Chapter 3
Coral Bleaching in Space and Time

J.K. Oliver, R. Berkelmans, and C.M. Eakin

3.1 Introduction

Coral reefs are facing a range of serious anthropogenic threats that may significantly alter their ecological composition and reduce their capacity to deliver essential ecosystem services. Human influences such as destructive fishing, terrestrial runoff, pollution, and uncontrolled coastal development have a direct and immediately apparent impact on reefs. However the impacts of human-induced climate change are increasingly being seen as a more pernicious and intractable problem to resolve which probably requires concerted social action at a global scale and over many generations (Hughes et al. 2003). Large-scale bleaching of reef corals, resulting in mass mortality, has emerged as a critical global threat to coral reefs and is clearly attributable to thermal stress. Thermal stress on coral reefs has clearly increased over the past century (Chap. 4). As global temperatures continue to rise, largely due to anthropogenic greenhouse gas emissions, the threat to coral reefs is expected to increase significantly.

Predictions based on climate models and thermal tolerance of corals suggest regular widespread catastrophic bleaching within the next 15–25 years (Hoegh-Guldberg 1999; Donner et al. 2005; Chap. 10). However, climate models deal with large-scale atmospheric and oceanic processes, which in themselves are highly complex with many parameters and feedback loops that are difficult to quantify. There is additional uncertainty in foreseeing human trajectories of resource use and change. Predictions of the impacts of climate change are thus uncertain even over large (ocean basin) scales. At the scale of coral reefs this uncertainty is compounded further by the physical and biological complexity of coral reef environments. Physical complexities include currents, tides, bathymetry, depth, water quality, 3D habitat structure, and weather, all of which can affect the temperature and light environment and hence the susceptibility of corals to bleaching. Biological complexities include the variable responses of coral species, the interaction of corals with their diverse and differentially susceptible symbionts, interactions with pathogens, acclimatization, and adaptation processes (Chap. 7). Coral mortality and reef recovery depend on numerous local factors, human use, and conservation. It follows then that the degree of destruction and the permanence of the impacts are uncertain over

M.J.H. van Oppen, J.M. Lough (eds.) *Coral Bleaching*.
Ecological Studies 205,

large spatial scales and that the extent and severity of coral bleaching actually observed may not be as simple as predicted from climate models. These uncertainties increase as scales become smaller. Many of these complexities may never be fully understood; however much can be learnt from studying spatial and temporal patterns in bleaching records. An analysis of past records is, therefore, useful in identifying large-scale spatial and temporal patterns in coral bleaching and identifying key data gaps and data deficiencies which can be addressed in the future.

In the following analysis we investigate the spatial and temporal patterns of coral bleaching that can be detected in the ReefBase global database of bleaching records. In particular we address the following questions:

1. Can discrete global bleaching events be identified from the records of bleaching?
2. How many global events have occurred in the past three decades?
3. Are major bleaching events increasing in frequency and intensity?
4. Is background (low-level) bleaching increasing in frequency and extent?
5. Are there any clear spatial patterns of coral bleaching at global, regional, and subregional scales?
6. Do the observed periods of significant global bleaching correspond with the periodic occurrence of El Niño–Southern Oscillation (ENSO) events?

3.1.1 Early Bleaching Records (Pre-1982)

The earliest confirmed record of reef-wide bleaching due to thermal stress is probably that of Yonge and Nicholls (1931). They mention that, during a period of high summertime temperatures at Low Isles (Great Barrier Reef; GBR) in 1929, many corals died and several corals (particularly *Goniastrea* spp., *Favia* spp.) were observed to have lost their zooxanthellae and turned white. Some weeks later these corals were observed to be recovering their colouration, and histological inspection revealed that they had lost and then started to recover their zooxanthellae populations.

Shinn (1961) notes that *Acropora cervicornis* that had been transplanted to an inshore site in the Florida Keys bleached on their upper surfaces during periods of maximum summertime temperatures. This was not, however, a normal habitat for these corals and no observations of bleaching in normal populations were recorded. Goreau (1964) is probably the first person to publish a specific report on mass bleaching of corals in the reefs around Port Royal, Jamaica, during the aftermath of Hurricane Flora in 1963. He concluded, however, that the main cause of this bleaching was low salinity following heavy rains and floodwaters, rather than the high temperatures associated with current mass bleaching events. It is also possible that the report by Mayer (1914), in which he refers to corals not exposed to the air being "injured" after exposure to several hot calm days, represents a bleaching event. There is no mention, however, in his paper of loss of colour or bleaching. There is a total of 26 records of coral bleaching before the first well documented global-scale coral bleaching event of 1982–1983.

Coffroth et al. (1990), Williams and Bunkely-Williams (1990), Glynn (1991, 1993), and Goreau and Hayes (1994) have compiled records of much earlier mass coral mortality, dating back to 1876. These earlier reports provide details for specific sites in terms of the pattern and extent of mortality and the probable causes. Factors other than high temperatures (e.g. aerial exposure, freshwater, "dark water") are most often used to explain the mortality and in these cases there is no firm evidence to suggest that the cause of the mortality was high temperatures and that corals had bleached prior to dying.

3.1.2 Bleaching Records from 1982 Onwards

It was not until the global bleaching event of 1982–1983, first documented by Glynn (1983, 1984) that widespread bleaching and mortality was recognized as a major phenomenon that could impact coral status and health at regional and global scales. The interest generated by Glynn's early papers on bleaching in the Eastern Pacific led to anecdotal reports from a wide range of sites across the world in subsequent years. These early reports were compiled by Brown (1987), Glynn, (1990, 1991, 1993), Williams and Bunkley-Williams (1990), and Goreau and Hayes (1994). More recent summaries of coral bleaching records were published by a number of authors (Wilkinson 1998, 2000, 2002; Wellington and Glynn 2007).

In the late 1990s the World Conservation Monitoring Center and the WorldFish Center (then called ICLARM) both developed databases that compiled published and unpublished records of coral bleaching from throughout the World. In 2001 these datasets were combined and updated into a single database which is maintained by WorldFish as part of its ReefBase database on coral reefs. The dataset is available through the ReefBase website (www.reefbase.org).

The ReefBase bleaching database includes virtually all records in the published literature, as well as unpublished records communicated directly to ReefBase and the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch (http://coralreefwatch.noaa.gov/) and those published on the coral list-server maintained by NOAA's Coral Health and Monitoring Network (http://coral.aoml.noaa.gov/). Despite increasing interest and commentary on global patterns of coral bleaching, this comprehensive dataset has not previously been analysed in any detail.

The majority of available bleaching records consist of descriptive accounts of the location of bleaching and, with varying degrees of detail, an assessment of the extent and severity of bleaching. Water depth and coral species affected are often not recorded. In a small number of cases, formal surveys using quantitative or semi-quantitative measurements provide estimates of the percentage of coral that bleached.

The minimum information in each bleaching record in the database is the date of observation, location, bleaching severity, and source of the information. Bleaching severity is a categorical variable. Table 3.1 shows the different categories, their descriptions and notes on how verbal reports have been translated into one of the categories.

Table 3.1 Coral bleaching categories used in ReefBase

Code	Category	Description	Notes
0	No bleaching	No bleaching observed	For quantitative surveys, no bleaching is recorded if the percentage of live coral cover bleached is less than 1%
−1	Bleaching (unknown severity)	Bleaching recorded	Bleaching observed but no information on severity. For the purposes of analysis this category is converted to 2 – moderate bleaching
1	Mild bleaching	Up to 10% of coral cover bleached	If no estimate of % of bleached corals or coral cover is provided then terms such as "light", "mild", "scattered", "occasional" are used to identify this category
2	Moderate bleaching	10–50% of coral cover bleached	If no estimate of % of bleached corals or coral cover is provided then terms such as "significant", "common", "frequent", "moderate" are used to identify this category
3	Severe bleaching	More than 50% of coral cover bleached	If no estimate of % of bleached corals or coral cover is provided then terms such as "heavy", "abundant", "severe" are used to identify this category

A total of 5215 records of coral bleaching in the ReefBase bleaching database were analysed, as of February 2007. Because many of these records provided information for adjacent areas within the same location, the data were first summarized by averaging all records from a single named place. This process reduced the number of records to 2808 records. Only a small number of records (<1%) did not include information on bleaching severity. Most of these were reports for early bleaching events prior to the major bleaching event of 1997–1998. For the purpose of the analysis, these records were reclassified as "moderate bleaching" since it is most likely that these early reports related to bleaching of more than 10% of coral cover. Very few (less than 3%) reports of mild bleaching were recorded in the database prior to 1997.

While the ReefBase bleaching database contains the most comprehensive archive of coral bleaching records and while all records are referenced either to a publication or a formal source, analysis of these records presented a number of problems. First, the records of severity are often quite subjective. This issue was addressed by grouping all records into a small number of broad categories. Second, some records of bleaching may be duplicates of other records of the same event reported by other sources. While some duplicates are likely to persist, we attempted to eliminate this through careful screening, and by grouping all records that relate to a single site into a single "site record".

Finally, the number of reports received can vary both as a function of the severity and extent of bleaching, but also as a result of increased numbers of observers with an interest in bleaching. This "reporting effect" represents an important potential sampling bias that cannot be discounted or completely eliminated. While there are no data on the extent of this reporting effect, it is likely that the total number of potential observers of bleaching and the proportion of these who would be motivated to report on bleaching have both increased over the past two decades as field-based coral studies have increased and media attention on the destruction of coral reefs from bleaching and climate change has grown. Despite these sources of bias, we believe that a cautious and conservative analysis of the bleaching records can yield important insights into the extent of coral bleaching in space and time, the relationship between bleaching and climate variability, and change at regional and global scales.

3.2 Global Patterns of Coral Bleaching

3.2.1 Temporal Patterns

3.2.1.1 Site Records

There are two very clear patterns that can be seen when examining all levels of bleaching severity (Fig. 3.1). First, there is a clear increase in the number of sites reporting bleaching in the past decade. Second, several dramatic peaks of one or two years duration show the episodic nature of bleaching.

The trend of increasing bleaching occurrence is driven largely by mild bleaching records and, to a lesser extent, by moderate bleaching records (Fig. 3.1a). If only severe bleaching records are considered then this trend nearly disappears. This is

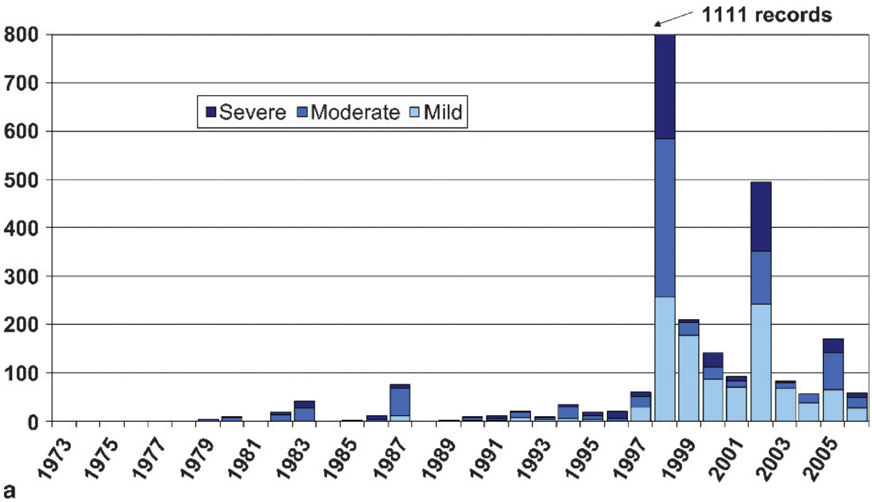

Fig. 3.1 Number of coral bleaching records in ReefBase by site and year for: **a** mild, moderate, and severe bleaching, **b** moderate and severe bleaching, and **c** moderate and severe bleaching, excluding Great Barrier Reef sites

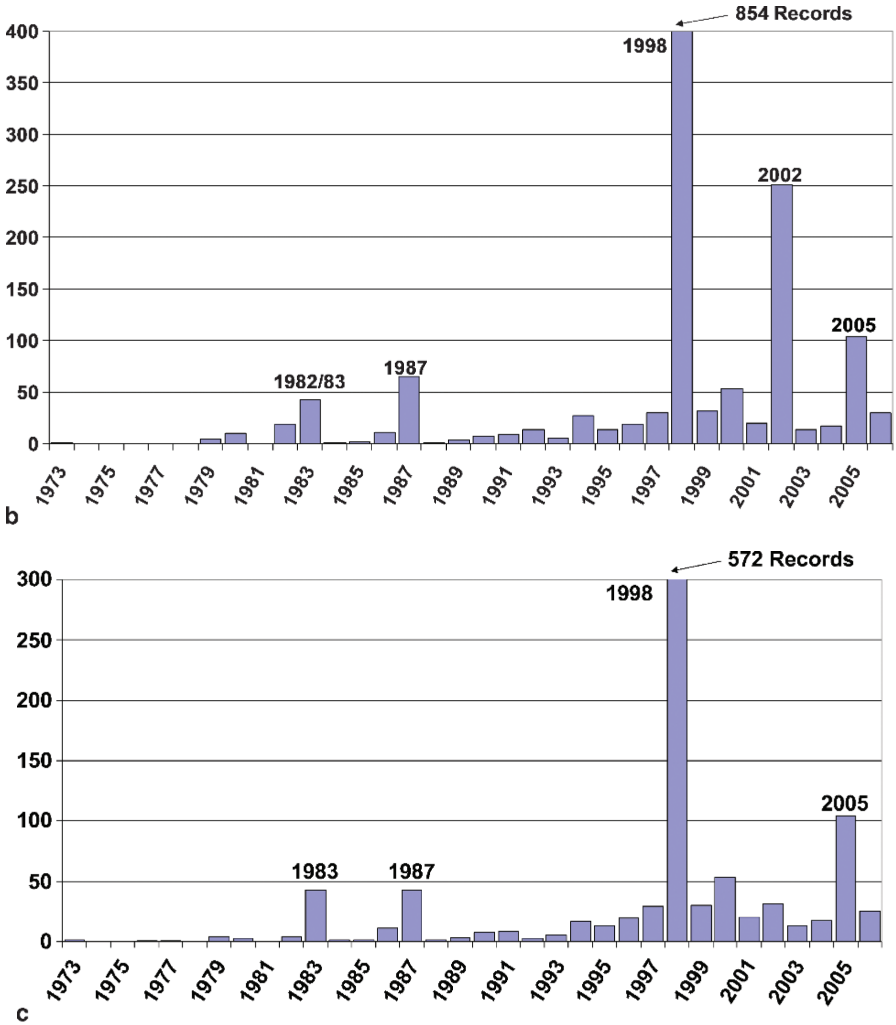

Fig. 3.1 (continued)

especially apparent when viewed as the proportion of bleaching events classified as severe (Fig. 3.2). While the increase in mild bleaching could be due to an increase in chronic low-level stress to corals it is also possible that the increased awareness of coral bleaching (particularly after 1998) has led to increased reporting of small amounts of bleaching that largely went unreported before then.

There are five clear peaks of varying magnitude that can be clearly identified: 1982/83; 1987; 1998; 2002, and 2005. If only severe and moderate bleaching events are considered, the same peaks remain (Fig. 3.1b). In 1998 and 2002 a very large number of sites were surveyed on the GBR, using aerial survey techniques, and this has contributed to the disproportionately large peaks for these years. If the GBR

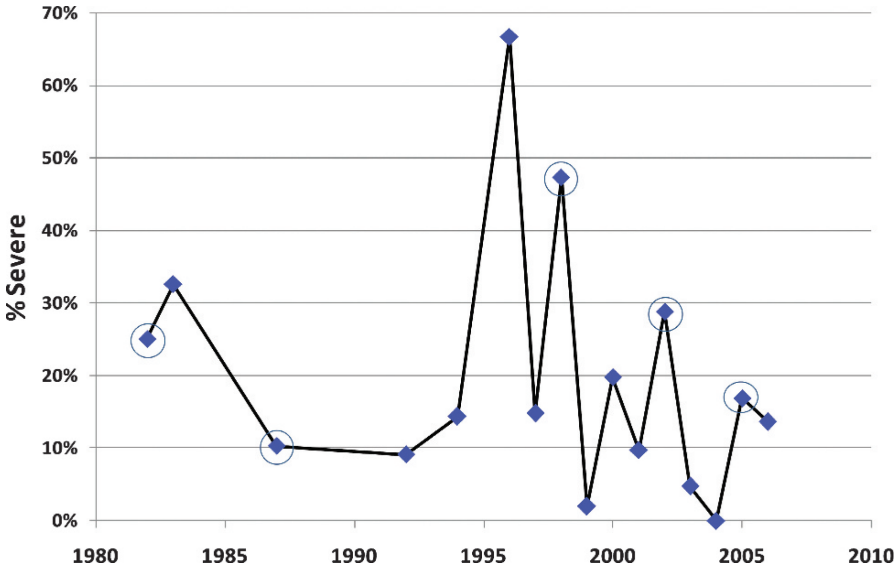

Fig. 3.2 Proportion of bleaching records classified as severe from ReefBase since 1982. *Circles* indicate years of major bleaching

records are eliminated from the graph, then the 2002 peak disappears (Fig. 3.1c), but all others remain.

3.2.1.2 Country Bleaching Records

Some countries have devoted much greater effort to monitoring and reporting bleaching than others. For instance, intensive aerial surveys of the GBR in 1998 and 2002 resulted in over 600 site records in these years. In other countries the total number of bleaching site records in a major bleaching year (1998) ranged from one to 45, with most countries having fewer than ten records. To reduce the distortion caused by this bias in sampling effort between countries, we looked at the presence or absence of bleaching per country and then examined trends in the number of countries reporting bleaching in any year.

The same two general patterns observed for site records are also apparent in the results for number of countries reporting bleaching (Fig. 3.3a). There are several clear peaks corresponding to major bleaching years and there is a very noticeable increase in the number of bleaching reports over time. The same peaks are evident as in Fig. 3.1. However, the peak for 2002 is missing in this case since the majority of bleaching occurred in one country (Australia). There is also a clear trend of increasing bleaching frequency over the past three decades. Again this trend is less distinct when only severe bleaching records are considered (Fig. 3.3b).

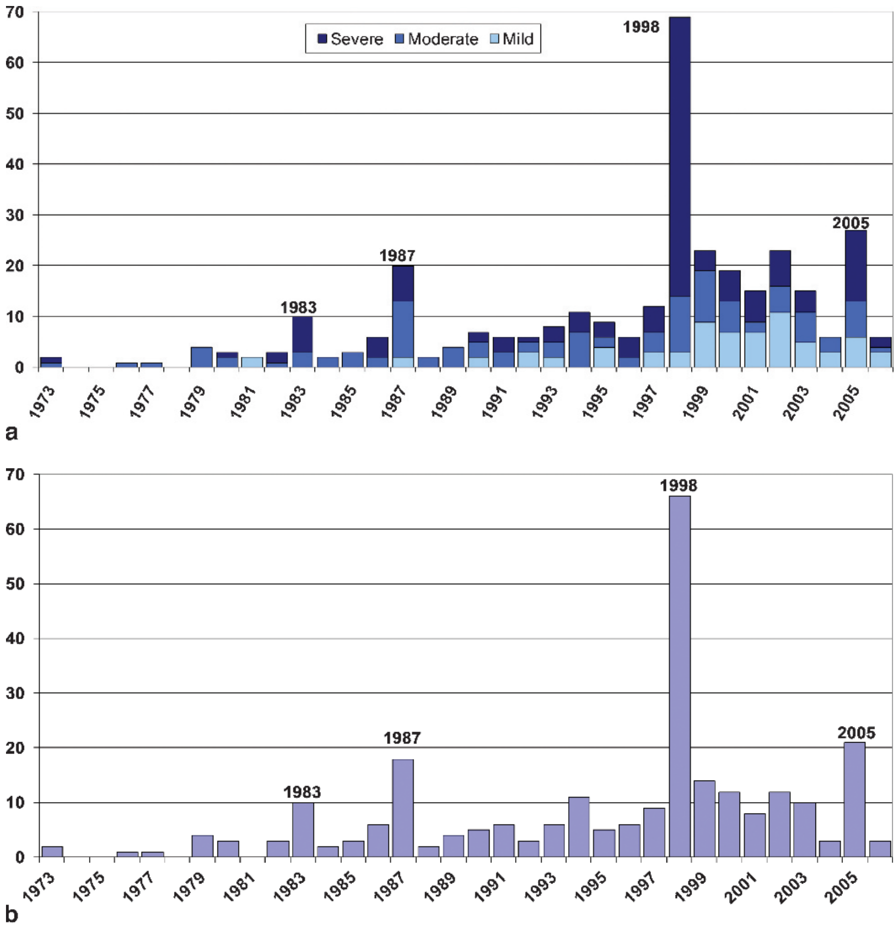

Fig. 3.3 Number of countries reporting bleaching in ReefBase by: **a** country and year and **b** country and year restricted to moderate or severe bleaching

3.2.2 Spatial Patterns in Bleaching Reports

As indicated in Fig. 3.1b, there are five distinct peaks in coral bleaching between 1973 and 2006. The spatial distribution of these records for each of these peak-bleaching periods (Fig. 3.4) shows that the 1997–1998 El Niño and 1998–1999 La Niña stand out as the most severe and spatially extensive period of coral bleaching so far recorded and provides the best opportunity to examine the spatial distribution of globally distributed bleaching. Bleaching records were submitted during 1998 from around the world, with the possible exception of the western Pacific, which has comparatively few records. Many western Pacific sites did bleach, however, during the 1998–1999 La Niña. No bleaching was recorded in 1998 from the

Fig. 3.4 Distribution and intensity of bleaching from records in ReefBase for the global bleaching years: **a** 1982–1983, **b** 1987, **c** 1998, and **d** 2005, and **e** the spatially restricted event of 2002. *Red dots* Severe bleaching, *yellow dots* moderate bleaching, *blue dots* mild bleaching, *green dots* no bleaching. Reef areas in *orange*

Solomon Islands, Hawaiian Islands, and New Caledonia. In French Polynesia, only mild to moderate bleaching was reported.

The lack of bleaching records from the Pacific in 1998 may predominantly be due to under-reporting. Comparatively few reports are available from most areas; the entire area from the Marshall Islands down to Tuvalu has no records at all and much of Melanesia experienced very low or no bleaching. The records of bleaching in Samoa may be due to an extreme low tide event rather than thermally induced bleaching. Given the high level of awareness of bleaching by the end of 1998 and the significant efforts of scientists to compile bleaching records for this particular event (e.g. Wilkinson 1998), it is likely that this relative absence of bleaching is real and may due to the fact that the Pacific islands are far from any continental land masses and less subject to the unseasonable increases in sea temperatures which occur on shallow continental shelves. During other years, however, severe bleaching has been recorded in the Pacific (e.g. Hawaii in 1996, Papua New Guinea and Fiji in 1999 and 2000). This suggests that local conditions can still produce thermal stress and bleaching, even in open oceanic areas.

In 1987, bleaching was also quite widespread, although the Pacific, Southeast Asia, and the Middle East are very poorly represented. In other years of major bleaching the distribution is less even. For instance in 1982–1983, the eastern Pacific was clearly the most severely affected region, while in 2002 and 2005 the GBR (see Sect. 3.3) and the Caribbean (Wilkinson and Souter 2008), respectively, were the clear focal areas for severe bleaching.

3.3 Great Barrier Reef

3.3.1 Time Series

Figure 3.5 shows that over the past 25 years, there are two major peaks in bleaching site records on the GBR, corresponding to the bleaching events of 1998 and 2002. These peaks are disproportionately high due to the intensive surveys conducted by Berkelmans and Oliver (1999) and Berkelmans et al. (2004). While the number of records is very low in the early years, there appear to be periods when significant bleaching was observed. In total there are eight discernable bleaching peaks. These bleaching years include 1980, 1982, 1987, 1992, 1994, 1998, 2002, and 2005. The proportion of these GBR bleaching events classified as severe has varied through the record, with no real trend (Fig. 3.2b). Anecdotal reports suggest that there may also have been a bleaching event sometime in the 1970s, but the year, extent, and intensity are unknown (Oliver 1985)[1].

[1] Oliver (1985) also states that "bleaching at Magnetic Island was not nearly as extensive in 1983 compared with 1982". This indirect reference to a bleaching event in 1983 is in fact a typographical error. It should have been a reference to the 1980 bleaching event.

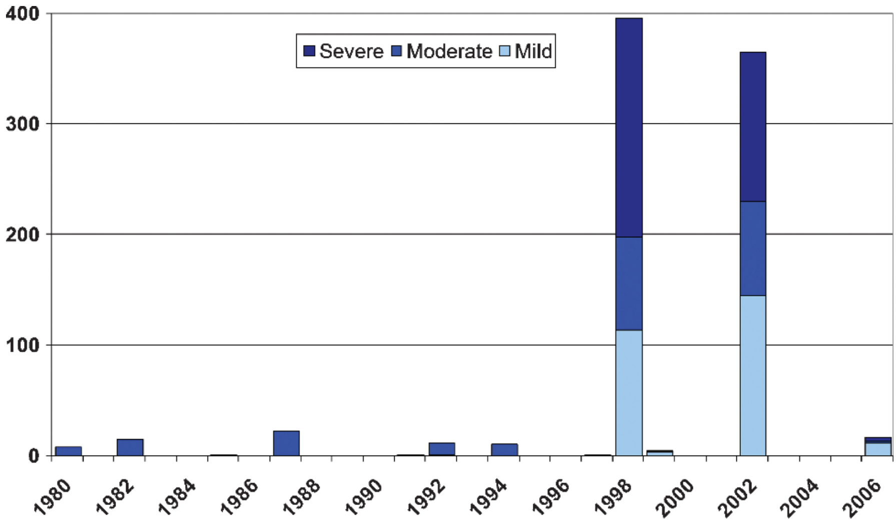

Fig. 3.5 Number of records of coral bleaching on the Great Barrier Reef

Extensive in-situ and satellite temperature data over the past 15 years also suggest that there were at least two "near-bleaching" years when bleaching thresholds were approached and noticeable paling commenced at a number of sites. These years include 1995 when Michalek-Wagner and Willis (2001) noted a mild bleaching event at Orpheus Island and early 2005 when mild bleaching was reported for several reefs on the GBR.

3.3.2 Spatial Patterns

The most striking similarity between the 1998 and 2002 beaching events on the GBR is the higher incidence and severity of bleaching on inshore reefs compared with offshore reefs (Berkelmans et al. 2004; Fig. 3.6). The same general pattern seems to hold in some of the other GBR bleaching events, particularly the mild bleaching events of 1992 and 1994, which affected predominantly inshore sites. The reasons for this pattern are not clearly understood but a number of plausible explanations, singly or in combination, may contribute to the observed effect. First, inshore shallow waters have a smaller volume and hence a reduced thermal capacitance compared with deeper offshore waters. Second, inshore waters may have a reduced ability to mix with cooler deeper water simply because the waters are warm for the full depth of the water column. Third, inshore corals are generally more darkly pigmented compared with their offshore relatives due to reduced light availability (higher turbidity) and higher nutrient loadings. The higher pigment density has been shown to increase solar absorption and raise the effective temperature experienced by corals

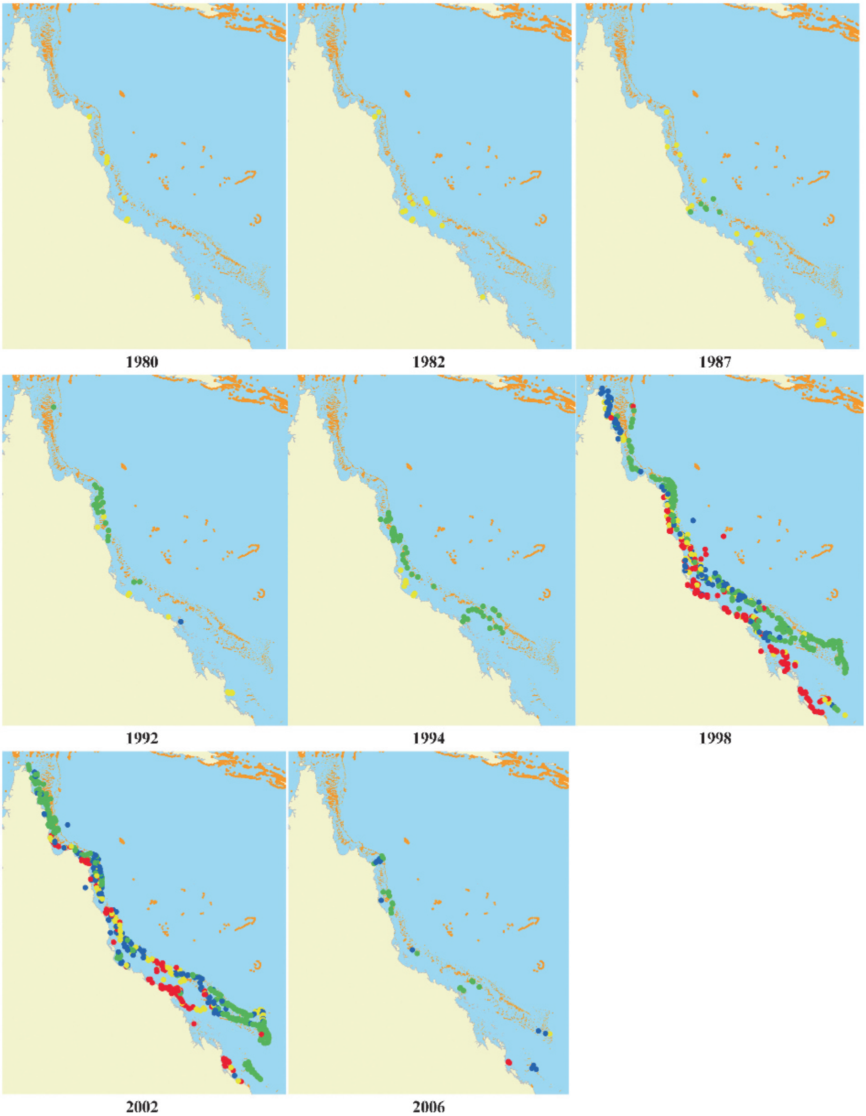

Fig. 3.6 Great Barrier Reef bleaching records. The maps for 1998 and 2002 include aerial survey data. Colours as per Fig. 3.4

by up to 1.5°C, exacerbating the bleaching risk for inshore coral communities (Fabricius 2006). Since anthropogenic impacts are also concentrated inshore, the clear management imperative to mitigate against additional stresses is doubly important in inshore environments. Good land management practices (river catchment, coastal development) and prudent fisheries management, especially for herbivorous fisheries, are particularly important priorities for management in these areas (Salm and Coles 2001; Marshall and Shuttenberg 2006).

3.4 Relationships with El Niño–Southern Oscillation Events

It is clear from Fig. 3.7 that the link between moderate–severe bleaching and powerful El Niño events is fairly strong at a global scale. Of the four global bleaching events identified above, three (1983, 1987, 1998) occur during or just after the most significant and sustained dips in the Southern Oscillation Index (SOI) since 1982/83 when attention first focussed on the phenomenon. The fourth bleaching event (2005) coincides with the second lowest dip in the SOI in the past 50 years, although it was very brief. During 1973 and 1978, similar sustained dips in the SOI are evident. The absence of coral bleaching during these periods may be due to lack of awareness and reporting. It is also possible that rising global temperatures are bringing corals closer to their bleaching thresholds and periods of warming during low SOI became sufficient to induce bleaching only after the 1978 phase shift (Trenberth and Hurrell 1994; Mantua et al. 1997). However some bleaching was indeed observed in 1973 and there are other unconfirmed reports on the GBR of significant bleaching in the early 1970s, The 1982–1983 bleaching is lower than expected given the intensity of the SOI phase, however this is probably due to reduced reporting. It was the first major bleaching event to receive widespread publicity; and scientific attention increased dramatically for subsequent bleaching events and El Niños.

On the GBR (Fig. 3.8) the relationship between El Niño events and coral bleaching is less straightforward. While the 1987 and 1998 events occurred during the height of El Niño phases, the 1982, 2002, and 2006 events occurred when the SOI was neutral. In 1982 this was just prior to a significant decline in the SOI, while in 2002 and 2006 bleaching occurred prior to less significant but still noticeable period of negative values.

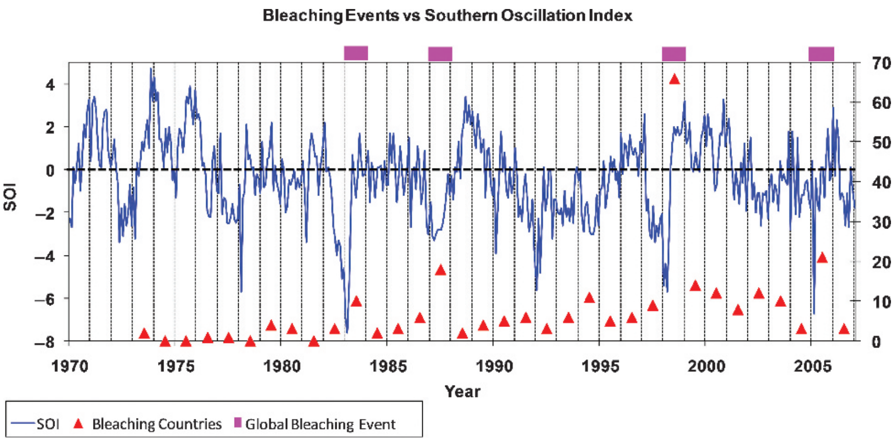

Fig. 3.7 Global bleaching events and the Southern Oscillation Index (*SOI*). The *shaded bars* at the top indicate years when global bleaching events occurred. *Solid triangles* show the number of countries which reported moderate to severe bleaching in each year

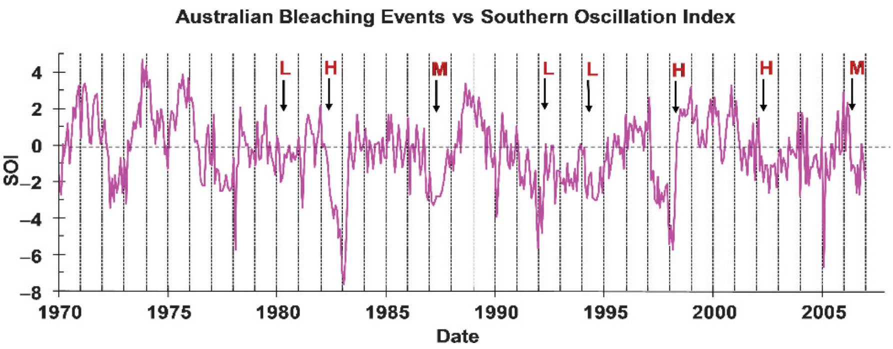

Fig. 3.8 Australian bleaching events and the SOI. *L*, *M*, *H* arrows indicate light, moderate, heavy bleaching events, respectively

3.5 Discussion

The results presented here represent the most comprehensive record of coral bleaching available on a global level. They provide a clear quantitative record of bleaching frequency and periodicity for the past three decades. We have identified four periods (1983, 1987, 1998, 2005) that can be called global bleaching events in terms of bleaching frequency and intensity and the number of countries affected.

Most authors who recently reviewed global patterns of coral bleaching (e.g. Glynn 1996, 2000, 2002; Wilkinson 1998) did not attempt to formally identify specific global events other than the 1982–1983 and 1998 events. In an early review, Williams and Bunkley-Williams (1990) clearly identified 1987 as a global bleaching event but this has received comparatively little attention since then. The most recent global event identified in our analysis (2005) received extensive media coverage; and formal reports are only now appearing in the scientific literature at the time of writing (Donner et al. 2007; Manzello et al. 2007; Whelan et al. 2007).

Goreau and Hayes (1994) and Glynn (1996, 2000, 2002) in their reviews of bleaching indicated that bleaching has increased in frequency since it was first reported at a global level in 1983. Other authors predicted an increasing frequency of occurrence based on climate models and specific bleaching thresholds (Hoegh-Guldberg 1999; Donner et al. 2007).

Our results clearly show an increase in the number of bleaching reports during the past three decades, with a major increase in the past decade after the 1998 event. The graphs in Fig. 3.1 suggest that, in the past decade, there was a low level of bleaching in all years, but these are easily differentiated from years with major bleaching episodes. Our data do not enable us to completely differentiate between true increases in bleaching frequency and increases in reporting effort. However, on the GBR and in much of the Caribbean, the level of scientific research and monitoring, together with the dedicated efforts of key institutions to record all bleaching events since 1983, makes it unlikely that major events have gone unreported. The same applies for many major coral reef areas around the world. Thus the major peaks in bleaching records are likely to be real phenomena, while the increase in annual background bleaching is more difficult to interpret. When we look only at major peaks in bleaching records, then at a global level we can clearly differentiate four global events. This is too small a number to quantitatively determine whether the frequency of severe events is increasing.

We conclude that there is insufficient evidence in the global database of bleaching records to either support or refute the hypothesis that major bleaching events are increasing in frequency. There is some evidence that low-level background bleaching has increased. A separate, but related issue is whether the intensity of bleaching is increasing. If this were the case, we would expect to see an increase in the proportion of severe bleaching reports, either on a year to year basis, or from one major bleaching event to the next. As can be seen in Fig. 3.2, the data do not indicate any such increase in the proportion of severe bleaching. This finding contrasts with data that show clear increases in both the frequency and intensity of bleaching-level thermal stress (Chap. 4). One potential reason is that the corals that survive severe events, such as 1998, are more capable of surviving subsequent thermal stress. A corollary is that severe bleaching events reduce diversity, removing the more thermally sensitive corals.

At the regional level, the spatial distribution of bleaching and the severity of bleaching on the GBR during the 1998 and 2002 bleaching events correlated strongly with thermal stress patterns (Berkelmans et al. 2004). Apart from the strong inshore–offshore effect, bleaching in these two events was patchy over scales of tens of kilometres, reflecting patterns in local weather and oceanography. As a result, many local-scale differences were evident between years. This makes prediction and scenario modelling particularly challenging at locals scales and highlights the need for a detailed understanding of the oceanographic environment and appropriate tools to draw inferences from diverse data sets (Wooldridge and Done 2004; Skirving et al. 2006; Wooldridge et al. 2006). A positive implication from this patchiness is that there is likely to be a proportion of reefs that will not bleach in successive events, giving affected reefs longer to recover. The Palm Islands in the central inshore GBR are a case in point. Coral cover was reduced by >50% at many sites dominated by *Acropora* spp. and, having avoided the 2002 event, recovery in this genus is well advanced after ten years.

The relationship between ENSO events and coral bleaching is highlighted repeatedly in the literature. In the eastern Pacific the relationship between El Niño and coral bleaching is both dramatic and unambiguous (Glynn 1984, 2000, 2002; Wellington and Glynn 2007). At a global level there is also a strong correspondence between the four major bleaching events and the occurrence of major negative deviations in the SOI (Fig. 3.5). This suggests that there are likely to be at least some links between the oceanographic and meteorological changes that accompany El Niño events. Not all teleconnections between the core canonical events of El Niño and thermal anomalies on coral reef areas have been clearly identified. Huppert and Stone (1998) suggest that additional stochastic triggering events may explain records of bleaching in non-El Niño years, and presumably also why no bleaching is recorded in some locations during El Niño years. Additionally, some regions of the western Pacific often cool down during El Niño events but warm up during La Niña events (e.g. Fiji, Papua New Guinea; Chap. 4). These sites show greater thermal bleaching during La Niña years.

On the GBR the records show a less direct correlation between negative SOI deviations and bleaching events, although the proximity of major bleaching to these deviations is very suggestive. The SOI may therefore be a poor direct indicator of ENSO events at a local or sub-regional scale even though it is possible that many of the GBR bleaching events are indirectly caused by ENSO-related anomalies. The reversals of normal ocean current directions, particularly in the equatorial Pacific during ENSO, events has a profound but indirect influence on local weather conditions. The nature and timing of the effects may be highly variable in different locations and from one event to another. For example, the western Pacific is generally cooler during an El Niño event which in theory suggests a low chance of bleaching. However, El Niño conditions in Australia generally bring drought and long periods of cloud-free, doldrum-like conditions. When this coincides with the austral summer, local heating of shallow inshore waters occurs. This would explain the observed inshore–offshore bleaching pattern during major bleaching events. El Niño weather patterns operate at regional scales and affect reef provinces only when they coincide with the regional summer. The GBR probably avoided a major bleaching event in 2005 only because ocean current anomalies returned to normal just before the austral summer.

Despite its limitation, the database of bleaching records in ReefBase is highly valuable for quantifying major bleaching events. Its utility could be greatly increased if monitoring and reporting effort could be standardized. This would enable smaller-scale patterns of milder bleaching events to be reliably detected, thus providing early verification of predicted increases in bleaching frequency due to climatic temperature increases. It would also provide much needed ground truth data for the bleaching HotSpots detected by satellite data (Chap. 4). Two key improvements in the bleaching reporting are standardization in the measurement of bleaching intensity and standardization in the number, location, and timing of bleaching surveys. The first issue was addressed by Oliver et al. (2004) and Marshall and Schuttenberg (2006). The adoption and use of a standard reporting protocol would greatly increase the reliability of bleaching records. The second issue will require a much greater level of coordinated effort by coral reef scientists and reef-users. Existing global networks such as the Global Coral Reef Monitoring Network and Reef Check are well placed to promote the regular reporting of bleaching conditions (both presence and absence) from standard locations; and we hope that these can encourage greater monitoring and reporting as a priority.

Overall, we conclude that the existing observations of coral bleaching enable us to confirm that severe bleaching events occurred at a global level on four recent occasions. Also, we have demonstrated that these events occurred in close temporal proximity to a strong negative deviation in the SOI. While there is no clear increase in the frequency or intensity of major global bleaching events, the number of bleaching records has clearly increased during the past three decades. However, increased vigilance and reporting of mild bleaching by an ever-increasing number of researchers and conservation-minded divers is confounding efforts to definitively separate changes in bleaching frequency from changes in reporting.

Acknowledgements C.M.E. thanks NOAA, including the Coral Reef Watch and the Coral Reef Conservation Program, for work that contributed to this manuscript. The manuscript contents are solely the opinions of the authors and do not constitute a statement of policy, decision, or position on behalf of NOAA or the US Government. We also thank Yusri bin Yusef for recent updates to the ReefBase bleaching database and Teoh Shwu Jiau for preparation of the maps.

References

Berkelmans R, Oliver J (1999) Large scale bleaching of corals on the Great Barrier Reef. Coral Reefs 18:55–60

Berkelmans R, De'ath G, Kininmonth S, Skirving W (2004) A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns, and predictions. Coral Reefs 23:74–84

Brown BE (1987) Worldwide death of corals – natural cyclical events or man-made pollution? Mar Pollut Bull 18:9–13

Coffroth MA, Lasker HA, Oliver JK (1990) Coral mortality outside of the eastern Pacific during 1982–1983: relationship to El Niño. In: Glynn PW (ed) Global ecological consequences of the 1982–83 El Niño–Southern Oscillation. (Elsevier oceanography series) Elsevier, New York, pp 141–182

Donner SD, Skirving WJ, Little CM, Oppenheimer M, Hoegh-Guldberg O (2005) Global assessment of coral bleaching and required rates of adaptation under climate change. Global Change Biol 11:2251–2265

Donner SD, Knutson TR, Oppenheimer M (2007) Model-based assessment of the role of human-induced climate change in the 2005 Caribbean coral bleaching event. Proc Natl Acad Sci USA 104:5483–5488

Fabricius KE (2006) Effects of irradiance, flow, and colony pigmentation on the temperature microenvironment around corals: implications for coral bleaching? Limnol Ocean 51:30–37

Glynn PW (1983) Extensive "bleaching" and death of reef corals on the Pacific coast of Panama. Environ Conserv 10:149–154

Glynn PW (1984) Widespread coral mortality and the 1982–83 El Niño warming event. Environ Conserv 11:133–146

Glynn PW (1990) Coral mortality and disturbances to coral reefs in the tropical eastern Pacific. In: Glynn PW (ed) Global ecological consequences of the 1982–83 El Niño–Southern Oscillation. (Elsevier oceanography series) Elsevier, New York, pp 55–126

Glynn PW (1991) Coral reef bleaching in the 1980s and possible connections with global warming. Trends Ecol Evol 6:175–179

Glynn PW (1993) Coral reef bleaching: ecological perspectives. Coral Reefs 12:1–17

Glynn PW (1996) Coral reef bleaching: facts, hypotheses and implications. Global Change Biol 2:495–509

Glynn PW (2000) El Niño–Southern Oscillation mass mortalities of reef corals: a model of high temperature marine extinctions. In: Insalaco E, Skelton PW, Palmer TJ (eds) Carbonate platform systems: components and interactions. Geol Soc Lond Spec Pub 178:117–133

Glynn PW (2002) Effects of the 1997–98 El Niño–Southern Oscillation on eastern Pacific corals and coral reefs: an overview. In: Moosa MK, Soemodihardjo S, Soegiarto A, Romimohtarto K, Nontji A, Soekarno, Suharsono (eds) Proc Int Coral Reef Symp 9-2:1169–1174

Goreau TF (1964) Mass expulsion of zooxanthellae from Jamaican coral reef communities after hurricane Flora. Science 145:383–386

Goreau TJ, Hayes RL (1994) Coral bleaching and ocean hot spots. Ambio 23:176–180

Hoegh-Guldberg O (1999) Climate change, coral bleaching and the future of the world's coral reefs. Mar Freshwater Res 50:839–866

Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke, Grosberg R, Hoegh-Guldberg O, Jackson JBC, Kleypas J, Lough JM, Marshall P, Nyström M, Palumbi SR, Pandolfi JM, Rosen B, Roughgarden J (2003) Climate change, human impacts, and the resilience of coral reefs. Science 301:929–933

Huppert A, Stone L (1998) Chaos in the Pacific's coral bleaching cycle. Am Nat 152:447–458

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. Bull Am Meteorol Soc 78:1069–1079

Manzello DP, Berkelmans R, Hendee JC (2007) Coral bleaching indices and thresholds for the Florida Reef Tract, Bahamas, and St Croix, US Virgin Islands. Mar Pollut Bull 54:1923–1931

Marshall P, Shuttenberg H (2006) A reef managers guide to coral bleaching. Great Barrier Reef Marine Park Authority, Townsville

Mayer AG (1914) The effects of temperature on tropical marine animals. Carnegie Inst Washington Pap Tort Lab 6:1–24

Michalek-Wagner K, Willis BL (2001) Impacts of bleaching on the soft coral *Lobophytum compactum*. II. Fecundity, fertilization and offspring viability. Coral Reefs 19:231–239

Oliver J (1985) Recurrent seasonal bleaching and mortality of corals on the Great Barrier Reef. In: Gabrie C, Salvat B (eds) Proc Int Coral Reef Congr 5-4:201–212

Oliver J, Marshall P, Setiasih N, Hansen, L (2004) A global protocol for assessment and monitoring of coral bleaching. WorldFish Center, Penang/WWF Indonesia, Jakarta

Salm RV, Coles SL (eds) (2001) Coral bleaching and marine protected areas. (Proceedings of the workshop on mitigating coral bleaching impact through MPA design, Bishop Museum, Honolulu, Hawaii, 29-31 May 2001. Asia Pacific coastal marine program report 0102) The Nature Conservancy, Honolulu

Shinn EA (1961) Coral growth-rate: an environmental indicator. J Paleontol 40:233–240

Skirving W, Heron M, Heron S (2006) The hydrodynamics of a bleaching event: implications for management and monitoring. In: Phinney JT, Hoegh-Guldberg O, Kleypas J, Skirving W, Strong A (eds) Coral reefs and climate change science and management. (Coastal and estuarine studies 61) American Geophysical Union, Washington, D.C., pp 145–161

Trenberth, KE, Hurrell JW (1994) Decadal atmosphere–ocean variations in the Pacific. Clim Dyn 9: 303–319

Wellington GM, Glynn PW (2007) Responses of coral reefs to El Niño–Southern Oscillation sea-warming events. In: Aronson RB (ed) Geological approaches to coral reef ecology. Springer, New York, pp 342–385

Whelan KR, Miller TJ, Sanchez O, Patterson M (2007) Impact of the 2005 coral bleaching event on *Porites porites* and *Colpophyllia natans* at Tektite reef, US Virgin Islands. Coral Reefs 26:689–693

Wilkinson CR (1998) Status of coral reefs of the world: 1998. Global Coral Reef Monitoring Network, Australian Institute of Marine Science, Townsville

Wilkinson CR (2000) Status of coral reefs of the world: 2000. Global Coral Reef Monitoring Network, Australian Institute of Marine Science, Townsville

Wilkinson CR (2002) Status of coral reefs of the world: 2002. Global Coral Reef Monitoring Network, Australian Institute of Marine Science, Townsville

Wilkinson C, Souter D (2008) Status of Caribbean coral reefs after bleaching and hurricanes in 2005. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville

Williams EH, Bunkley-Williams L (1990) The worldwide coral bleaching cycle and related sources of coral mortality. Atoll Res Bull 335:1–71

Wooldridge S, Done T (2004) Learning to predict large-scale coral bleaching from past events: a Bayesian approach using remotely sensed data, in situ data, and environmental proxies. Coral Reefs 23:96–108

Wooldridge S, Brodie J, Furnas M (2006) Exposure of inner-shelf reefs to nutrient enriched runoff entering the Great Barrier Reef lagoon: post-European changes and the design of water quality targets. Mar Pollut Bull 52:1467–1479

Yonge CM, Nicholls AG (1931) The structure, distribution and physiology of the zooxanthellae. (Studies on the physiology of corals IV) Sci Rep Great Barrier Reef Exped 1928–29 1:135–176