Future Scenarios: a Review of Modelling Efforts to Predict the Future of Coral Reefs in an Era of Climate Change

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Chapter 10
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10.1 Introduction

Observations of mass coral bleaching over the past 25 years are linked to periods of anomalously warm sea surface temperatures (Glynn 1991; Hoegh-Guldberg 1999; Wellington et al. 2001). This leads to speculation that climate change has increased the frequency and severity of coral bleaching events worldwide (Hoegh-Guldberg 1999). Global climate models predict that the planet's climate could warm by 2–4°C by the year 2100, without substantial effort to reduce greenhouse gas emissions far below current levels (IPCC 2007). This continued climate warming may, therefore, pose a serious threat to the long-term health of coral reef ecosystems (Hughes et al. 2003). At the same time, higher concentrations of atmospheric carbon dioxide are expected to reduce the rates of coral calcification and reef accretion (Kleypas et al. 1999; Guinotte et al. 2003).

This chapter reviews recent efforts to predict the effect of future climate change on coral reefs, focussing on coral bleaching. The chapter includes an introduction to climate modelling, a review of the application of climate models to coral bleaching, a case study on the Great Barrier Reef, and a discussion of future research needs.

10.2 Modelling Future Climates

Global climate models, which can simulate the response of the earth to the emissions of greenhouse gases, provide the basis for predictions of the response of coral reefs to climate change. The earliest climate models were simple representations of radiative properties of the atmosphere and the earth's surface, based on the energy from the sun and the composition of the atmosphere. These simple one-dimensional models evolved into today's complex general circulation models (GCM) that use physical principles to describe the transfer of heat, moisture, and momentum in a three-dimensional grid representing the global climate system.

The current generation of GCMs used in the Intergovernmental Panel on Climate Change (IPCC) assessments link the major components of the climate

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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 models are continually updated to improve the representation of important physical processes and are rigorously tested against observed data. One generic metric for contrasting GCMs is their "climate sensitivity", the predicted level of warming caused by a doubling of atmospheric carbon dioxide (CO_2) concentrations. The GCMs used in the IPCC Fourth Assessment Report (AR4) have climate sensitivities ranging from 2.0°C to 4.5°C, with a long-established mean of 3°C (IPCC 2001, 2007).

Forecasts of sea surface temperatures (SSTs) from GCMs are the most reliable information available for predicting the thermal environment that will influence coral reefs in the future. However, there are several key limitations to the modelled representation of future climates that are particularly relevant to the study of coral reefs. These include: (1) the coarse spatial resolution of GCMs, (2) the representation of natural modes of climate variability, and (3) the uncertainty over future greenhouse gas emissions.

First, the coarse spatial resolution of climate models limits their ability to provide forecasts for coral reefs. For example, the models employed in the IPCC Third Assessment Report and most coral reef studies to date had horizontal resolution of around 250 km and vertical resolution on the order of 100s of metres (i.e., depth of each ocean grid cell). Several of the models used in the AR4 operate at a horizontal resolution of 1° (~100 km) or better in the atmosphere and ocean and at a vertical resolution of 10–100 m in the surface ocean (e.g., Delworth et al. 2006).

Without a representation of the complex bathymetry and hydrodynamics of individual coral reefs, neither of these sets of GCMs can capture processes like the local upwelling of cooler deep waters or heating of shallow waters on the reef flat (Skirving and Guinotte 2001; Wooldridge and Done 2004). The direct GCM output is better suited to represent the mean temperature of an area of ocean containing coral reefs than the temperature surrounding an individual coral reef or an individual coral. Higher resolution regional information can be obtained by downscaling GCM output using dynamical or statistical methods. For example, predictions for an individual reef could be made by forcing a high-resolution hydrodynamic model with the coarser output from a GCM (see Sect. 11.5). Alternatively, statistical relationships between the average temperature for a region and the temperature at specific reef locations could be used to translate GCM output to a higher resolution (Donner et al. 2005).

Second, the ability to project future ocean temperatures for many coral reefs depends on model representation of natural modes of climate variability. Mass coral bleaching events have been linked to large-scale oscillations in the atmosphere–ocean system such as the El Niño–Southern Oscillation (ENSO), the Pacific Decadal Oscillation and possibly the Atlantic Multi-Decadal Oscillation (Wilkinson et al. 1999; Donner et al. 2007; Chap. 4). Therefore, the reliability of future projections for coral reefs will depend on a model's ability to reliably represent such natural modes of climate variability in the existing climate and the response of those natural modes of variability to human-induced climate warming.

Third, future climate projections depend on assumptions about future changes in climate "forcings", including rates of emission of primary greenhouse gases. The IPCC's Special Report on Emissions Scenarios (SRES) developed 40 different scenarios based on various assumptions about demographic, economic, and technologic change over the twenty-first century (Nakicenovic and Swart 2000). Higher emissions scenarios imagine a future with more reliance on fossil fuel use (e.g., SRES A1f). Middle of the road or "business as usual" scenarios imagine a rough continuation of previous rates of increase in annual greenhouse gas emissions (e.g., IS92A, SRES A1b). The lower, more optimistic emissions scenarios imagine the annual emissions rate increasing slowly over time and eventually decreasing (e.g., SRES B1).

These future scenarios prescribe the emissions, not the atmospheric concentrations, of greenhouse gases and aerosols. The concentration of greenhouse gases in the atmosphere depends both on the emissions and on the response of the planet's ecosystems (e.g., CO_2 uptake) and feedback mechanisms (e.g., melting permafrost, leading to CH_4 release). Since the current rate of CO_2 emissions exceeds the rate of CO_2 uptake by the planet's ecosystems, freezing *emissions* at today's rate will cause a continued increase in atmospheric CO_2 *concentrations*.

"Stabilisation" scenarios are designed to represent the stabilisation of atmospheric greenhouse gas *concentrations* at some point in the future due to emission controls. These scenarios involve large reductions in the rate of emissions. Due to the long residence time of CO_2 and other greenhouse gases in the atmosphere, a certain level of climate warming is expected to occur because of past emissions. As such, GCMs show that, even if the concentration of greenhouse gases were frozen tomorrow, there would still be 0.3–0.9°C of residual or "committed" warming by the end of the twenty-first century (IPCC 2007).

10.3 Predicting Coral Bleaching from Climate Models

The heterogeneity of coral responses to temperature stress poses a central challenge in predicting the impact of climate warming on coral reefs. Hughes et al. (2003) summarised the possible theoretical models describing temperature thresholds for coral reefs under climate change. The simplest model (Hoegh-Guldberg 1999) assumes that mass coral bleaching or mortality will occur when the temperature exceeds some threshold (Fig 10.1a). An alternative model recognises different thresholds based on thermal tolerances (e.g., between coral species or growth forms) or possibly different thresholds for bleaching and mortality (Fig. 10.1b). An adaptive model envisions thresholds that might increase over time due to temperature acclimatisation and/or evolution by corals and their symbionts (Fig. 10.1c). While some of the adaptive model's thresholds change due to acclimatisation in the coral or changes in their endosymbionts (Chap. 7), much of the change would be due to the loss of more temperature-sensitive coral species.

Most studies to date used a single temperature-based threshold of 1–2°C above the usual summer maximum to predict whether mass coral bleaching or coral mortality

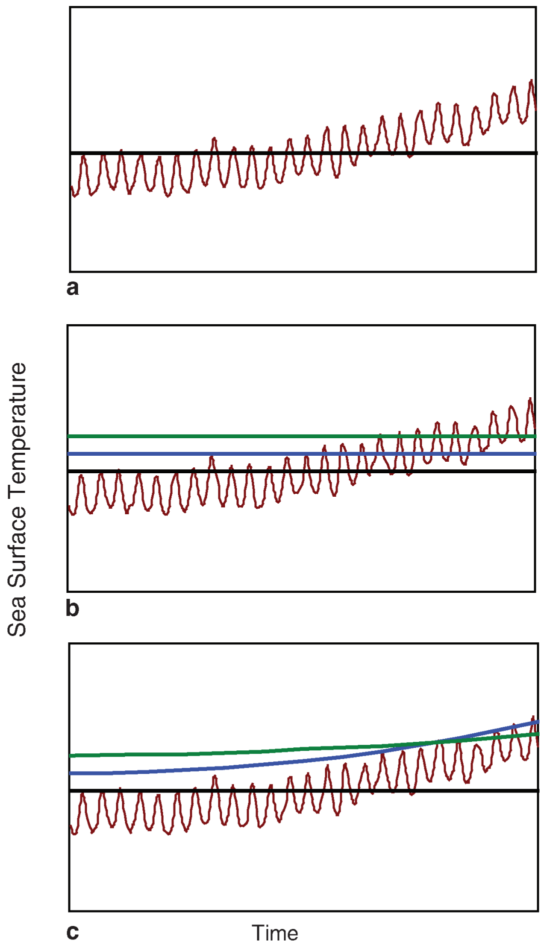

Fig. 10.1 Three models for describing temperature thresholds (*blue* and *green* lines) for predicting coral bleaching: **a** a single constant threshold across all species, **b** multiple constant thresholds, reflecting either differences in bleaching susceptibility (e.g., between species or growth forms) or severity (bleaching vs. mortality) and **c** multiple thresholds that increase in time, due to acclimation and/or evolution by corals and their symbionts (adapted from Hughes et al. 2003). The *red line* represents sea surface temperature, as it increases over time

will occur under future climate scenarios (Hoegh-Guldberg 1999; Sheppard 2003; Donner et al. 2005). Some recent studies also investigated the effect of possible temperature adaptation on the projected frequency of bleaching events, a variant of the approach depicted in Fig. 10.1c (Sheppard 2003; Donner et al. 2005).

The first group of climate change and coral bleaching studies determined temperature thresholds for individual sites from historical observations of coral bleaching or mortality (Hoegh-Guldberg 1999; Sheppard 2003; Jones 2004). Hoegh-Guldberg (1999) was the first major review of the effect of climate change on the occurrence of mass coral bleaching. In that study, the projected future SSTs from three different GCMs (ECHAM4, ECHAM3, CSIRO DAR, see references therein) under a business as usual scenario (IS92a) were used to predict the occurrence of coral bleaching at sites in French Polynesia, Jamaica, Rarotonga, Thailand, and at three sites on the Great Barrier Reef (GBR). For each site, in situ records of monthly SST and observations of mass coral bleaching were used to determine a monthly averaged temperature threshold. That study assumed that if the projected future SST[1] during a given year exceeded the temperature threshold for the site, mass coral bleaching would occur that year. The results suggested that coral bleaching at the level observed during the 1997–1998 mass bleaching event at the seven sites would occur biannually within 20–40 years under business as usual conditions (for further discussion, see Sect. 11.4). The sharp increase in bleaching frequency was predicted to lead to long-term decline of coral cover and ecosystem function.

Sheppard (2003) made future predictions for 33 Indian Ocean coral reefs using temperature thresholds based on observations during the 1998 coral bleaching event. Analysis at the time suggested Indian Ocean coral reefs damaged during 1998 required a minimum of five years for recovery. The study therefore defined the "extinction date" for 33 Indian Ocean reefs as the year in which the probability of SST for the warmest month or the warmest three months surpassing that of 1998 exceeded 20% (once every five years).

A key difference between the Sheppard (2003) analysis and that of Hoegh-Guldberg (1999) is the method of combining historical and modelled future SSTs. Sheppard (2003) blended the historical monthly SSTs from the HadISST 1° × 1° resolution global dataset and simulated future SSTs from the HacCM3 model under a business as usual scenario (IS92a) into one continuous dataset. The projected SSTs for 2000–2100 were estimated by adding the monthly GCM anomalies to the observed climatology and then applying the seasonal amplitude from the historical time series, using statistical fitting between observed and simulated monthly SSTs for the 1950–1999 period. This method accounted for the fact that many GCMs underestimated the seasonal amplitude in SSTs.

The study found the extinction date should occur between 2010 and 2030 for most Indian Ocean coral reefs south of the equator, but not until the latter half of the century for some coral reefs north of the equator (Fig. 10.2). The date for high-latitude reefs in the Arabian Sea may be delayed until the end of the century due to cold water upwelling. At each site, the projected increase in SSTs suggested that adaptation or acclimatisation by corals and their symbionts by 2°C could delay the extinction date beyond the end of this century. Recovery of only 20–30% of the corals in the five years since the 1998 bleaching (Wilkinson 2004) suggests that these extinction dates may be optimistic.

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[1] To eliminate systemic difference between modelled and observed temperatures, the future temperatures are estimated as the sum of model "anomalies" (i.e., modeled January, 2050 SST minus modelled mean January SST for today's climate) and the observations (i.e., January in today's climate).

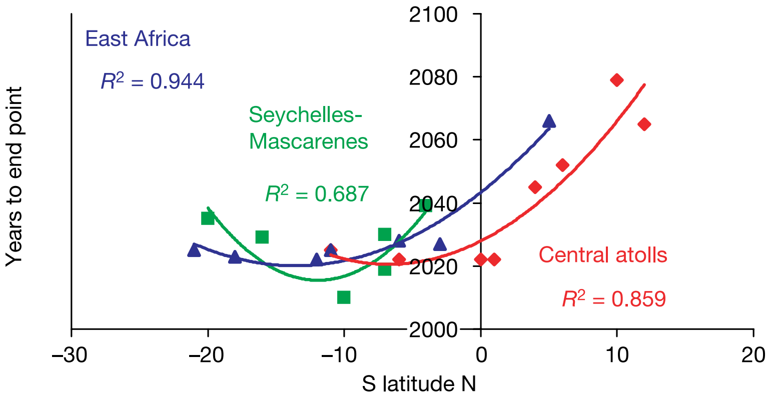

Fig. 10.2 "Extinction dates" for coral reefs across the Indian Ocean. The data points represent the year that the probability of exceeding the SST threshold (the warmest three months of 1998) reaches 0.2, or once every five years, for the individual site. The curves are significant fits for the three main coral reef regions in the eastern Indian Ocean (from Sheppard 2003)

The "blending" of model and instrumental data was also applied to HadCM3 simulated SSTs in the Caribbean Sea (Sheppard and Rioja-Neito 2005). The results demonstrated that the peak temperature observed during 1998, when bleaching occurred in parts of the Caribbean, would be surpassed biannually across most of the Caribbean before the year 2050.

A second approach to modelling coral bleaching uses average maximum temperatures in observed climate data to determine bleaching thresholds (Hoegh-Guldberg 2001, 2005; Donner et al. 2005). The NOAA Coral Reef Watch satellite-based coral bleaching prediction program predicts the onset of bleaching using the degree heating week (DHW), a measure of the accumulated temperatures in excess of the usual summer maximum (Liu et al. 2006; Skirving et al. 2006; Chap. 4). Donner et al. (2005) took advantage of these satellite-derived data products to estimate the frequency of coral bleaching and required rates of temperature adaptation for thousands of locations worldwide for upper and lower business as usual climate scenarios (SRES A2, SRES B2). The historical satellite SST and DHW data provided a reliable way to develop algorithms for predicting the occurrence of thermal stress that can cause bleaching at sites worldwide from GCMs.

Algorithms were developed by transforming the observed 36 × 36 km resolution twice-weekly satellite SST data for 1985–2002 into monthly SSTs at the same satellite resolution and into monthly SSTs at the resolution of the two different GCMs (HadCM3, US National Center for Atmospheric Research's PCM, see references therein). From these a degree heating month (DHM) index was calculated. Historical data analysis showed that DHM > 1°C·month and DHM > 2°C·month were the best proxies for the lower and upper bleaching thresholds, DHW > 4°C·week and DHW > 8°C·week, used by the NOAA Coral Reef Watch program (Liu et al. 2006). A statistical downscaling relationship between the maximum annual SST at the satellite resolution and at the GCM resolution was also developed for each 36 × 36 km grid cell containing a coral reef (3379 cells with HadCM3, 2023 cells with PCM).

The results of Donner et al. (2005) showed the variation in thermal stress and the required temperature adaptation for extended survival of corals under different climate models and emissions scenarios. The accumulation of DHMs exceeds the upper bleaching thresholds across much of the tropics by the 2050s in both models and under either scenario (Fig. 10.3a). Warming is projected to be greatest in the central equatorial Pacific, as both GCMs predict that ENSO-like conditions prevail in a warmer climate. The lower (DHM > 1°C·month) and upper (DHM > 2°C·month) bleaching thresholds are surpassed at the majority of the world's reefs every two years by the 2050s (Fig. 10.3b).

Following a method similar to Sheppard (2003), Donner et al. (2005) estimated the rate of temperature adaptation or acclimatisation required to avoid surpassing the coral bleaching thresholds in future decades. The results indicated the majority of the world's coral reefs would require adaptation of at least 0.2–0.3°C per decade to ensure that low-intensity bleaching events (DHM > 1°C·month) do not occur more than once or twice a decade by the 2030s to 2050s (Table 10.1). The required rates of adaptation vary widely across the tropics, with values of up to 0.5–1.0°C per decade in parts of the central Pacific and Polynesia, even in the GCM with low climate sensitivity.

A third approach to modelling coral bleaching under climate change uses temperatures or thermal stress indices averaged over a large region as representative of the extent of bleaching in the region. McWilliams et al. (2005) contrasted historical SSTs in the Caribbean from the MOHSST6 historical dataset with historical data

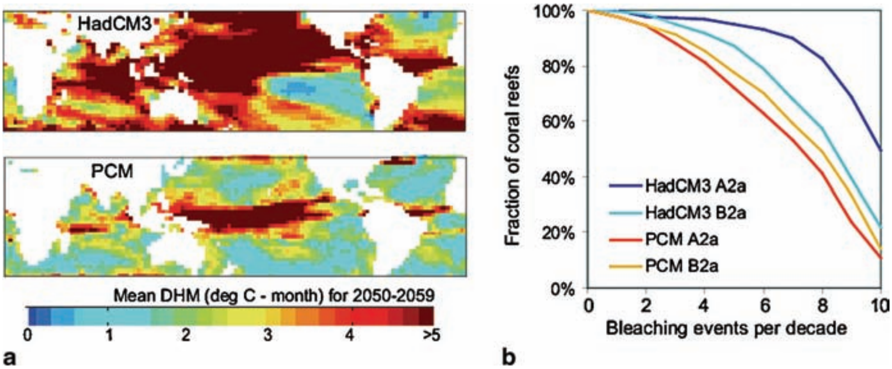

Fig. 10.3 Projected thermal stress measured as degree heating months (*DHM*) for 2050–59 (from Donner et al. 2005): **a** annual mean DHM for 2050–59 according to HadCM3 and PCM in the SRES A2 scenario, **b** number of times per decade that thermal stress exceeds the upper bleaching threshold (DHM > 2°C), expressed as a fraction of world's coral reefs. Significant bleaching is expected at DHM > 1°C·month, mass bleaching and significant mortality are expected at DHM > 2°C·month

Table 10.1 Percentage of reefs requiring thermal adaptation by 2030–2039. Shown is the percent of coral reef grid cells, in the SRES A2 and B2 emissions scenarios that require a 0.5°C or 1.0°C increase in the temperature threshold at which degree heating months begin to accumulate in order to avoid mass bleaching more than once every five years

Ocean region	Coral reefs (%)			
	HadCM3		PCM	
	+0.5°C	+1.0°C	+0.5°C	+1.0°C
Indian Ocean	83–92	46–55	38–57	10–19
SE Asia	58–62	16–17	39–40	6–9
Micronesia	58–79	13–54	58–79	6–7
GBR/Coral Sea	29–67	7–40	17–53	4–6
Polynesia	69–81	24–39	58–82	19–31
Caribbean	75–78	22–30	13–40	0–11

on spatial extent of bleaching determined from the reports to ReefBase (http://www.reefbase.org). Regressions estimated that a 0.1°C increase in Caribbean-average SST would cause a 35% increase in the number of 1° × 1° coral reef cells reporting some bleaching and a 42% increase in the fraction of coral colonies bleached. Although this type of regional bleaching prediction is less meaningful for individual coral reefs, it is well-suited to the application of coarse GCM predictions for the future.

In a recent study of the role of climate change in the 2005 Caribbean bleaching event, Donner et al. (2007) examined the mean thermal stress over the affected region rather than the SSTs at individual sites or individual model grid cells. By focussing on a large region, the study was able to use historical datasets and GCMs (CM2.0, CM2.1, from the US Geophysical Fluid Dynamics Laboratory) to examine the probability of the 2005 bleaching event occurring with and without the effect of past greenhouse gas emissions on the climate. The analysis showed that anthropogenic forcing increased the chance of a coral bleaching event such as that observed in the Caribbean in 2005 by at least an order of magnitude.

The Donner et al. (2007) study also provided further insight into the effect of different emissions scenarios and possible adaptation or acclimatisation by corals and their symbionts on the frequency of mass bleaching events in the future. The GCMs predict that mean DHM over the study region would exceed 2°C·month at least biannually by the 2020s or 2030s under both a business as usual scenario (SRES A1b) and a lower-emissions scenario (SRES B1), in which atmospheric CO_2 concentrations stabilise at double the pre-industrial levels in the year 2100.

However, the results change if corals and their symbionts are able to adapt or acclimatise by 1.0–1.5°C, as observed for some corals (Berkelmans and van Oppen 2006; Chap. 7). In the business as usual scenario, such adaptation would postpone the mass coral bleaching from occurring once every five years until the latter half of the century. In the stabilisation scenario, such adaptation could prevent mass coral bleaching from occurring in the eastern Caribbean more than once a decade throughout this century.

10.4 The Great Barrier Reef: a Case Study

The Great Barrier Reef (GBR) is the world's largest coral reef system, stretching over 2000 km along the northeast coast of Australia at the edge of the Indo-Pacific biodiversity hotspot. It comprises over 3000 individual reefs found inshore, mid-shelf, and up to 200 km offshore. The reefs are subject to a variety of disturbances, including agricultural runoff, riverine flood plumes, crown-of-thorns starfish outbreaks, severe tropical storms, fishing, tourism, and marine shipping. The GBR is also one of the world's most protected reef regions. The Representative Areas Program and the Reef Water Quality Protection Plan have been recently implemented as part of a strategy to maintain biodiversity and support the ecosystem's resilience to aid survival of the reef through climate change (www.gbrmpa.gov.au).

Prior to 1979, no mass bleaching events were reported for the GBR. Since that time, seven mass bleaching events have been recorded: 1980, 1982, 1987, 1992, 1994, 1998, 2002, and most recently in 2006 (Berkelmans and Oliver 1999; Hoegh-Guldberg and Hoegh-Guldberg 2004; Lough et al. 2006). Average SST decreases to the south (poleward) along the GBR and, due to localised adaptation, the threshold temperature at which corals bleach also decreases to the south (Berkelmans 2002). The bleaching events have generally increased in their intensity and extent over time. The 1998 event (40% of reefs bleached) and subsequently the 2002 event (50% of reefs bleached) were each described as the most severe bleaching events recorded on the GBR (Berkelmans and Oliver 1999; Berkelmans et al. 2004).

Using data collected by ships of opportunity, Lough (2001) found that there had been an increase of 0.6°C in the annual average sea surface temperature (SST) for the GBR during the twentieth century. Several studies specifically examined projected increase in SST on the GBR. Lough et al. (2006) extended the Lough (2001) data to 2006 and presented the projected temperature increase on the GBR according to two business as usual climate scenarios (Fig. 10.4). These forecasts suggest that the waters of the GBR will be 1–3°C warmer than at present by the end of this century. The Hoegh-Guldberg (1999) study concluded that temperatures would exceed those observed in 1998 at sites in the northern, central, and southern GBR by the year 2020. Done et al. (2003) found that present-day temperatures in the northernmost tip of the GBR will be experienced at the southern end of the GBR by 2050 in a pessimistic emissions scenario, or by 2100 in an optimistic emissions scenario.

Hoegh-Guldberg (1999) found that the modelled temperature increases are expected to induce annual bleaching events across the GBR by 2050 (Fig. 10.5). The Donner et al. (2005) global assessment generally confirms that result, suggesting that coral bleaching would occur at least once every two years across 83–100% of the GBR by 2050–2059. Done et al. (2003) show that even the most optimistic climate scenario predicts that catastrophic thermal events are possible at mid- and outer-shelf reefs by 2050.

More explicit analysis of predictability of bleaching in the GBR and the impact on community structure was conducted using Bayesian belief networks (BBN; Wooldridge and Done 2004; Wooldridge et al. 2005). BBN link various systemic

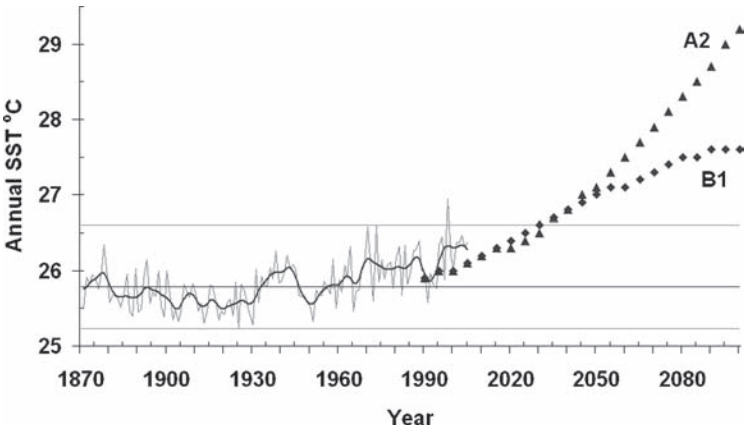

Fig. 10.4 Observed and projected annual mean SST for the Great Barrier Reef. The *thin line* is the annual mean instrumental SST record, 1871–2005 (HadISST and NOAA OI.v2 SST); the *thick black line* is the 10-year Gaussian filter. The *horizontal lines* denote the 1871–1989 mean SST (25.8°C) and the observed range (25.2–26.6°C). Projected SSTs are given for GBR 1990–2100 (ReefClim, Roger Jones, CSIRO) for the B1 (*diamonds*) and A2 (*triangles*) middle of the road climate scenarios. Both scenarios suggest that, by 2035, average GBR SSTs will be outside the range observed in the instrumental record prior to 1990 (adapted from Lough et al. 2006)

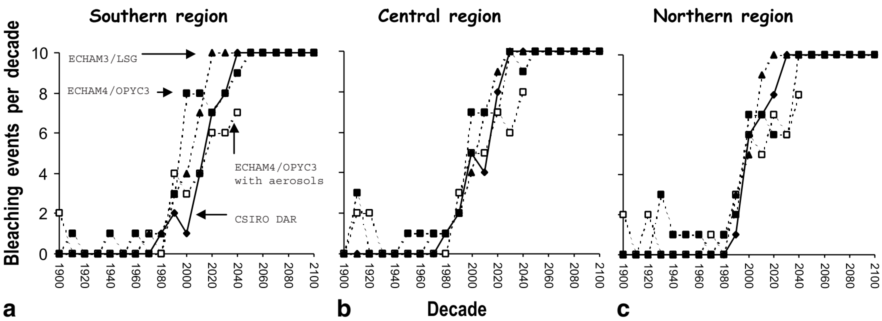

Fig. 10.5 The number of times (per decade) that predicted SSTs will exceed coral bleaching thresholds for: **a** southern (23.5°S, 149.5°E), **b** central (18.0°S, 147.5°E), and **c** northern (11.0°S, 143.0°E) sites on the Great Barrier Reef. The models are ECHAM4/OPYC3 (*black squares*), ECHAM4/OPYC3 with aerosol effect added (*white squares*), ECHAM3/LSG (*black triangles*), and CSIRO DAR GCM (*black dots*; from Hoegh-Guldberg 1999)

variables, their dependencies, and probabilistic outcomes. Wooldridge and Done (2004) described a BBN that linked coral habitat and community type, local SST, climatological SST, and potential for cooling by upwelling of deep water. The BBN successfully predicted the coral mortality category (low, medium, high) for 71% of field observations following the 2002 bleaching on the GBR.

Wooldridge et al. (2005) used another BBN to predict change in the community structure of inshore locations in the central GBR under two climate warming scenarios (1.0–1.5°C or 2.0–2.5°C increase from 1990 to 2050). The BBN determined the probabilistic composition of hard coral, algae, and bare substrate, based on the warming scenario and the mortality and recovery likelihoods of the hard corals. The analysis included two characteristic hard-coral types, predicted SST, varying constraints on algal growth rate, and thermal adaptation of the corals. The study found that natural (i.e., herbivory) or managed constraint of algal growth would be essential to allow recovery of coral populations after bleaching episodes but would not halt long-term climate-related coral reef decline.

The bleaching predictions for the GBR largely assume no temperature adaptation or acclimatisaton by corals over time. Donner et al. (2005) estimates that 17–67% of the coral reefs across the GBR will require at least a 0.5°C increase in their thermal tolerance, while 4–40% will require an increase of 1.0°C, by the year 2030 to avoid frequent harmful bleaching events. Multiple occurrences of bleaching at sites on the GBR are cited as evidence that corals at these sites are not developing greater thermal tolerance (Hoegh-Guldberg 1999). However, recent field and laboratory evidence suggest that the common GBR species *Acropora millepora* can increase its thermal tolerance level by 1.0–1.5°C by shuffling the dominant symbiont in its tissue (Berkelmans and van Oppen 2006; Chap. 7). Such an increase in thermal tolerance might help GBR corals avoid predicted bleaching events in the next several decades, but it is insufficient to meet the larger temperature increase predicted for the latter half of the century (Hoegh-Guldberg 1999; Done et al. 2003; Berkelmans and van Oppen 2006; Lough et al. 2006). An increased understanding of adaptation would aid in determining management strategies for the GBR (Hoegh-Guldberg and Hoegh-Guldberg 2004).

10.5 Future Improvements in Physical Modelling

The general projected increase in thermal stress on coral reefs under future emission scenarios is so rapid and global in scale that it is unlikely to change with future improvement in GCMs (Donner et al. 2005). Future models operating at high horizontal resolution (<1 km) may be instrumental in making specific predictions for individual coral reef complexes. Advances in the application of fluid dynamics theory and computing power are already increasing the resolution of GCMs and hydrodynamic models. For example, the Hybrid Coordinate Ocean Model (HYCOM) can presently operate globally at a horizontal resolution as fine as 1/12° (Metzger et al. 2006) and regionally at horizontal resolution of 1/25° (Kourafalou and Balotro 2006; Prasad and Hogan 2007).

Modelling efforts are being conducted at very high spatial resolutions (<1 km) in and around coral reefs. Skirving et al. (2004) describe a hydrodynamic model of Palau with ~250 m resolution. Mapped ocean currents have been used to determine the vertical mixing of water across the Palau lagoon during periods of low-wind that are characteristic of bleaching events (Skirving and Guinotte 2001). Skirving et al. (2006) describe the reduction in SST due to vertical mixing and link this to the capacity of a water column to absorb solar radiation. Well-mixed regions distribute heat throughout the water column, incurring a small temperature increase throughout the column. In stratified regions, heat is contained near the surface, causing a significant rise in SST. This suggests different temperature climates in which corals exist and, therefore, a different level of acclimatisation to thermal events. The design of protected areas can include the modelled thermal capacitance to provide protection for corals during climate-induced bleaching events (Skirving et al. 2006).

Bode et al. (1997) describe a parameterisation scheme for sub-resolution features, such as those seen in and around coral reefs. This scheme was applied to a tidal model of the southern GBR with a resolution of ~8 km that successfully simulated the tidal amplitude and phase throughout the region. Development of such modelling techniques at various horizontal resolutions will improve the accuracy of forecasts of the effects of climate change and assist design of marine protected areas for coral reef ecosystems.

10.6 Conclusions

Various GCM-based studies present an overall picture of the effect of climate change on the frequency and severity of mass coral bleaching and bleaching-induced mortality around the world. Several studies confirm the original conclusion of Hoegh-Guldberg (1999), that mass coral bleaching could become a biannual event by the 2020s or 2030s at many coral reefs without any thermal adaptations by corals and their symbionts, although important local and regional exceptions have been noted (Sheppard 2003; Donner et al. 2005). Recent work also argues that human-induced warming has already increased the likelihood of mass coral bleaching events in some regions (Donner et al. 2007).

This result is generally robust across different emissions scenarios. Due to time lags in the climate system (between emissions and climate impact) and in the economic system (between a decision to reduce emissions and actual emissions reduction), the simulated climate in different emission scenarios does not diverge until the latter half of the century. There is a greater range in future projections between different GCMs, with different climate sensitivities, than between different emissions scenarios. Nevertheless, even the lowest estimate of business-as-usual projected ocean warming (from the NCAR parallel coupled model) indicates that mass coral bleaching would occur biannually on the majority of coral reefs worldwide by 2050 (Donner et al. 2005).

Corals and their symbionts will have to adapt to rising temperatures to avoid bleaching events that are too frequent to allow the communities to recover. The rate and magnitude at which corals and their symbionts will have to adapt to increasing temperatures appears to vary across the globe (Sheppard 2003; Donner et al. 2005). Climate projections for this century indicate that temperature adaptation might postpone the occurrence of frequent harmful bleaching events and allow corals to survive, provided that policies and technologies alter the path of greenhouse gas emissions and future warming. However, in that case, long-term "committed warming" beyond 2100 could still represent a serious threat to coral reefs (Donner et al. 2007).

An important area for future research is the effect of climate-induced coral bleaching and other disturbances on coral reef community structure. More frequent coral bleaching events, especially when combined with local disturbances such as fishing, pollution or sedimentation, are expected to keep coral and fish species richness low (Wilson et al. 2006; Chap. 10). Ecological models (e.g., Mumby 2006) could be instrumental in describing the effect of higher bleaching frequencies and other disturbances on the extent of coral and macroalgal cover. As more field data become available, models could include multiple coral taxa with different temperature tolerances, growth rates, and reproduction rates (e.g., Wooldridge et al. 2005).

Such combined physical and ecological models will also be critical in estimating the ability of reefs to adapt or acclimatise to warmer ocean temperatures, as well as other local (e.g., fishing pressure) and global (e.g., rising pCO_2) stressors. Models could be used to examine the ecological impact of adaptation by corals and their endosymbionts, such as switching to more temperature-tolerant symbionts (Little et al. 2004; Chap. 7), increased dependence of corals on heterotrophic feeding (Grottoli et al. 2006) or community shifts to more heat-tolerant species (Done 1999). These efforts will help define any management activities that could minimise the effect of the more frequent coral bleaching events expected to occur as the climate continues to warm.

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