Chapter 3
Coral Bleaching in Space and Time

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3.1 Introduction

Coral reefs face 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 and overfishing, 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 a more pernicious and intractable problem to resolve, and this requires concerted social action at a global scale and over many generations (Hoegh-Guldberg 1999; Gattuso et al. 2015; Hughes et al. 2003, 2017; Spalding and Brown 2015). Large-scale bleaching of reef corals, resulting in mass mortality, is now a critical global threat to coral reefs and is clearly attributable to thermal stress (Baker et al. 2008; Heron et al. 2016) with excess light playing a key additional role (Brown 1997; Fitt et al. 2001). Thermal stress on coral reefs has clearly increased over the past century (Heron et al. 2016; Chap. 4). As global temperatures continue to rise, due to anthropogenic greenhouse gas emissions, the threat to coral reefs is increasing 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; Logan et al. 2014; van Hooidonk et al. 2016; Chap. 13). 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

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foreseeing human trajectories of resource use and change. Predictions of the impacts of climate change are thus uncertain even over large (ocean basin) scales. Even satellite-based observations, while improving both in spatial and temporal resolution and in accuracy of prediction, only measure the heat stress to which corals are exposed, not the response of the corals (Heron et al. 2016). 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 microbial symbionts, interactions with pathogens, acclimatisation, and adaptation processes (Chap. 9). Coral mortality and reef recovery depend on numerous local factors, human use, and conservation status. It follows then that the degree of destruction and the permanence of the impacts are uncertain over 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, and in any case each bleaching event is a unique case with its own suite of causal factors. 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 this chapter, we investigate the spatial and temporal patterns of coral bleaching that can be detected in the global database of bleaching records published by Donner et al. (2017) and supplemented by additional records from the recent literature. 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 and, if so, where?

3.1.1 Early Bleaching Records (Pre-1982)

There is a total of 26 records of coral bleaching before the first well-documented global-scale coral bleaching event of 1982–1983. 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 (1966) 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.

Coffroth et al. (1990), Williams and Bunkley-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) and Coffroth et al. (1990), that widespread bleaching and mortality were recognised as a major phenomenon that could impact coral reef 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 Centre 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

Table 3.1 Coral bleaching categories used in ReefBase and Donner et al. (2017) and adopted here

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	1–10% of coral cover bleached	If no estimate of % of bleached corals or coral cover is provided, then terms such as "light", "mild", "scattered", and "occasional" are used to identify this category
2	Moderate bleaching	11–50% of coral cover bleached	If no estimate of % of bleached corals or coral cover is provided, then terms such as "significant", "common", "frequent", and "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", and "severe" are used to identify this category

datasets were combined and updated into a single database within ReefBase. More recently, Donner et al. (2017) have comprehensively revised the ReefBase bleaching database, nearly doubling the number of observations and including records up until 2010. This new database is available online and, with some revisions, is used as the basis for the present analysis.[1]

Many 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 growing 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 current 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.

For the global analysis conducted here, a total of 9005 records in the bleaching database were included, up to 2010. 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 (<3%) reports of mild bleaching were recorded in the database prior to 1997.

[1]simondonner.com/bleachingdatabase/

While the Donner et al. (2017) bleaching database contains the most comprehensive archive of coral bleaching records and all records are referenced either to a publication or a formal source, analysis of these records is hampered by the presence of multiple records at a single location. Donner et al. (2017) addressed this issue by grouping all records into 0.04° grid cells. For our analysis at a global scale, we chose a 1° grid scale to concentrate the bleaching phenomena at a subregional scale and to minimise the distorting influence of highly concentrated monitoring at some locations, especially the Great Barrier Reef (GBR), Australia. A further issue is that the number of reports received can vary both as a function of the severity and extent of bleaching and 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 increased over the past two decades as field-based coral studies have increased, media attention on the destruction of coral reefs from bleaching and climate change has grown, and easier systems for online reporting have been provided. 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 and the relationship between bleaching and climate variability and change at regional and global scales.

For our detection of bleaching at a regional scale through time, 1098 records were added to the Donner et al. (2017) database from the following sources: (1) Reef Check,[2] new ReefBase data,[3] and additional records obtained from the literature. These records (from 2011 to 2016) are not a comprehensive list for all locations, but the data were sufficiently detailed to allow a more comprehensive determination of the presence/absence of bleaching in each of seven regions[4] up to 2016:

1. Caribbean
2. Eastern Pacific
3. Central and western Pacific
4. Southeast Asia
5. Eastern Indian Ocean
6. Gulf Region
7. Central and Western Indian Ocean

[2]Online data from data.reefcheck.us

[3]www.reefbase.org

[4]These correspond to the regions in Burke et al. (2011) but divide the Pacific into east (east of longitude 120 °E) and central west (including eastern Australia) and the Indian Ocean into east (east of the Andaman's & Christmas I. including Western Australia) and west. The Australian region is not used.

Since this extended dataset (up to 2016) included observations based only on a named location rather than geographic coordinates, the records were grouped by named location rather than 1° grid cell.

3.2 Global Patterns of Coral Bleaching

3.2.1 Temporal Patterns

3.2.1.1 Location Records

This analysis was restricted to the period 1979–2010 due to the lack of comprehensive quantitative records for later years. Two very clear patterns emerge when examining all levels of bleaching severity (Fig. 3.1). First, there is a clear increase in the number of grid cells for which bleaching has been reported from 1998 to 2010 compared with prior years. Second, several clear peaks show the episodic nature of bleaching through time.

The trend of increasing bleaching occurrence is driven to some extent by mild bleaching records, but all years since 1991 have reports of bleaching in all severity categories. From 1998 there has been a minimum of 36 grids with bleaching (median 64), while prior to 1998 the minimum is 2 (median 12). While this increase in bleaching could be due to an increase in chronic stress to corals or an increase in small outbreaks at different locations, it is also possible that the increased awareness of coral bleaching is due to increased reporting of small amounts of bleaching that largely went unreported before then. Also apparent (Fig. 3.1) is the increase in the number of reports of zero bleaching since 1998. This has been driven by a significant increase in the number of formal monitoring programmes, such as Atlantic and Gulf Rapid Reef Assessment (AGRRA) and Reef Check, and systematic bleaching surveys that formally report the absence as well as the presence of bleaching.

Peaks of varying magnitude can be clearly identified (Fig. 3.1): 1998 is by far the dominant feature, with 2002, and 2005 also clearly distinguishable, but there is some suggestion of peaks in 1983, 1987, and 2010. In 1998 and 2002, a very large number of sites were surveyed on the GBR, using aerial survey techniques, while in 2005 additional survey effort to document the Caribbean bleaching event also occurred, and this has contributed to the disproportionately large peaks for these years. If the GBR and Caribbean records are eliminated from the graph, then the 2002 and 2005 peaks nearly disappear (Fig. 3.1b). The early peaks in 1983 and 1987 are less distinct, and 2010 remains as a fairly discrete peak. In summary, the data on frequency of bleaching reports per 1° grid cell indicate only major peaks (1998 and 2010). While the above analysis was restricted to the period 1979–2010, in the next section, we extend the analysis period up to 2016 by considering only the presence or absence at the regional level rather than actual counts of bleaching reports.

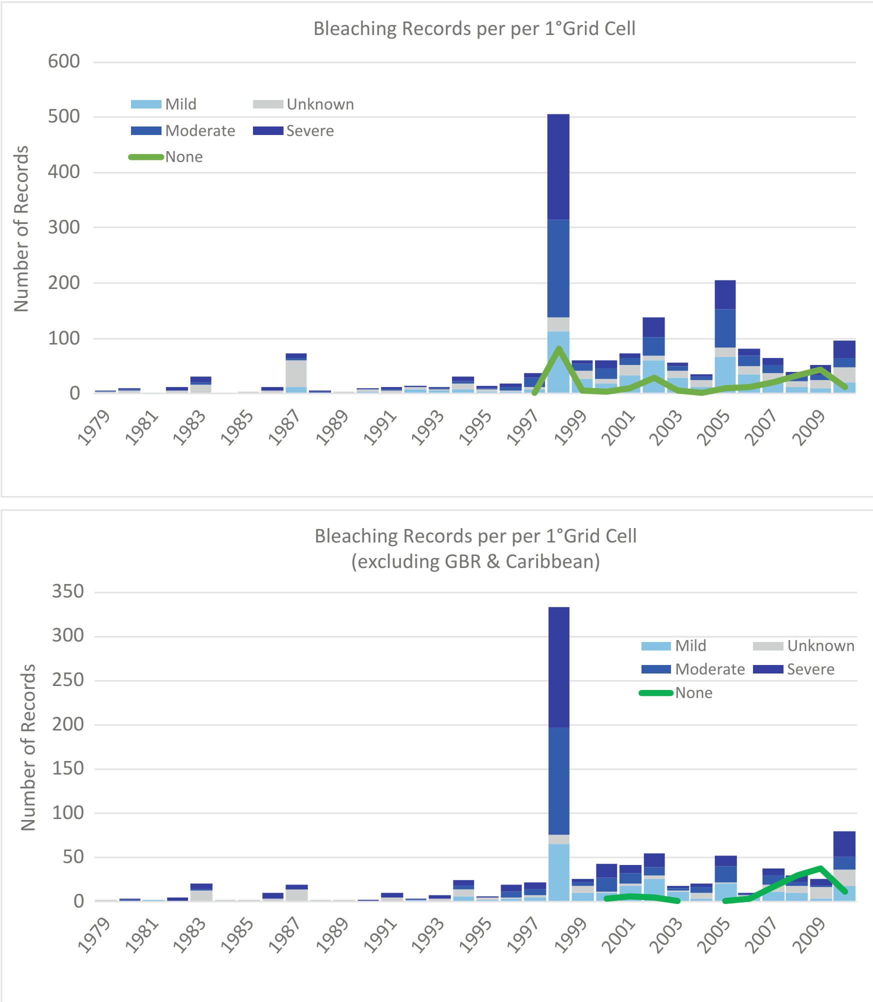

Fig. 3.1 (**a**) Yearly coral bleaching records by 1° grid cell. (**b**) The same graph with records from the GBR and Caribbean removed

3.2.1.2 Identification of Global Bleaching Events

The detection of peaks in the frequency of bleaching over time described above does not necessarily demonstrate global extent. One way of dealing with this problem is to further group records into geographic regions and test for bleaching presence in each region. Recent publications from the US National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch (Eakin et al. 2016, 2017; Heron et al. 2016) suggested that there had been two global bleaching events (prior to the 2014–2017 event) based on the occurrence of widespread bleaching in all three major oceans

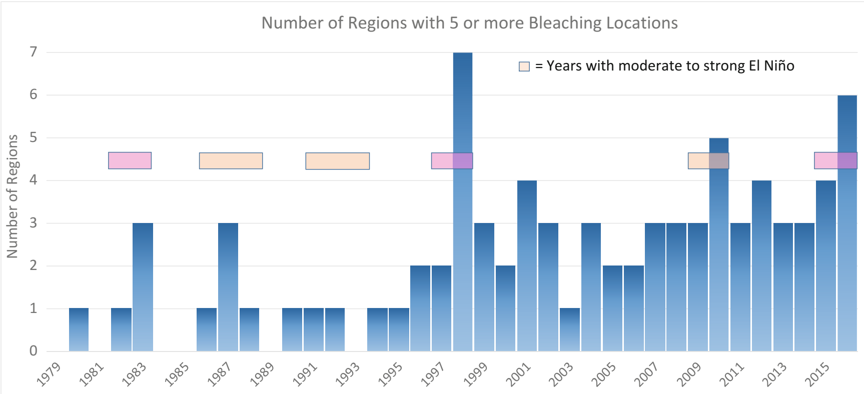

Fig. 3.2 Number of regions reporting bleaching at a moderate to severe level in at least five locations per region. Coloured horizontal bars indicate years with moderate (orange) and major (pink) El Niño events

(Atlantic, Pacific, Indian) in 1998 and 2010. This criterion is further enhanced here by examining bleaching at a more detailed geographic scale across seven regions and specifying that a region must have at least five locations with moderate or severe bleaching levels before bleaching is considered to be "present" and contribute to a global event over the period 1979–2016 (Fig. 3.2).

The two dominant peaks over the period 1979–2016 (Fig. 3.2) correspond to the two major El Niño events in 1997–1998 and 2015–2016 affecting all or all but one of the regions. These two events have also been associated with major, widespread coral mortality (Wilkinson 1998; Hughes et al. 2017). A smaller peak (five of seven regions affected) in 2010 is also clearly distinguishable. Unfortunately, a decline in global coral reef monitoring and reporting programmes in 2009–2010 may have contributed to the lower level of reports during 2010. Interestingly, 1983 and 1987, while exhibiting bleaching in only three regions, still stand out compared to adjacent years with much lower bleaching occurrence. It is plausible that lack of reporting effort masked more significant bleaching in 1983 and 1987. While only three regions had five or more bleaching events in these years, five regions reported bleaching in two or more locations in 1983 and 1987, suggesting that these years could also be considered to have been global events of at least moderate severity.

A clear feature is the increase in the global extent of bleaching from 1997 onwards (Fig. 3.2). During these two recent decades, only 1 year showed bleaching restricted to just 1 region, while 16 years (80%) had bleaching in at least 3 regions, and in 13 of these, some bleaching occurred in all 3 ocean basins. This may indicate the development of chronic albeit scattered bleaching of the world's reefs since 2007.

Overall, the evidence from the analysis of bleaching frequency at the 1° grid scale and regional presence/absence at the global scale suggest that two major and one moderate global bleaching events have occurred over the last two decades. Prior to that, low reporting effort may have masked major global events, but the relative frequencies of bleaching at grid and regional levels suggest that there may have been two widespread bleaching events during the two decades leading up to 1997. There is good evidence that major regional bleaching events occurred in the GBR and the Caribbean in 2002 and 2005, respectively, and this is backed up by separate detailed studies (Berkelmans et al. 2004; Eakin et al. 2010).

3.2.2 Spatial Patterns in Bleaching Reports

Temporal analysis at the grid and regional level indicates that there were three significant bleaching events between 1997 and 2016 and possibly two others prior to that. Detailed and comprehensive spatial records for the 2014–2017 event are still being assembled (Eakin et al. 2017), but the prior events are mapped in Fig. 3.3. The 1998 map clearly shows the high frequency of moderate to severe bleaching in most regions[5] and this year stands out as the most severe and extensive event up to 2010. The 2010 event also shows multiple occurrences of major bleaching in most regions, although there is an almost complete lack of bleaching on the GBR. In 1987 bleaching was mostly reported from the Caribbean and the GBR but still included some records in other regions and all oceans. In 1982–1983 multiple bleaching records predominate in the Caribbean, the Eastern Pacific, and the GBR (in 1982), but a few records (<5) occur in the Indian Ocean and Southeast Asia.

3.2.3 Trends in Bleaching Severity

There are several ways of addressing the question of whether bleaching severity is increasing over time. The first would be to examine only significant bleaching events to determine if the proportion of severe bleaching records increases in more recent events. However, the data for the 2014–2017 bleaching event are still not fully compiled, and earlier bleaching events (prior to 1998) were not well documented, making this type of analysis unfeasible. Another approach is to examine the frequency of severe bleaching across all years since 1979 (with the exception of 2014–2017) and look for increases in the frequency of severe records and a corresponding decrease in mild records (Fig. 3.4). While both severe and mild bleaching show a small positive correlation with year and frequency ($r = 0.32$ and 0.26, respectively), neither of these is significant ($p > 0.05$). These two weak positive trends may be explained by the fact that the proportion of records with unknown severity has significantly decreased ($r = 0.57$, $p < 0.01$) during this period.

[5]While the Andaman and Nicobar Islands appear to be severely affected, subsequent reports of impacts in the region by Rajasuriya et al. (2004) suggest that these two areas escaped major mortality and that the reports of bleaching during the event may have been an overestimate.

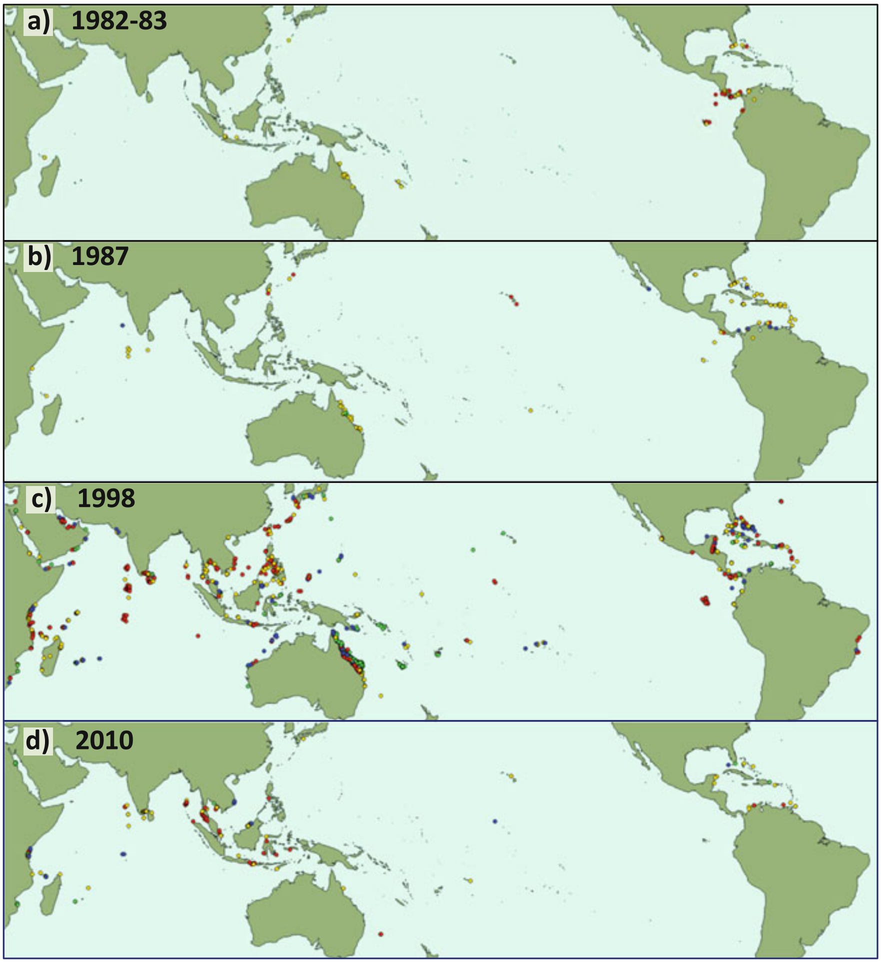

Fig. 3.3 Distribution and intensity of bleaching from records in the Donner et al. (2017) database for the global bleaching years: (**a**) 1982–1983, (**b**) 1987, (**c**) 1998, and (**d**) 2010. *Red dots* severe bleaching, *yellow dots* moderate bleaching, *blue dots* mild bleaching, *green dots* no bleaching

It can be concluded that there is little, if any, evidence that bleaching is becoming more severe over time, at least up until 2010. The recent bleaching in 2014–2017 is widely referred to as the worst ever, and further analysis of this event may change our conclusions. Finally, the severity of a bleaching event might also be determined by its ecological impact. Unfortunately, the database does not contain enough information on ecological impacts, such as mortality, to allow this analysis. In general, given the low number of global bleaching events so far, analysis of trends in their severity is not realistic from bleaching reports alone.

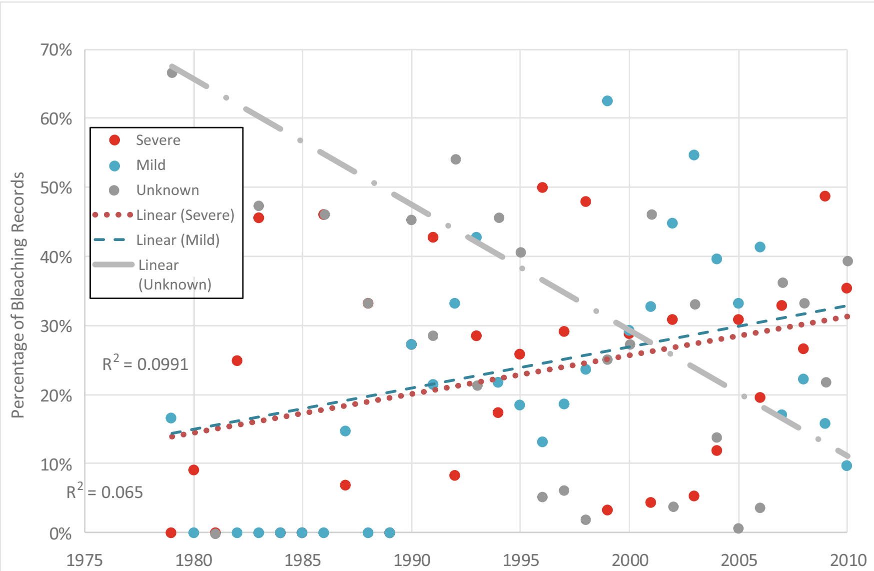

Fig. 3.4 Proportion of bleaching records classified as mild (blue circles), severe (red circles), and unknown severity (grey circles). Linear trends are also shown

3.3 Great Barrier Reef

3.3.1 *Time Series*

The GBR is the largest contiguous reef system in the world, and much of it has been intensively and continuously monitored for over 30 years. As such it represents a useful case study for a more detailed analysis of spatial and temporal patterns of bleaching than is possible at a global scale. Analysis of GBR records is based on four data sources: Donner et al. (2017), GBRMPA (2017), Reef Check (2017), and COECRS (2017a, b). Because some data did not contain specific coordinates, the data were grouped by named location, and an additional bleaching category of moderate/severe was included to enable the summaries of aerial surveys in 2016 to be included (COECRS 2017a,b). Over the past 25 years, there were three major peaks in bleaching on the GBR, corresponding to the bleaching events of 1998, 2002, and 2016 (Fig. 3.5). These peaks are disproportionately high compared to other years due to the intensive surveys conducted by Berkelmans and Oliver (1999), Berkelmans et al. (2004), and COECRS (2017a, b; Hughes et al. 2017). Although no quantitative data are available at the time of writing, severe bleaching also occurred in 2017 (Fig. 3.7). While the number of records is very low in the early years, there appear to be periods when significant bleaching was observed as early as 1980. Anecdotal reports suggest that there may also have been a bleaching event sometime

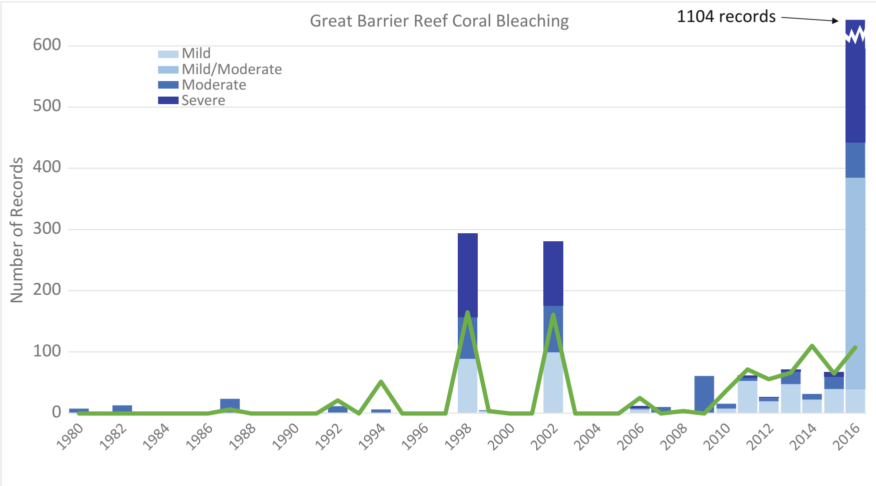

Fig. 3.5 Number of records of coral bleaching on the Great Barrier Reef

in the 1970s, but the year, extent, and intensity are unknown (Oliver 1985).[6] A further feature is that small bleaching events of moderate to severe intensity occur almost every year since 2006 (Fig. 3.5). This parallels a similar pattern already noted in the global time series (starting from the mid-1990s; see Fig. 3.1).

3.3.2 *Spatial Patterns*

The spatial distribution of bleaching at named sites on the GBR is shown for years of significant bleaching in Figs. 3.6 and 3.7. Overall there is a pattern of more severe bleaching in inner shelf regions, although in the most severe events of 2016–2017 bleaching extended across the entire shelf in some areas. Bleaching was recorded across more than two thirds of the length of the GBR in all bleaching years, but for years when comprehensive aerial surveys were conducted (1998, 2002, 2016, 2017), different latitudinal regions were affected in each year. The northern GBR has only shown severe bleaching during the 2016 event, and the far southern offshore reefs have only rarely recorded bleaching, and this has never been widespread. The specific spatial patterns for each of these years have been demonstrated to be highly correlated to elevated sea surface temperatures (SST, Berkelmans et al. 2004; Hughes et al. 2017).

[6]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.

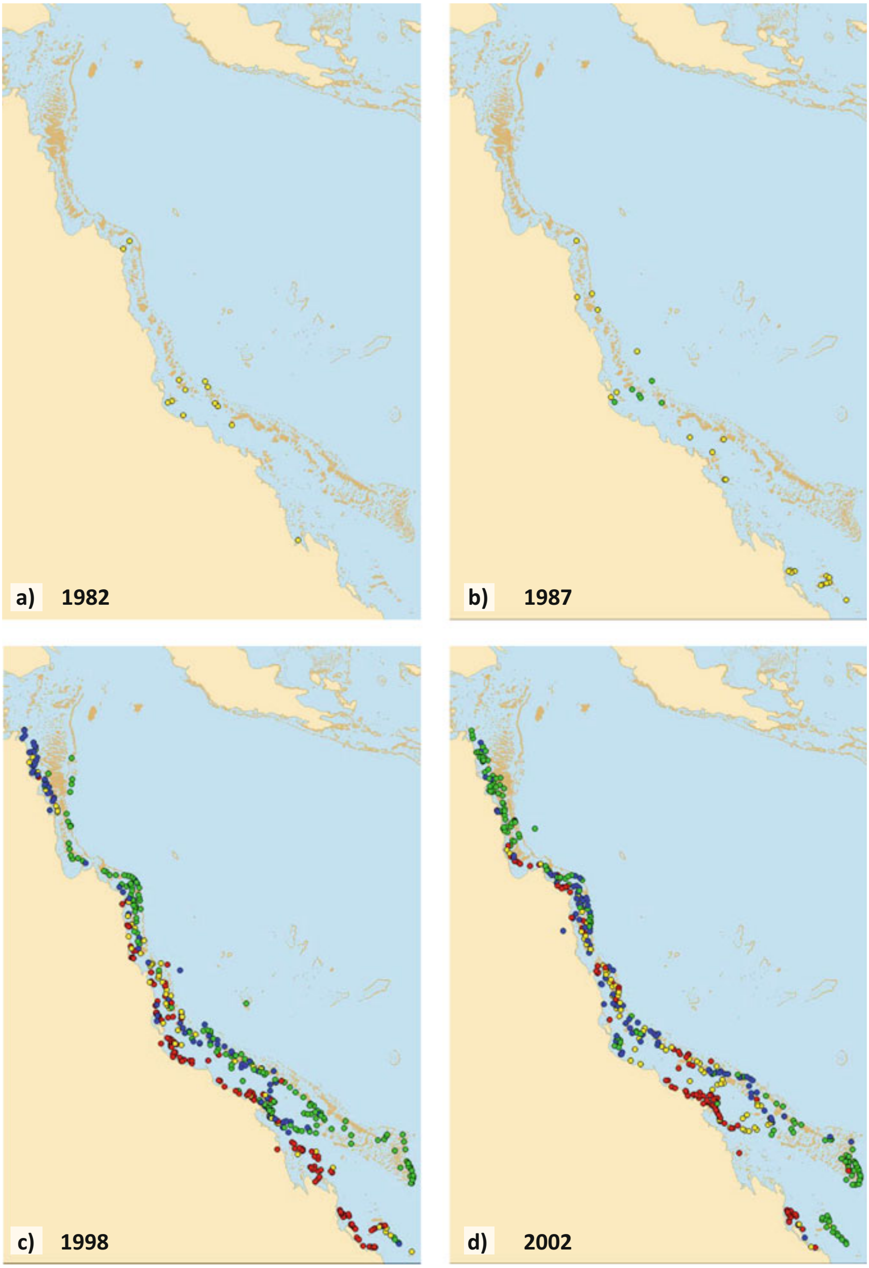

Fig. 3.6 Great Barrier Reef bleaching records. The maps for 1998 and 2002 include aerial survey data. Colours as in Fig. 3.4

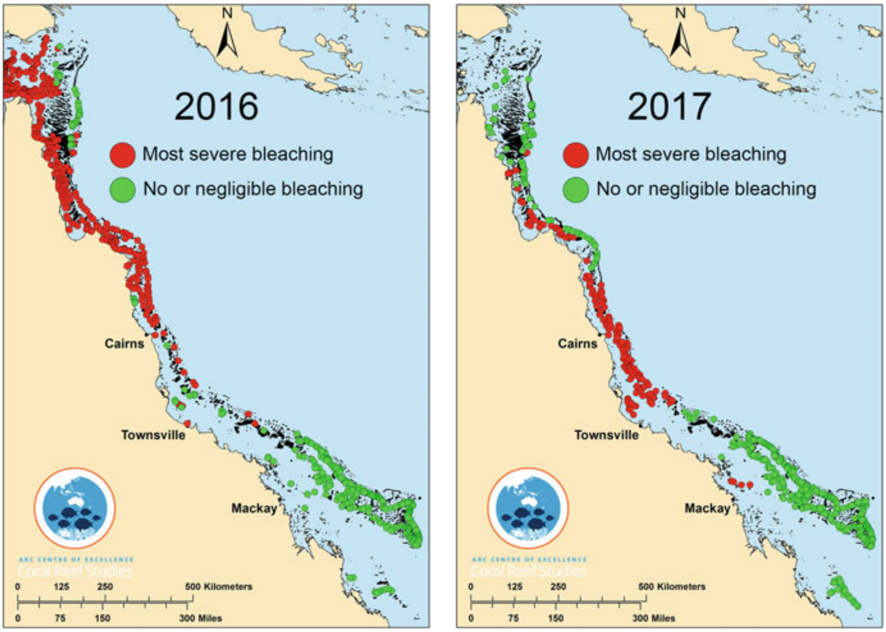

Fig. 3.7 Great Barrier Reef bleaching records for 2016 and 2017 (source: COECRS 2017b). Not all data are shown, only reefs at either end of the bleaching spectrum: red circles indicate reefs undergoing most severe bleaching (60% or more of visible corals bleaching), and green circles indicate reefs with no or only mild or no bleaching (10% or less of corals bleaching)

3.4 Relationships Between Global Bleaching and El Niño Events

It is clear that the link between moderate to severe bleaching and powerful El Niño events is fairly strong at a global scale (Fig. 3.8). All five global bleaching events identified above (1983, 1987, 1998, 2010, 2016) occurred during or just after moderate or major El Niño years. Based on a classification of El Niño years by Null (2017), the two most severe bleaching events (1998 and 2016) occurred during the second year (year +1) of strong El Niño events (1997–1998, 2015–2016). The 1982–1983 El Niño also resulted in widespread, and perhaps global, bleaching as summarised in Coffroth et al. (1990), although records are too sparse to firmly classify this as a major event. The 2010 global bleaching and less well-defined bleaching event of 1987 both occurred during or just after moderate El Niños. Years in which regional bleaching occurred (2002 in the GBR and 2005 in the Caribbean) also coincided with moderate or weak El Niños. Additionally, some regions, particularly the western Pacific, and also southern Western Australia have bleached during the first year of La Niña events, although the quick transition from the 1997–1998 El Niño to the 1998–1999 La Niña can make such distinctions challenging.

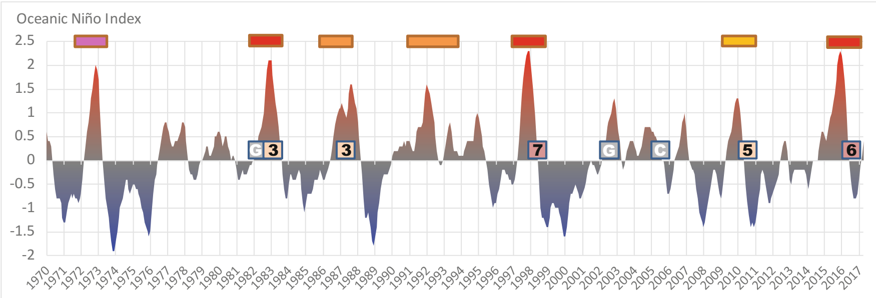

Fig. 3.8 Global bleaching events and the Oceanic Niño Index (ONI, NOAA 2017). The *shaded bars* at the top indicate moderate (orange), strong (pink), and very strong (red) El Niño events [categories from Null (2017)]. Solid boxes indicated years of near-global or global bleaching with numbers of regions affected or areas of regional bleaching in the Caribbean (C) or Great Barrier Reef (G)

3.5 Discussion

The spatial distribution and frequency of bleaching over time are both continuous variables which allow bleaching events to vary from singular minor events to ones that are spread densely across the globe over extended periods. This makes the identification of global bleaching events a somewhat subjective issue, even though there is value, from both an ecological and environmental management perspective, in distinguishing discrete severe events that have had major impacts on reef systems.

The identification of global bleaching events is predicated on a clear definition of the term, but this has not been explicitly addressed in the literature. An implicit definition in many treatments of global bleaching is that it occurs with moderate to high impact in many countries throughout the world, but this leaves questions regarding the required frequency, severity, extent, and uniformity unanswered. A more specific implicit definition, which refers to widespread bleaching in all three ocean basins, was used by NOAA's Coral Reef Watch (Eakin et al. 2016, 2017; Heron et al. 2016). They identified two global events in 1998 and 2010. Eakin et al. (2016) suggested an earlier global event may have occurred in 1983 based on work by Coffroth et al. (1990). Here we present bleaching frequency across 1° grid cells and regional presence/absence data for seven regions and visually identified peaks in the frequency distribution as a first approximation of discrete major bleaching years. This analysis suggests that over the last two decades, during which reporting efforts at a global scale have been high, 1998 and 2016 can be classified as severe global bleaching events and that 2010 is more usefully classified as a moderate global event. Prior to 1998 reporting efforts were lower, but there are discrete peaks suggesting that 1983 and 1987 experienced global-scale bleaching of at least moderate severity (Table 3.2).

Heron et al. (2016) have carried out a similar type of analysis using satellite SST data to plot the incidence of bleaching-level thermal stress (≥4 °C-weeks) over time

Table 3.2 Classification of global bleaching events since 1979

Year	Global event	Comments
2014–2017	Severe	• Data still being compiled • Very high frequency of bleaching reports at 1° grid and regional scale • Bleaching reports extend from 2014 to 2017 with peak in 2016 • Major mortality impacts already reported in some areas
2010	Moderate	• Lower frequency of bleaching at 1° grid and regional scale compared to 2016 and 1998 • Mortality impacts also reported
1998	Severe	• Highest frequency of bleaching at 1° grid and regional scale • Extensive well-documented mortality
1987	Possible moderate?	• Discrete peak in bleaching frequency at 1° grid and regional scale • Absolute frequencies lower than later years that have not been classified as bleaching, but this could be due to lower reporting effort • Heat stress reached critical levels in a small percentage of global reefs
1983	Possible moderate?	• Discrete peak in bleaching frequency at 1° grid and regional scale • Absolute frequencies lower than other years not classified as bleaching, but this could be due to lower reporting effort • Bleaching on GBR occurred in 1982—well-documented mortality • Heat stress may have reached critical levels in a small percentage of global reefs

for different regions during 1985–2012. At the global scale, their analysis shows peaks in bleaching-level stress, corresponding to the 1998 and 2010 events described in Table 3.2. There is also an indistinct peak around 1987–1988 which approximately matches the possible moderate event for 1987 (Table 3.2). Newer analyses by NOAA (Eakin, pers. obs.) find that the extent of heat stress in 1983 and 1987 may have been less than half that seen in 2010. It is possible that other stressors such as light or water motion played a role in bleaching during these periods, but given the doubt surrounding the adequacy of the reporting effort on coral bleaching, and the importance of thermal stress in the development of mass bleaching events, the lack of a major bleaching-level stress peak for 1987 in Heron et al. (2016), comparable to 2010 or 1998, suggests that if there was a global bleaching event in 1987, it was not a major one. The same may also be true for 1983.

Donner et al. (2017) have recently conducted a comprehensive analysis of bleaching records based on a major revision of the ReefBase database. Their analysis of bleaching records over time differs from ours in grouping records to a much finer 0.4° grid and by excluding records with no bleaching or unknown bleaching severity. In general, our analysis agrees with Donner et al. (2017); however in our analysis the peaks for years 2000, 2007, and 2009 are much lower, probably due to less extensive spatial coverage of bleaching in those years.

The proximate cause of virtually all mass bleaching events is widely acknowledged to be thermal stress, with light, water motion, and ocean circulation acting as important modifiers (Brown 1997; Wilkinson 1998; Glynn 1993; Hoegh-Guldberg 1999; Mumby et al. 2001; Hughes et al. 2003, 2017). These reviews and others

(Glynn 1984, 2000, 2002; Wellington and Glynn 2007) have stressed the role of El Niño as one of the higher-level causes, especially for major events in 1983, 1998, and now 2016. The comparison of major El Niño events with the five global and possible global events identified here (Figs. 3.2 and 3.8) indicates that each one was associated with one of the eight most severe El Niño events in the last half century (NOAA 2017). Even the two significant but more regionally restricted bleaching events in the GBR and the Caribbean (2002 and 2005, respectively) were associated with weak or moderate El Niño events. The only exception to the close relationship between moderate to strong El Niño years and global bleaching is the extended moderate El Niño of 1991–1993, during which no major bleaching occurred. 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. The role of the Indian Ocean Dipole and the Madden-Julian Oscillation as modulators of ocean basin-scale heat stress has also been noted by Heron et al. (2016) and Zhang et al. (2017).

On the GBR, the records show a less direct correlation between El Niño strength (positive ONI, NOAA 2017) and bleaching events, although the proximity of major bleaching to these deviations is very suggestive. The ONI may, therefore, be a poor direct indicator of the impacts of ENSO events at a local or subregional scale even though it is possible that many of the GBR bleaching events are indirectly caused by ENSO-related climate anomalies. The reversals of normal ocean current directions, particularly in the equatorial Pacific during ENSO events, have 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 (Chap. 4). In contrast, the western Pacific is generally warmer during strong La Niña years, increasing the 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.

At the global scale, identification of detailed spatial bleaching patterns is hampered by the lack of detailed records for the most recent events, which have not yet been published, and probable under-reporting of events prior to 1998. In general, records are more likely to be complete in areas where there are concentrations of research activity and programmes of regular monitoring, especially in the GBR and parts of the Caribbean. In this respect 2010 stands out. Despite the presence of bleaching in five regions, very little bleaching occurred in the central and western Pacific and almost none on the GBR (Fig. 3.3). In the analysis of bleaching-level thermal stress carried out by Heron et al. (2016), the Pacific (excluding Australia) is the only region that does not show a peak for 2010. However, the Australian region (mostly comprising the GBR) has a peak in thermal stress for 2010 that is equal to that of the major bleaching year of 1998. The GBR may have been subject to localised influences independent of SST that prevented significant bleaching in 2010, although the lack of major tropical cyclones at this time rules out cyclonic cooling (Carrigan and Puotinen 2014) as a mitigating factor. Outside the GBR and much further south, however, Lord Howe Island reported severe bleaching in 2010 (Harrison et al. 2011).

Spatial bleaching patterns within the GBR (Figs. 3.6 and 3.7) show distinctive longitudinal and cross-shelf patterns that vary between years. In general, more frequent and severe bleaching is seen on inshore reefs and on reefs in the central GBR. The primary driver for these patterns is SST (Berkemans et al. 2004, Hughes et al. 2017). A number of factors, singly or in combination, may contribute to the observed effect. First, inshore shallow waters have a smaller volume and hence a reduced thermal capacity 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 by up to 1.5 °C, exacerbating the bleaching risk for inshore coral communities (Fabricius 2006). More recently Wiedenmann et al. (2013), Wooldridge (2016), and Pogoreutz et al. (2017) have suggested that increased nutrients can lead to an imbalance between the metabolic activities and zooxanthellae and the coral host, leading to bleaching. 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). However, at times of severe heat stress, such management may be insufficient to protect corals (Hughes et al. 2017).

Apart from the strong inshore-offshore effect, bleaching in the most recent severe bleaching event on the GBR was patchy over scales of tens of kilometres, reflecting patterns in local weather and oceanography. Specific oceanographic features have also been shown to explain some of the detailed patterns of bleaching. The unusual bleaching of northern GBR reefs in 2016, for instance, has been explained by Wolanski et al. (2017) by a combination of a shutdown in the North Queensland Coastal Current, sea level-mediated transport of warm water from the Gulf of Carpentaria into the Torres Strait, and local solar heating. The lower levels of bleaching in the central and southern GBR compared to previous sever events can also be explained in terms of local weather events: ex-Tropical Cyclone Winston brought increased cloudiness and cooler temperatures to the region (Hughes et al. 2017). These local to subregional processes make prediction and scenario modelling particularly challenging at local scales and highlight 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 some affected reefs longer to recover. Unfortunately, climate change may disrupt some circulation patterns eliminating past "protection" in future years.

Our results clearly show an increase in the number of bleaching reports between 1983 and 2017, with a major increase in the past decade after the 1998 event. In addition to three major global events, there has been a low level of bleaching in all years and in multiple regions (Figs. 3.1 and 3.2). While this may be partly due to an increase in the level of reporting, the level of scientific research and monitoring, together with the dedicated efforts of key institutions to record all bleaching events since 1983, makes it likely that this is a real trend. This confirms the analyses of Heron et al. (2016) and Donner et al. (2017) who found, respectively, a threefold increase in the frequency of bleaching-level stress and an eightfold increase in the number of reefs with a greater than 50% probability of bleaching. When we look only at major peaks in bleaching records, then at a global level we can clearly differentiate three to five global events. This is too small a number to quantitatively determine whether the frequency of severe events is increasing. However, the two lesser events preceded 1990, and the more severe events occurred in 1998, 2010, and 2014–2017. While there is insufficient evidence in the global database of bleaching records to statistically support or refute the hypothesis that major bleaching events are increasing in frequency, there is growing evidence that low-level background bleaching has increased to the point where most regions and ocean basins are reporting some level of bleaching every year. This is most likely linked to the rise in ocean temperatures.

A separate, but related, issue is whether the intensity of bleaching is increasing. As discussed above, our results (Fig. 3.4) do not support this notion based on the relative frequency of the severe bleaching category in the database. This finding contrasts with data that show clear increases in both the frequency and intensity of bleaching-level thermal stress (Heron et al. 2016; Chap. 4). It is possible that a real increase in severity is not discernable from an analysis of bleaching categories but would require more information on subsequent mortality impacts. If the lack of a trend is real, one potential reason is that the corals that survive severe events, such as 1998, are more capable of surviving subsequent thermal stress. Studies on this hypothesis have reported mixed results so far (Carilli et al. 2012; Guest et al. 2012; Pratchett et al. 2013; Hughes et al. 2017). A corollary is that severe bleaching events reduce diversity, removing the more thermally sensitive corals.

The revised global database of Donner et al. (2017) represents an important resource for documenting and understanding the impacts of coral bleaching. Its utility could be greatly increased if monitoring and reporting effort could be standardised. 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 bleaching reporting are standardisation in the measurement of bleaching intensity and standardisation 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 Reef Check and the currently semi-operative Global Coral Reef Monitoring Network, together with major regional monitoring programmes such as the AGRRA and National Coral Reef Monitoring Program (NCRMP) and the programmes in Australia by the Australian Institute of Marine Science (AIMS) and the Great Barrier Reef Marine Park Authority (GBRMPA), 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 three recent occasions and possibly on two other occasions prior to 1998. Also, we have demonstrated that each of these events occurred in close temporal proximity to a strong El Niño event. While no clear increase in the frequency or intensity of major global bleaching events is so far discernable using bleaching records alone, the observed and predicted increase in ocean temperatures to which El Niños add extra warming throughout much of the tropical oceans (Chap. 4) has been predicted to dramatically increase the frequency and severity of bleaching events. In addition, the frequency and extent of annual bleaching records have clearly increased over the period 1979–2016 to the point where bleaching is now reported at various sites around the world every year. If trends in global ocean warming continue, reefs may be faced with a combination of both chronic bleaching and more frequent and highly destructive events.

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