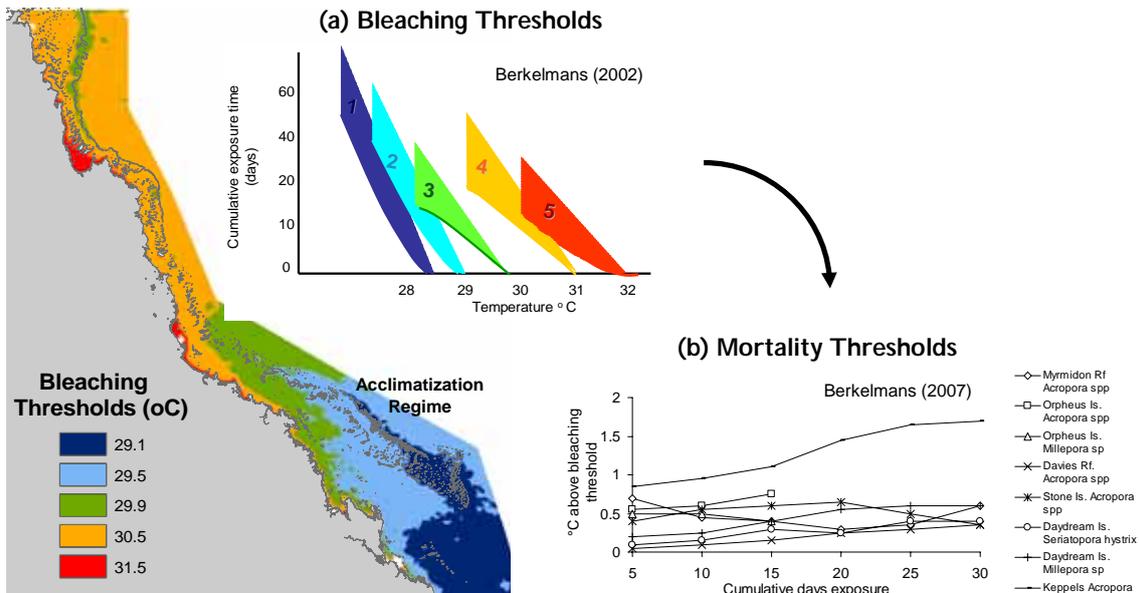
1. SST changes expressed as change per degree of global warming for eight climate models sourced from four laboratories
2. Projected increase in monthly maximum SST for the A1T (IPCC, 2001) global warming scenario
3. Regionalised coral bleaching and mortality thresholds
4. Conceptual representation of the z-score approach to calculating bleaching threshold exceedence
5. Standard deviation of monthly maximum summer (Dec-Feb) SST based on a 15-year remotely-sensed climatology
6. Exceedence probability of the 2°C (degraded reef state) threshold based on the A1T global warming scenario (a) 1990, (b) 2010, (c) 2030, (d) 2050



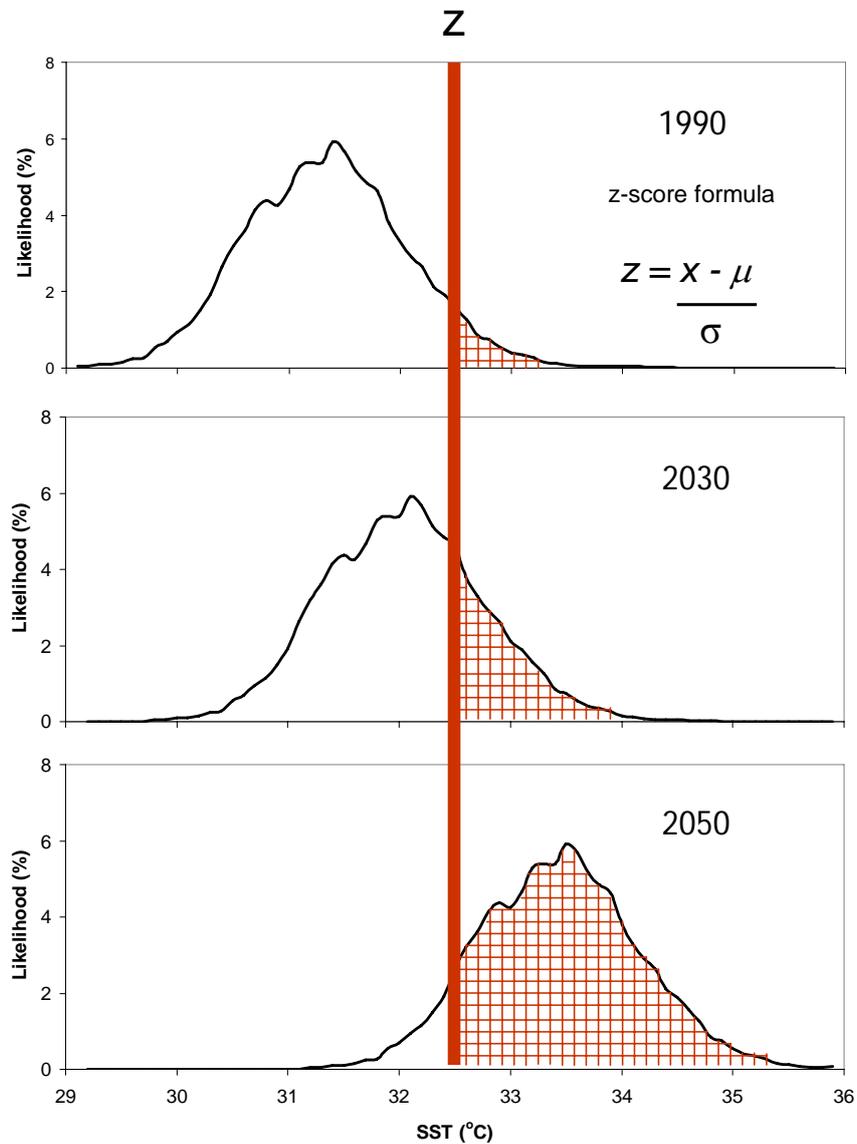
**Fig. 1** SST changes expressed as change per degree of global warming for eight climate models sourced from four laboratories



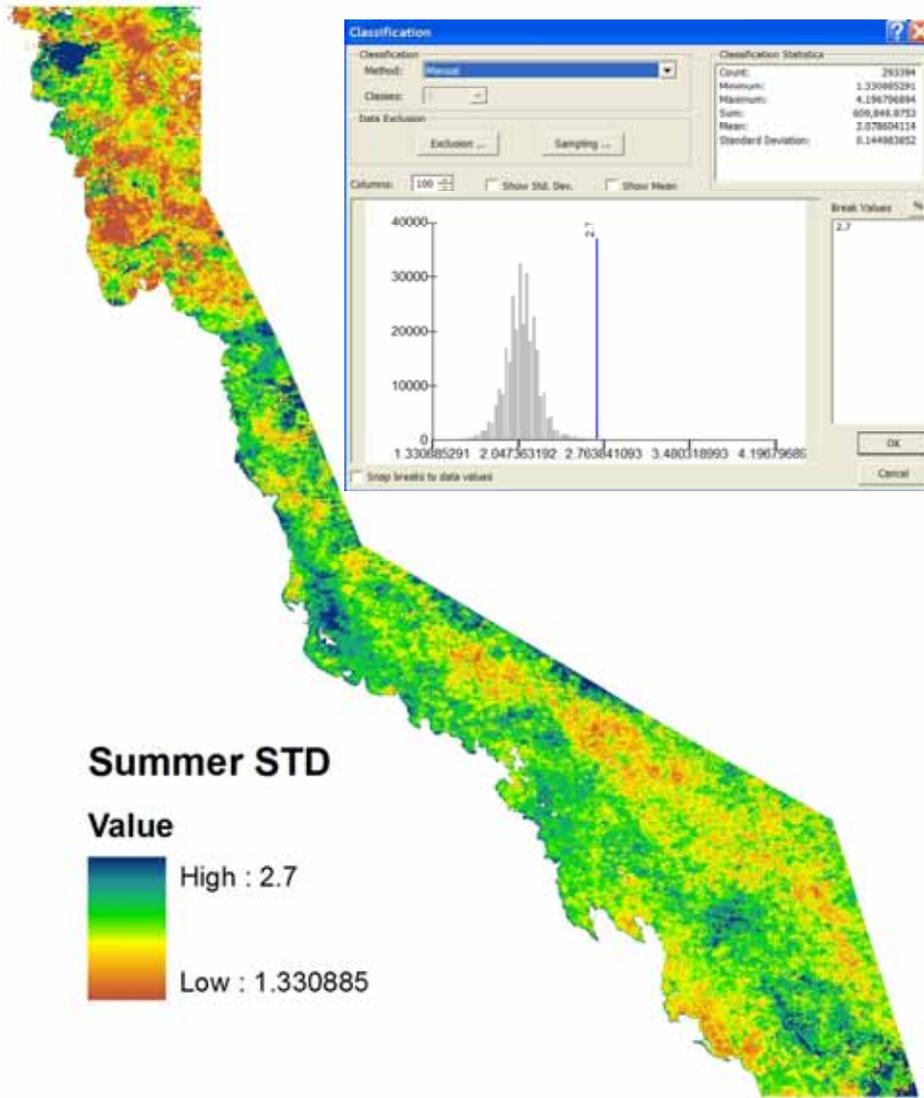
**Fig. 2.** Projected increase in monthly maximum SST for the A1T (IPCC, 2001) global warming scenario



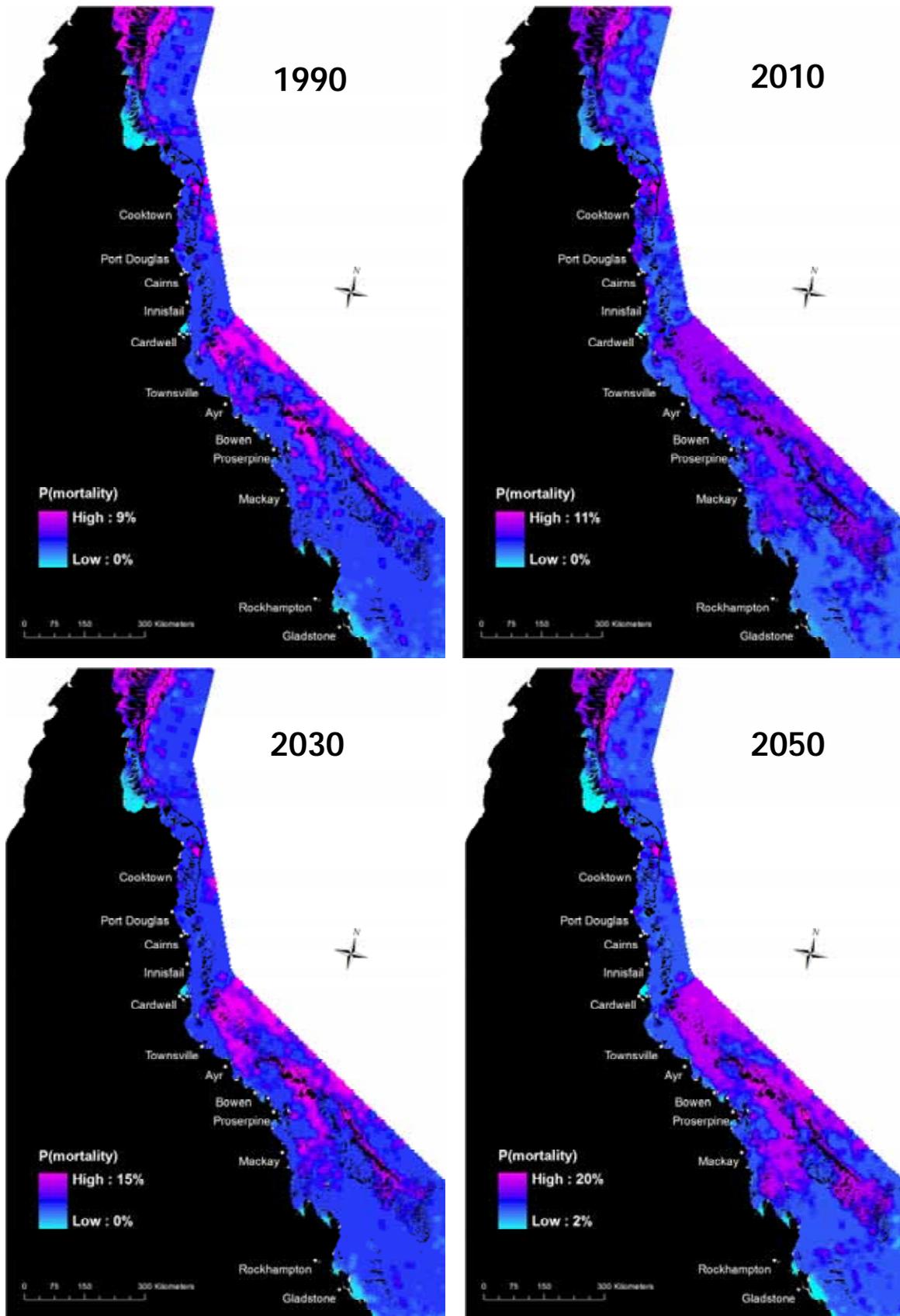
**Fig. 3.** Regionalised coral bleaching and mortality thresholds



**Fig. 4** Conceptual representation of the z-score approach to calculating bleaching threshold exceedence



**Fig. 5.** Standard deviation of monthly maximum summer (Dec-Feb) SST based on a 15-year remotely-sensed climatology



**Fig. 6.** Exceedence probability of the 2°C (degraded reef state) threshold based on the A1T global warming scenario (a) 1990, (b) 2010, (c) 2030, (d) 2050