Chapter 4
Climate Variability and Change: Monitoring Data and Evidence for Increased Coral Bleaching Stress

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4.1 Introduction

Coral reefs live within a fairly narrow envelope of environmental conditions constrained by water temperatures, light, salinity, nutrients, bathymetry and the aragonite saturation state of seawater (Buddemeier and Kinzie 1976; Kleypas et al. 1999; Hoegh-Guldberg 2005). Their natural environment, at the interface of land, sea and the atmosphere, can vary quickly and potentially be stressful. Reef organisms have, over millions of years, evolved strategies to cope with occasional environmental disturbances (such as tropical cyclones). Given sufficient time between disturbances, damage or destruction would normally be followed by recovery and regrowth (Buddemeier et al. 2004). As documented in numerous scientific studies and reports, the world's coral reefs are "in crisis" as a result of direct local- and regional-scale human impacts on their environment. These impacts include overfishing, destructive fishing practices, changed land-use that increases sediment, nutrient and pollutant flows into reef waters, and poorly designed coastal development. This ecosystem degradation is largely occurring in the many tropical countries whose increasing populations are heavily dependent on coral reefs yet have insufficient resources to develop appropriate, sustainable management practices (Wilkinson 2004). Coral reefs are now confronted with additional global-scale stresses due to the introduction of enhanced greenhouse gases that are rapidly changing coral reefs' environmental envelope through both ocean acidification and increased thermal stress due to climate change (Hoegh-Guldberg et al. 2007).

There are several aspects of global climate change that are already impacting the environments of coral reef ecosystems (Chap. 1). The most immediate is rising sea surface temperature (SST) that is correlated with an increased frequency of mass coral bleaching reports since the early 1980s (Glynn 1993; Chap. 3). Pioneering studies in the 1970s demonstrated just how close (within 1–2°C) reef-building corals were living to their upper thermal tolerance limits before bleaching occurred (Coles et al. 1976; Jokiel and Coles 1977; Glynn and D'Croz 1990). The threshold for bleaching becomes critical during the seasonal SST maximum. Maximum SSTs at 1000 reef locations average 29.5°C, but range from 28.2°C to 34.4°C (Kleypas et al. 1999). These studies and others have identified that temperature thresholds at

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which corals bleach vary with the ambient water temperatures on each reef, such that corals have adapted to their local environmental conditions over long timescales (Chap. 7).

The first, most alarming, reports of mass coral bleaching events were not immediately linked with unusually warm global SSTs, although a connection eventually was made with El Niño warming (Glynn 1983, 1984). This was largely due to the lack of reliable, long-term records of SSTs and other environmental variables in the vicinity of coral reefs. Gradually, as more mass bleaching events occurred and observations improved, the link was made with unusually warm SSTs (Brown 1987; Glynn 1990, 1991, 1996). Unfortunately, the reporting of bleaching events is still incomplete in many parts of the world and the ability to tease out causal relationships between bleaching and environmental conditions is confounded by two simultaneous factors: (1) the rising thermal stress and (2) the recent increase in monitoring and reporting (Chap. 3). Nevertheless, the evidence that mass bleaching of coral reefs might be linked to global climate change due to enhanced greenhouse gas emissions (Smith and Buddemeier 1992; Brown 1997), which was considered unconvincing in the early 1990s (Glynn 1993), is now considered incontrovertible (Hughes et al. 2003).

This chapter focuses on the changing physical environment of coral reef ecosystems and especially SSTs that are responsible for most mass coral bleaching events. We use long-term climatic datasets to document SST changes near coral reefs over the past 150 years (future scenarios are considered in Chap. 10). SST conditions conducive to coral bleaching are considered in the context of observed global-scale ocean warming and climatic variability (e.g., El Niño–Southern Oscillation or ENSO). Since the 1980s, satellite-based observations of the oceans have dramatically increased our capability to observe ocean variations globally and provide the basis for identifying bleaching conditions in near-real-time. We describe the application of satellite-based SST and other products to detect and monitor environmental conditions related to coral bleaching events.

4.2 Data for Understanding Thermal Stress and Bleaching Patterns Worldwide

To date, no dataset provides continuous coverage spanning modern satellite and instrumental observations back through multiple decades or centuries. However, good data do exist at various temporal and spatial scales. For this study, two primary datasets are used: (1) century-length reconstructions generated from available instrumental observations of global SST and (2) modern near-real-time satellite observations and reanalyses of these records. Because both of these data are calibrated from similar instrumental datasets from recent years, both are considered to accurately represent large-scale patterns of thermal conditions that influence coral reefs.

4.2.1 Century-Length Global SST Reconstructions from Instrumental and Paleoclimatic Data

Unfortunately, continuous observations of physical parameters have been taken at only a limited number of reef sites and for no more than a couple of decades. Observations from other parts of the global ocean are not much more complete. The need for long records of SSTs has driven the development of new local to global ocean observing systems, satellite observations and algorithms to reconstruct past SSTs from instrumental data that are heterogeneous in space and time. Two such reconstructions efforts have developed at the Hadley Centre of the UK Meteorological Office [Hadley Centre sea Ice and Sea Surface Temperature (HadISST) data] and the National Climatic Data Center of the US National Oceanic and Atmospheric Administration [NOAA: Optimum Interpolation Sea Surface Temperature analysis (OISST) and Extended Reconstructed Sea Surface Temperature (ERSST) data]. Both organizations have developed global, gridded SST fields at a variety of temporal and spatial scales that are available online (Reynolds and Smith 1994; Rayner et al. 1996, 2006; Reynolds et al. 2002; Smith and Reynolds 2003, 2004; HadISST data available at: http://www.hadobs.org/; OISST and ERSST data available at: http://www.cdc.noaa.gov/PublicData/). While the methods used in developing these data sets are similar, users should examine each one to select the methods that best meet the needs of the application.

Paleoclimatic data also extend our understanding of climate patterns into the past (Jones and Mann 2004). Massive coral skeletons contain a rich archive of past climatic and environmental conditions in coral reef environments, which can be extracted, for example, using the ratios of stable isotopes ($\delta^{18}O/^{16}O$) or trace metals (Sr/Ca) in annual growth bands (Gagan et al. 2001; Felis and Patzold 2003). One approach reconstructed temperature fields from coral $\delta^{18}O$ data (Evans et al. 2002), but unfortunately there is no organization that is regularly updating this record with data from more recently collected coral cores. One problem noted by Evans et al. (2002) is the sparse array of available data that increases the error in global reconstructions. The other approach is to use regional composites or sets of records to characterize the patterns seen in particular ocean basins (Bradley et al. 2003; Grottoli and Eakin 2007) or to use nearby records if they exist. Both of these approaches have demonstrated that high-resolution paleoclimatic records can provide useful extensions of instrument-based reconstructions of tropical SSTs, but we now need new, longer paleo-records to significantly improve these historical perspectives on coral reef climates (Lough 2004).

4.2.2 Satellite Observations of SST and Thermal Stress

Polar-orbiting satellites provide near-real-time observations across the globe. A trade-off to their global coverage is relatively low spatial (1 km to tens of kilometers) and temporal (at best, four times each day) resolution. NOAA's Coral Reef

Watch (CRW) uses polar-orbiting satellite data to observe SSTs and other parameters that influence the health of coral reefs. The primary suite of CRW satellite products include near-real-time satellite global 0.5° (approx. 50 km) night-time SSTs and anomalies, coral bleaching HotSpots, and coral bleaching Degree Heating Weeks (DHW), updated twice each week (Fig. 4.1; Liu et al. 2006). These satellite data products are available online in graphical formats and as data files for the period from late-2000 to the present (CRW 2007; http://coralreefwatch.noaa.gov/). Animations of SST, SST anomaly, HotSpot and DHW charts over the most recent two, four and six months are also available. Other products, such as the Tropical Ocean Coral Bleaching Indices (Virtual Stations) webpage, the SST time series for selected reef sites and automated Satellite Bleaching Alert e-mails are especially targeted to provide needed information to coral reef resource managers and scientists. The current suite of near-real-time products were developed based on earlier monthly analyses of satellite and in situ SST data (Montgomery and Strong 1994; Gleeson and Strong 1995; Strong et al. 1997; Goreau et al. 2000).

4.2.2.1 HotSpots

The coral bleaching HotSpot (Fig. 4.1c) is the positive anomaly of temperatures that exceed the maximum monthly mean (MMM) for each 50-km pixel, thus identifying regions that are currently undergoing thermal stress. The SSTs and monthly climatology are derived from the Polar-orbiting Operational Environmental Satellite (POES) Advanced Very High Resolution Radiometer (AVHRR) night-time SSTs. The MMM climatology for each pixel, indicating the expected summer maximum temperature, is based on the period 1985–1993 with 1991–1992 excluded due to volcanic aerosol contamination. NOAA/NESDIS developed the satellite coral bleaching HotSpot product in 1996 based on the “ocean hot spots” concept introduced by Goreau and Hayes (1994) from analyses by Atwood et al. (1992) and experiments by Glynn and D’Croz (1990). HotSpots were produced experimentally over 1997–2002 and became CRW’s first operational product in September 2002.

4.2.2.2 Degree Heating Weeks

While the HotSpot product is extremely useful, it only provides an instantaneous measure of thermal stress. Corals respond to the cumulative thermal stress to which they are exposed. By accumulating the positive anomalies of SST above the maximum monthly mean, NOAA’s DHW index provides a measure of the cumulative thermal stress that corals experience (Fig. 4.1d). The DHW product was produced experimentally starting in 2000 and became operational in September 2003. Following Glynn and D’Croz (1990) and Atwood et al. (1992), the threshold for bleaching was established to be 1°C above the expected summer maximum temperature; and the DHW is calculated by summing all HotSpot values ≥1°C in each pixel over a 12-week period (Liu et al. 2003; Skirving et al. 2006a). In most cases, HotSpot values <1°C do not result in widespread coral bleaching. This high-pass

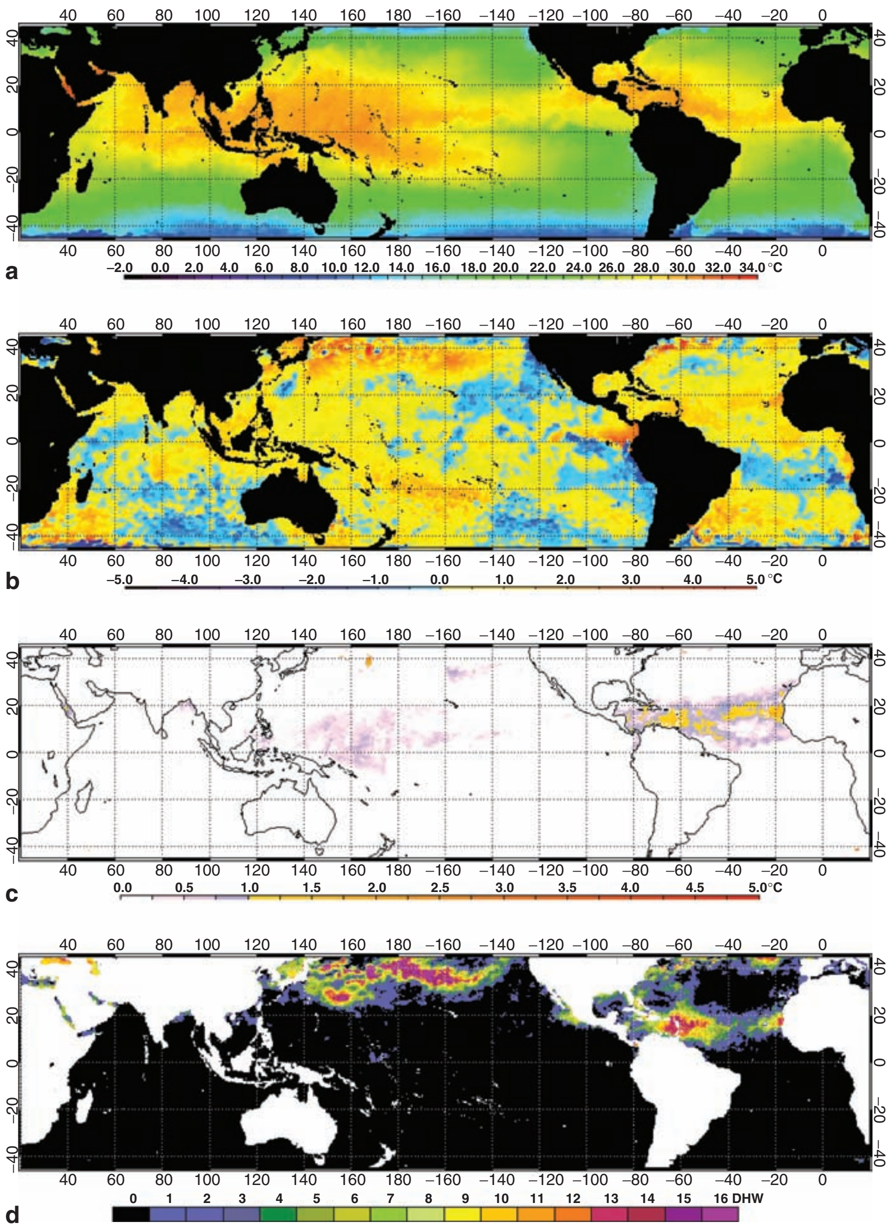


Fig. 4.1 NOAA Coral Reef Watch near-real-time satellite global 50 km night-time product suite for 22 October 2005: **a** sea surface temperatures (SST), **b** SST anomalies, **c** coral bleaching HotSpots and **d** coral bleaching Degree Heating Weeks (DHW)

clipping filter reduces runaway accumulations that can result when SSTs remain very close to the maximum monthly mean for long periods of time, a condition often encountered in equatorial mid-Pacific regions. A value of 2 DHW is equivalent to 2 weeks of HotSpot values of 1°C or 1 week of HotSpot values of 2°C and so forth. NOAA issues a coral bleaching alert via e-mail when values near a reef reach DHW values ≥4°C-weeks (Alert level 1). Significant coral bleaching is expected to occur 1–3 weeks after reefs begin to experience DHW values ≥4°C-weeks. Mass bleaching and the onset of coral mortality are expected after reefs experience DHW values ≥8°C-weeks (Alert level 2).

To date, the DHW index has been a nearly perfect, but conservative, predictor of bleaching around the world. For 23 of the 24 virtual stations monitored, bleaching has been reported in all cases when NOAA has issued a coral-bleaching alert. Recently, non-bleaching reports suggested a likely false alert in Oman (Coles, personal communication), probably resulting from an error in the climatology. There are a limited number of other regions (e.g., Gulf of Panama) where errors in the climatology have been identified. As a conservative predictor, many local-scale bleaching events are not predicted by the DHW index. However, the DHW index reliably provides the large- to basin-scale information needed for coral reef managers and scientists to anticipate mass bleaching.

4.2.2.3 Reprocessed Satellite Observations of SST

In addition to the operational near-real-time satellite observations, retrospective analyses of satellite SST data have been produced and periodically updated. The Pathfinder ver. 5.0 dataset (NOAA 2007; http://www.nodc.noaa.gov/sog/pathfinder4km/) provides daily global SST data at approximately 4 km resolution (Global Area Coverage) for the period 1985–2006. The Pathfinder product cannot run operationally, but it provides new value in that the data are reprocessed with the benefit of hindsight to reduce systematic bias and short-term errors that result from clouds and other atmospheric contamination of the SST signals (Kilpatrick et al. 2001). From the Pathfinder source data, an SST archive was produced at 0.5° (50 km) and half-weekly resolution, mimicking the methods for the near-real-time SST product (see Sect. 4.2.2). Using this dataset and following the methodology for the NOAA Coral Reef Watch product suite, SST anomalies [i.e., the difference between the SST and the climatology (average) value at a location and for that time of year], HotSpots and DHWs were constructed (as described previously). This 22-year record allows us to examine recent global and regional trends in SST anomaly and thermal stress. A new Pathfinder-based climatology has been developed to improve the near-real-time CRW products.

4.2.2.4 Bleaching Weather: A New Doldrums Product

While basin-scale coral bleaching occurs as a result of large-scale climatic phenomena, local weather patterns greatly influence bleaching variability among sites within the basin. Three related factors that influence local bleaching patterns are temperature, light and water-column mixing. One parameter that exerts a common influence to all of these is wind. When wind speeds drop, reduced vertical mixing, evaporative cooling and sensible heat transfer all increase the likelihood of high temperatures and light penetration (Dunne and Brown 2001; Mumby et al. 2001a; Skirving and Guinotte 2001; Obura 2005). Additionally, low winds can increase stratification in the water column, resulting in enhanced photo-degradation of colored dissolved organic material and, thereby, reducing shading (Manzello et al. 2006). CRW has developed an experimental Doldrums product using the NASA SeaWinds scatterometer onboard the QuikSCAT satellite that provides 0.25° (approx. 25 km) resolution wind fields for 90% of the Earth's ocean surface every 24 h (Perry 2001). The current experimental product identifies regions where multi-day average wind speeds have remained below 3 m/s and records the persistence (doldrums-days) of such conditions (Fig. 4.2; CRW 2007; http://coralreefwatch.noaa.gov/satellite/doldrums/). NOAA expects to use this product to augment SST-based algorithms to help detect conditions suitable to coral bleaching.

4.2.2.5 Future Products

To further refine its satellite product suite, CRW is developing products to monitor additional parameters that influence bleaching and coral reef health. Some parameters that further address the needs described in Sect. 4 include ocean surface solar insolation, cloud cover and turbidity. These will directly address parameters that influence the quantity and quality of light that reaches reef corals. Most are

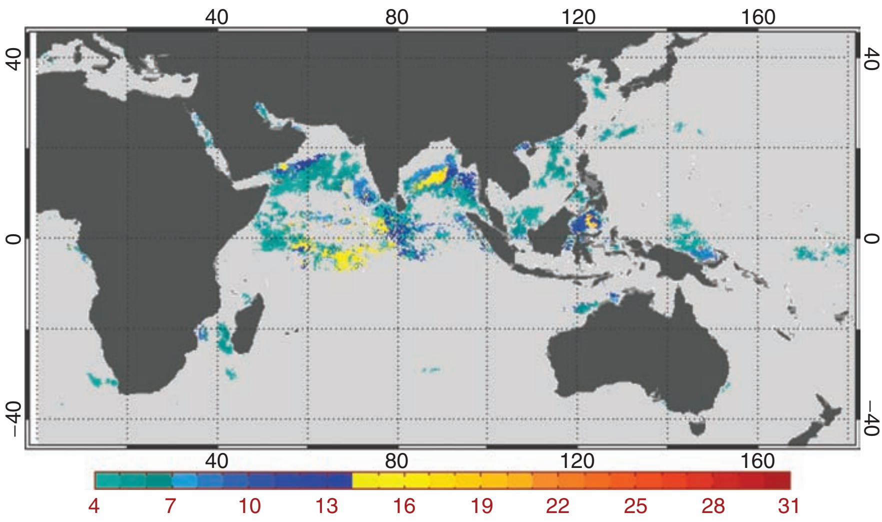


Fig. 4.2 NOAA Coral Reef Watch near-real-time satellite 25 km doldrums product for 24 April 2005 in the Indian Ocean region. The color scale indicates the number of days over which the multi-day mean QuickScat winds remained below 3 m/s

likely to use geostationary satellites rather than the polar-orbiting satellites that CRW uses today. Geostationary satellites provide more frequent sampling and better measures of variability and patterns throughout the day, but with coverage limited to part of one hemisphere. International data sharing agreements will hopefully provide access to data for most coral reef areas.

Also, CRW is working on improving the spatial and temporal resolution of its global data products. However, finer resolution in both space and time comes at a price, including an increased need to gap-fill cloudy regions and the greater influence of chaotic variability in coastal SSTs. Geostationary satellite data or blended geostationary–polar data may aid in this effort. Two such high-resolution efforts are already underway. In 2007, a joint project between the Great Barrier Reef Marine Park Authority (GBRMPA) and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) released a 2-km product suite for Australia's Great Barrier Reef (GBR) that includes SST, positive SST anomaly, heating rate and degree heating day products (Maynard et al. 2008; CSIRO at http://www.cmar.csiro.au/remotesensing/gbrmpa/ReefTemp.htm). The Institute for Marine Remote Sensing at the University of South Florida is developing 1-km SST and degree heating week products for Florida and the Caribbean (Muller-Karger, personal communication). These efforts will help define the requirements and limitations to developing global high-resolution SST products. Additionally, NOAA is researching the application of global climate model-derived SSTs to forecast conditions that are conducive to coral bleaching weeks to seasons in advance. Similar GBR-only forecasting is under development by the Australian Bureau of Meteorology and GBRMPA.

4.3 Tropical SST Trends Since the Nineteenth Century

The SST maxima reached during recent mass coral bleaching events were unprecedented in the available instrumental records at a range of coral reef sites (Hoegh-Guldberg and Salvat 1995; Brown et al. 1996; Winter et al. 1998; Lough 1999, 2000a; Mumby et al. 2001b; Wellington et al. 2001; Eakin 2007; Wilkinson and Souter 2008). A number of correlated indices of local thermal stress and other contributors to bleaching have been identified: absolute SST maximum, SST maximum anomaly, heating rate, number of days above a particular threshold, etc. (Podesta and Glynn 1997; Liu et al 2006; Strong et al. 2006; Maynard et al. 2008).

Here we used global compilations of monthly SSTs averaged over 1° latitude–longitude boxes to assess large-scale variations and trends in the tropical oceans and typical patterns associated with ENSO events, 1870–2005 (HadISST 1.1; Rayner et al. 2003). Such data are extremely useful for providing long-term perspectives on the changing tropical ocean climate in relation to coral bleaching events (Sheppard and Rayner 2002; Barton and Casey 2005; Sheppard and Rioja-Nieto 2005). It should, however, be recognized that these large-scale averages can disguise the considerable small-scale thermal variability on coral reefs (Potts and Swart 1984) and can significantly underestimate the real water temperature ranges experienced by corals. For example, monthly HadISST data in the vicinity of offshore Myrmidon Reef in the central GBR indicates an annual range of 5–6°C, matching the 5°C annual range of daily-average SSTs recorded by an automatic weather station (http://www.aims.gov.au/pages/facilities/weather-stations/weather-index.html). However, the recorded variation between observed daily maxima and minima was ~9.5°C (Lough 2001). Furthermore, the modelling inherent within reconstructed SST datasets can also introduce errors in seasonal signals – a predecessor of the HadISST data (GISST 2.2) indicates an annual range of 2–3°C in monthly SSTs for the same location.

4.3.1 Tropical SST and Global Temperature Trends

The instrumental record of global land and sea temperatures (Fig. 4.3a) illustrates the significant warming that has occurred since the end of the nineteenth century (Brohan et al. 2006). Average temperatures for the most recent 30-year period, 1976–2005, are +0.5°C warmer than the first 30-year period of the record, 1871–1900 – a significant change in climate (i.e., the average expectation of weather). This warming also has occurred in the tropical oceans (30°N to 30°S) with maximum SSTs (Fig. 4.3b) averaging +0.4°C warmer in the most recent 30-year period compared with the late nineteenth century. Paleoclimatic data from a pan-tropically distributed set of 32 coral records confirm that the twentieth century oceans are warmer and fresher than the previous two centuries at most sites (Fig. 4.4; Grottoli and Eakin 2007).

Significant linear trends over the 135-year HadISST reconstruction yielded a +0.7°C warming for the global temperature series and +0.5°C for the tropical SST series. The major bleaching year of 1998 was, at the time, the warmest year on record for global temperatures and tropical maximum SSTs. Continued warming over the next seven years produced warmer global temperatures and major bleaching in the Caribbean in 2005 (Shein 2006; Eakin 2007; Wilkinson and Souter 2008). The increasing concentrations of greenhouse gases in the atmosphere trap more energy in the global climate system and this is causing warming of the system that is now affecting both the surface ocean and penetrating into deeper waters (Barnett et al. 2005; Levitus et al. 2005). This global-scale warming has been, and is projected to be, amplified in continental interiors compared to the oceans and at higher latitudes compared to the tropics (IPCC 2001, 2007a).

The trends in the HadISST dataset indicate that the tropical oceans have warmed ~70–80% of the global average value. A rise in maximum SSTs has occurred throughout the tropical oceans, with greatest warming in the southern Atlantic, Indian Ocean and parts of the central and eastern tropical Pacific and less warming in the north-central and south-central Pacific (Fig. 4.5).

Evidence from reef cores covering the past three millennia (Aronson et al. 2002) and observations of the bleaching-induced death of centuries old, slow-growing and thermally more resistant *Porites* corals (Mumby et al. 2001b) strongly suggests that

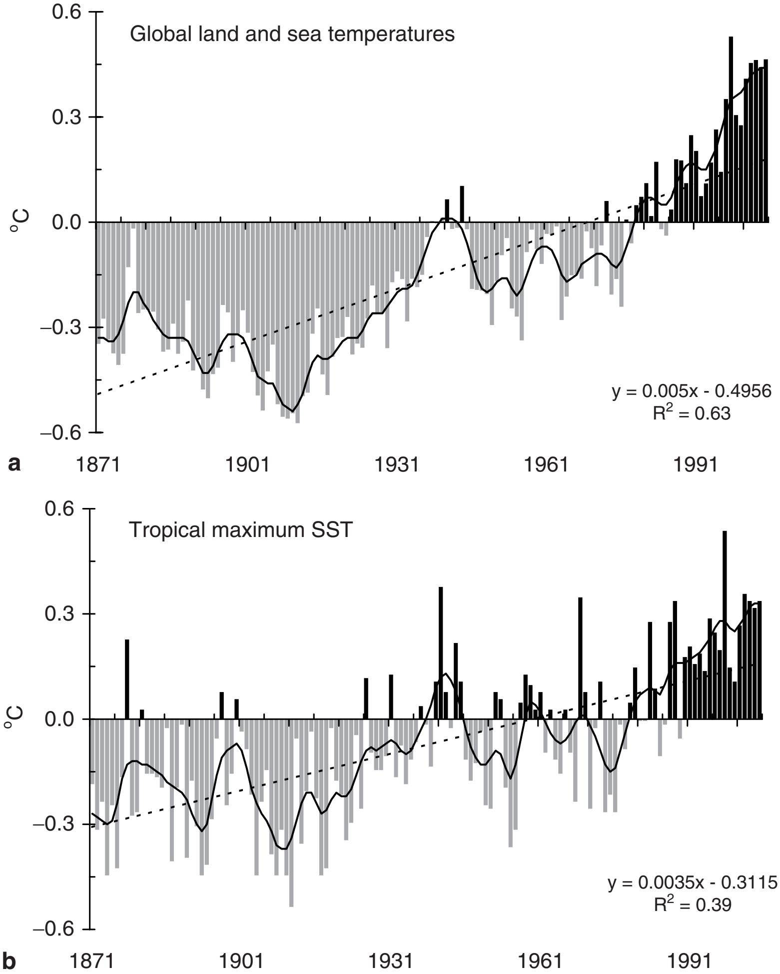


Fig. 4.3 **a** Global land and sea annual temperatures anomaly (data from Climate Research Unit, http://www.cru.uea.ac.uk/cru/info/warming/). **b** Tropical (30°N–30°S) annual maximum SST anomalies (HadISST data from British Atmospheric Data Centre, http://badc.nerc.ac.uk/home/index.html). Both **a** and **b** show annual values, 1871–2005, as anomalies from 1961–1990 mean; *thick line* is 10-year Gaussian filter emphasising decadal variability; linear trend is also shown

we have reached unprecedented thermal environmental conditions on coral reefs. Additionally, bleaching mortality of branching corals allowed corallivorous crown of thorns starfish, *Acanthaster planci*, to reach unprotected massive corals in Panama in 1983 for the first time in almost 200 years. The age of these massive corals was then used to estimate the return frequency of El Niño events to reefs in Pacific Panama (Glynn 1985). All of these data sources point to the likelihood that the recent severe El Niño events and the ocean temperature increases of the past 50 years are unique in at least the past few centuries.

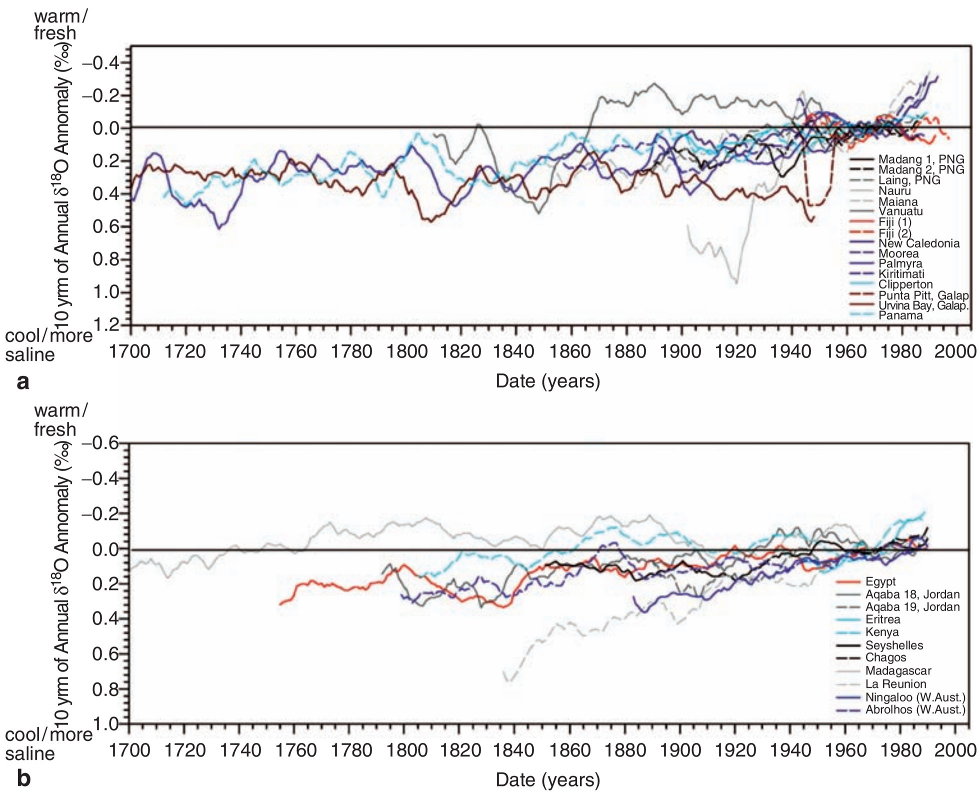


Fig. 4.4 10-year running mean annual coral $\delta^{18}O$ stable oxygen isotope anomalies: **a** Pacific Ocean, **b** Red Sea and Indian Ocean. All records normalized to the 1962–1979 period and centered on the fifth year of each 10-year period (from Grottoli and Eakin 2007). *Galap* Galapagos, *PNG* Papua New Guinea, *W. Aust.* Western Australia

4.3.2 Regional Trends in Thermal Stress

The 22-year satellite record (see Sect. 4.2.2.3) was used to examine the global and regional trends in SST anomalies at 50 coral reef sites that bleached during 1997–1998 (Lough 2000b). Grouping these 50 sites into five geographic regions, annual average SST anomalies for each region are shown in Fig. 4.6. The slopes of trend lines (Table 4.1) for each region over the 22-year record consistently range within 0.23–0.26°C/decade, with the exception of reef sites in the Pacific Ocean for which the trend is 0.18°C/decade. While not significantly different from the other regions, the lower trend in the Pacific Ocean anomaly may be important for the ability of

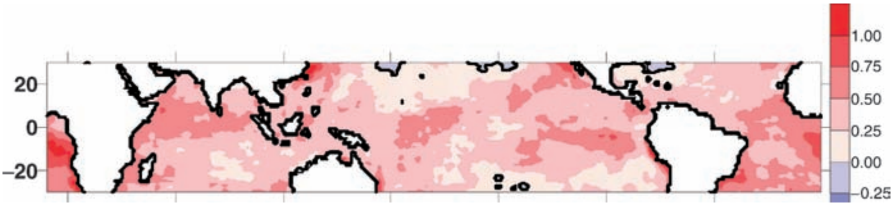


Fig. 4.5 Difference in average annual maximum SST, 1976–2005 minus 1871–1900, using 0.5°C contour intervals (HadISST data from British Atmospheric Data Centre, http://badc.nerc.ac.uk/home/index.html)

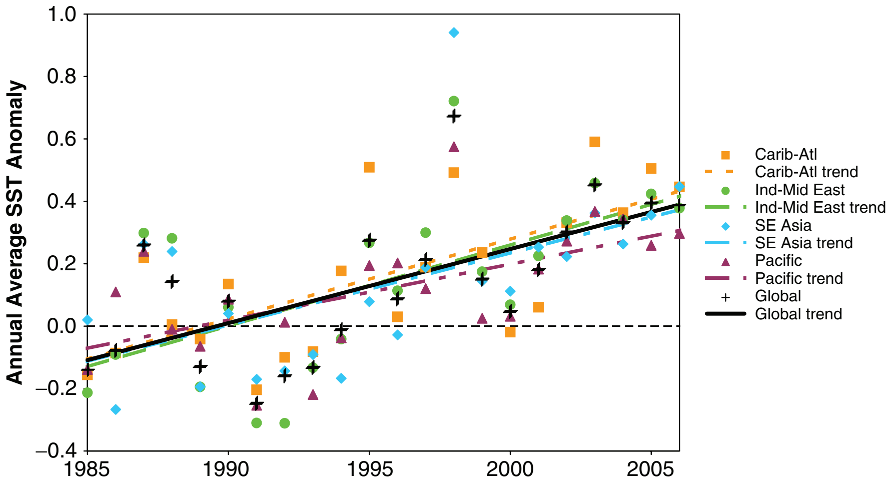


Fig. 4.6 SST annual anomalies and trends, 1985–2006, averaged for each year for the indicated sets of coral reef sites from the Pathfinder reanalysis of the 22-year satellite record: 50 global coral reef sites that bleached in 1998 (*black pluses*, *solid line*), 18 sites in Indian Ocean and Middle East (*green circles*, *dashed line*), 9 sites in southeast Asia (*blue diamonds*, *dash-dot line*), 11 sites in Pacific Ocean (*purple triangles*, *dash-dot-dot line*) and 12 sites in the Caribbean and Atlantic Ocean (*orange squares*, *dotted line*). The *black thin-dash line* shows the zero trend. Trend values for each line listed in Table 4.1

Table 4.1 Trends (and standard errors; *S.E.*) in SST anomalies across five geographic regions from the Pathfinder reanalysis of the 22-year satellite record, 1985–2006 (as displayed in Fig. 4.6). The SST anomaly values are averaged across specific reef pixels within each region and for each year

Region	Number of reef pixels	Trend in SST anomaly (°C/decade)	S.E. in trend (°C/decade)
Global	50	0.237	0.061
Indian Ocean and Middle East	18	0.261	0.074
Southeast Asia	9	0.232	0.078
Pacific Ocean	11	0.181	0.056
Caribbean and Atlantic Ocean	12	0.257	0.061

corals to thermally adapt and survive through climate change (Donner et al. 2005). The global rate of increase in SSTs is already at the rate predicted for the twenty-first century by global climate models where emissions are not reduced below current levels (2–4°C/century; IPCC 2007a). Further considerations of the impacts of future climate change on the bleaching of corals are discussed in Chap. 10. Comparing the annual global and regional average SST anomalies (Fig. 4.6) shows that, while the values are fairly consistent across the globe within each year, there are important spatial patterns of SST anomaly that change through time. The role of large-scale patterns in regional bleaching events is discussed in Sect.4.3.3.

Typical SST conditions that result in coral bleaching include not just unusually high maximum SSTs but also sustained warmer waters over a number of weeks. The NOAA DHW index (see Sect. 4.2.2.2) is a highly accurate predictor of such conditions. The record of NOAA's DHWs over 1985–2006 (Sect. 4.2.2.3) for 50 coral reef sites that bleached during 1997–1998 show increasing thermal stress throughout the 22-year period (Fig. 4.7). In this record, 1998 stands out as the year with the greatest cumulative reef thermal stress both globally (Fig. 4.7a) and in the Indian Ocean, southeast Asia and the Pacific Ocean (Fig. 4.7b, c, d). The exception to this pattern is the Caribbean/Atlantic (Fig. 4.7e) where thermal stress in 2005 greatly exceeded that of prior years.

The longer-term context of the increasing cumulative thermal stress on coral reefs shown by the satellite data can be determined using a degree-month index developed from multi-century records of reconstructed SST data. Similar to NOAA's DHWs, degree heating months sum the monthly anomalies above the long-term average monthly maximum and have been used to analyze climate model outputs for future bleaching potential (Lough 2000b; Donner et al. 2005). Using the HadISST and NOAA ERSST data based on SST anomalies from the same time period, indices were created for the same 50 coral reef sites discussed above for the period January 1871 to October 2006. With the exception of the 1877–1878 El Niño event, the regionally averaged degree-month values show very low thermal stress until the latter half of the twentieth century (Fig. 4.8a). 1998 was the most extreme year in terms of cumulative reef thermal stress when averaged over all 50 reef locations and for coral reef regions of the Indian Ocean, southeast Asia and the Pacific Ocean (Fig. 4.8a–d), consistent with the satellite record. Thermal stress in the Caribbean (Fig. 4.8e) peaked in 2005; however, the Caribbean region showed

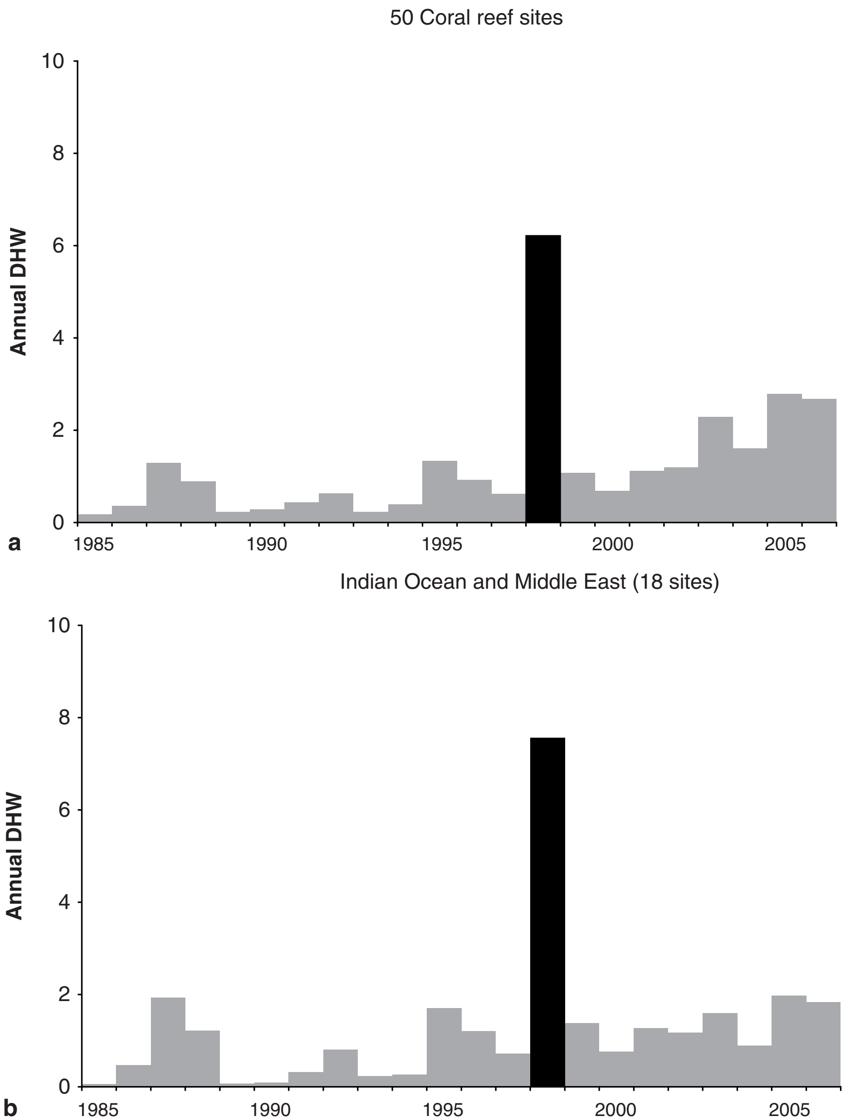


Fig. 4.7 Annual Degree Heating Week (*DHW*) indices, 1985–2006, averaged over the indicated number of 50 km Coral Reef Watch pixels for each region: **a** 50 coral reef sites that bleached in 1998, **b** 18 sites in Indian Ocean and Middle East, **c** 9 sites in southeast Asia, **d** 11 sites in Pacific Ocean and **e** 12 sites in the Caribbean and Atlantic Ocean (http://coralreefwatch.noaa.gov). Moderate bleaching has been shown to occur at DHW ≥ 4°C-weeks; severe bleaching occurs at DHW ≥ 8°C-weeks. *Black bar* shows most extreme year in 22-year record

significant thermal stress beginning decades earlier than the other regions (c.f., Lough 2000b; Barton and Casey 2005). It is unclear how much of the severe degradation of coral reefs in the Caribbean over recent decades resulted from this early increase in thermal stress (Gardner et al. 2003).

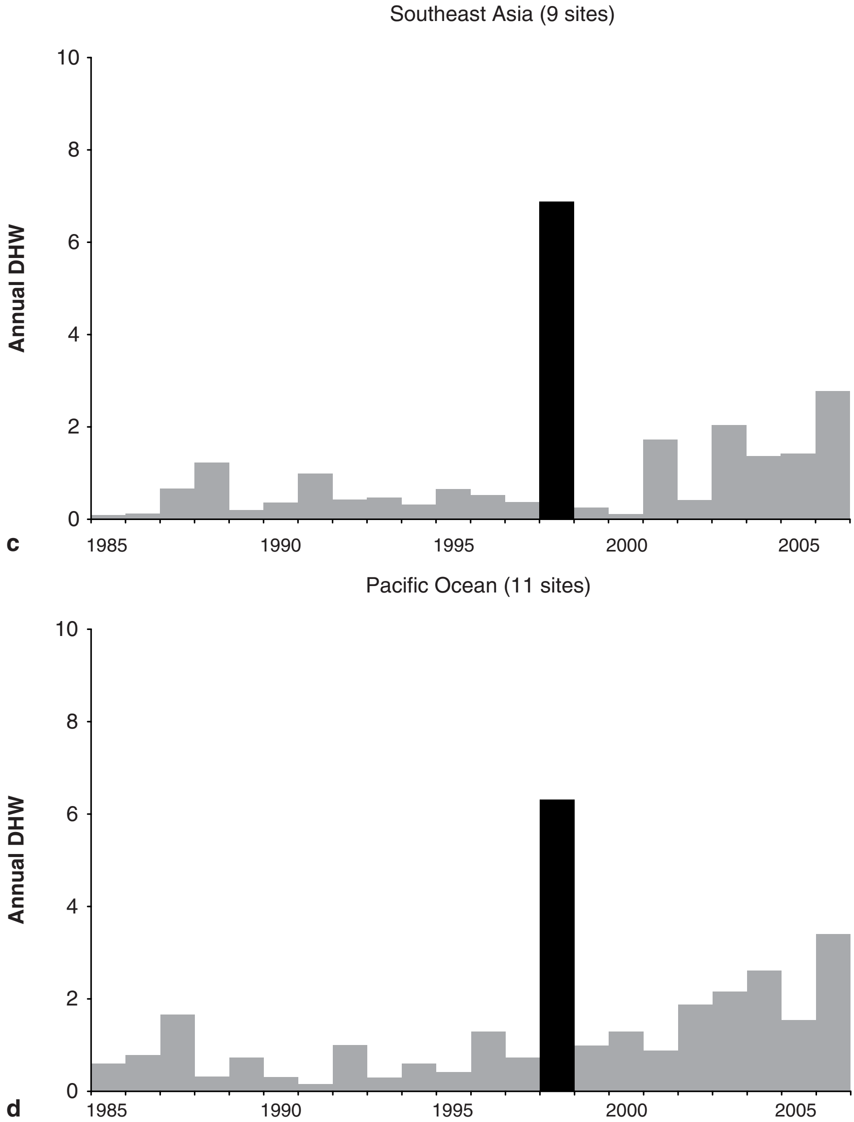


Fig. 4.7 (continued)

4.3.3 Role of El Niño–Southern Oscillation and Other Large-Scale Patterns

El Niño–Southern Oscillation (ENSO) events are the major source of short-term climatic variability within the tropical ocean-atmosphere system (McPhaden 2004). It was the major 1982–1983 El Niño event that first triggered warnings of a link between ENSO and mass coral bleaching events (Glynn 1983; Williams and

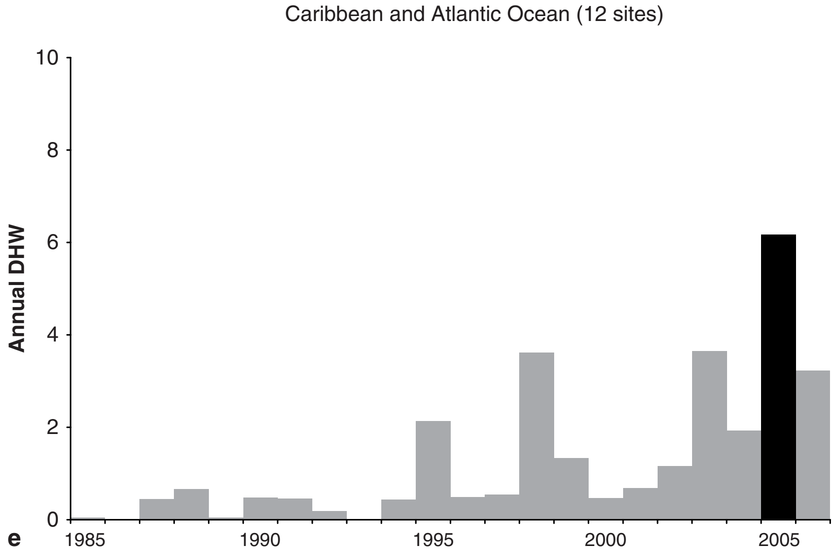
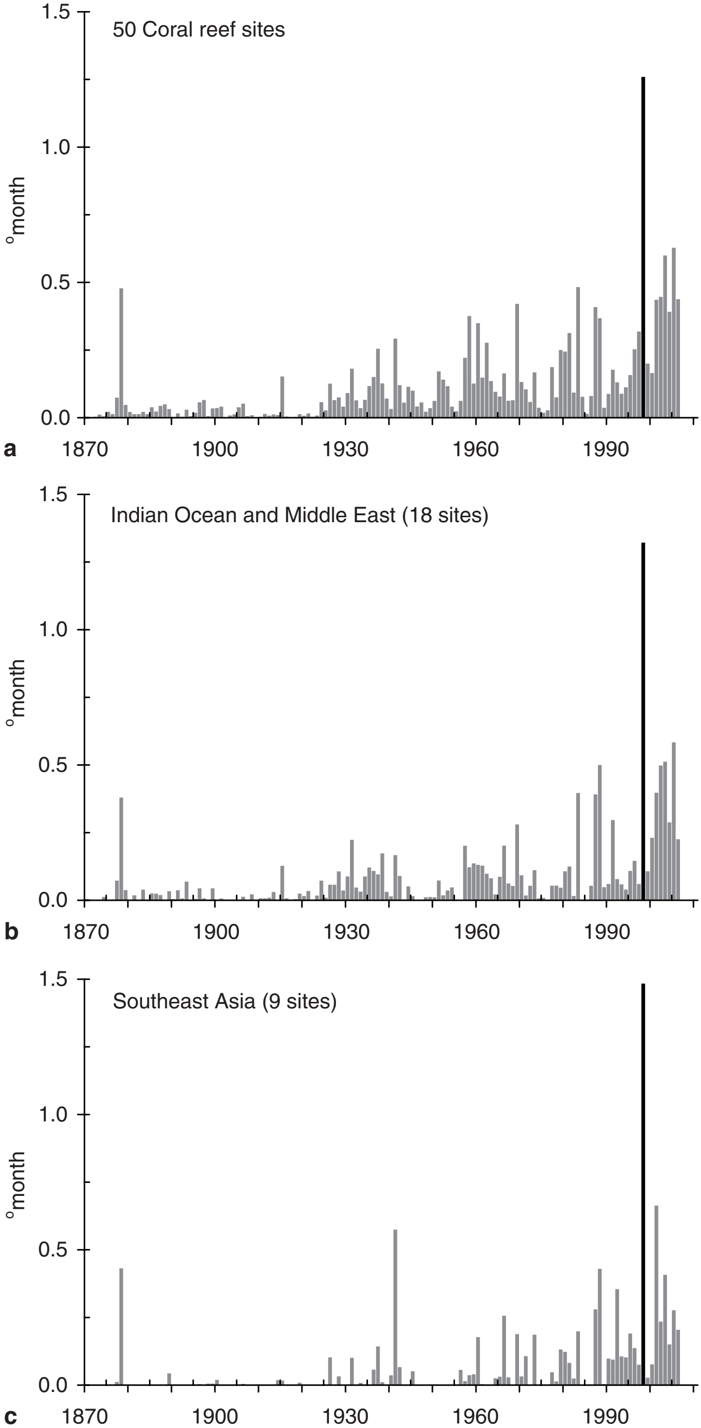


Fig. 4.7 (continued)

Bunkley-Williams 1990). The 1997–1998 El Niño event (coinciding with what was then the warmest year on record; Fig. 4.3a) was the other of the two most extreme El Niño events on record (Wolter and Timlin 1998; McPhaden 1999) and coincided with the greatest thermal stress at many coral reef sites (Figs. 4.7a, 4.8a). Over 15% of the world's reefs died and many reefs suffered over 90% bleaching in 1998 (Wilkinson 2000). ENSO events do not cause mass coral bleaching but instead increase the likelihood of anomalously warm SSTs in particular regions that result in coral bleaching. Major and minor ENSO years can be seen in the increased anomalies in Fig. 4.6 (i.e., 1987–1988, 1994–1995, 1997–1998, 2002–2003; but note the absence of signal for the 1991–1992 event). Mass coral bleaching can occur in the absence of ENSO extremes when other climate anomalies cause regional warming: e.g., GBR in early 1982 (Coffroth et al. 1990), Moorea in 1994 (Hoegh-Guldberg and Salvat 1995), Hawaii in 1996 (Jokiel and Brown 2004) and the Caribbean in 2005 (Eakin 2007; Wilkinson and Souter 2008).

Here we define the phases of ENSO by the Southern Oscillation Index (SOI), calculated as the difference in standardized sea-level pressure at Darwin, Australia and Tahiti, French Polynesia (Troup 1965; obtained from the Australian Bureau of Meteorology, at: http://www.bom.gov.au/climate/soihtm1.shtml). This index was used to identify 20 El Niño events, 20 La Niña events and 20 years of ENSO-neutral

Fig. 4.8 Annual degree heating month indices (°*month*), 1871–2006, from HadISST and Reyn_SmithOIv2 data, for: **a** 50 coral reef sites that bleached in 1998, **b** 18 sites in Indian Ocean and Middle East, **c** 9 sites in southeast Asia, **d** 11 sites in Pacific Ocean and **e** 12 sites in the Caribbean and Atlantic Ocean. Data are available from http://www.aims.gov.au/pages/research/coral-bleaching/thermal-stress/thermal-stress-indices.html. *Black bar* shows most extreme year in 136-year record


50 Coral reef sites
Indian Ocean and Middle East (18 sites)
Southeast Asia (9 sites)
°month
1.5
1.0
0.5
0.0
1870
1900
1930
1960
1990
a
b
c

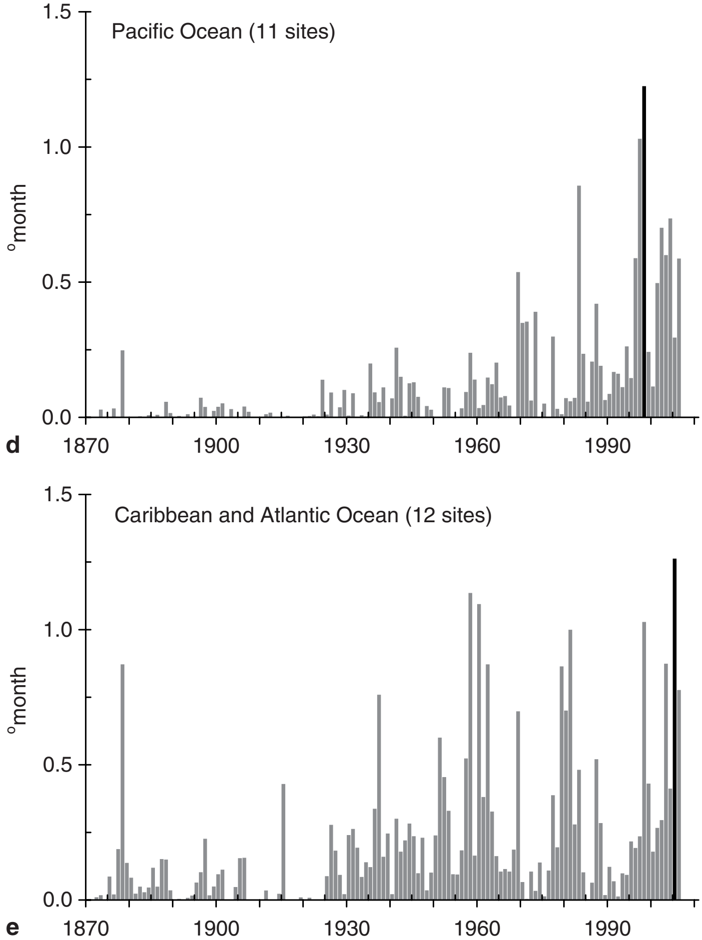


Fig. 4.8 (continued)

conditions from the upper, lower and middle percentiles, respectively, of the annual May–April values over the period 1871–2005. Monthly maxima were then averaged for each set of 20 years for both the target year and the following year (year *t* and year *t*+1; e.g., 1982 and 1983) for the tropical oceans. For each 1° latitude–longitude box, the average values for the 20 El Niño years and 20 La Niña years were tested for significant difference from the average of the 20 ENSO-neutral years.

The two extreme phases of ENSO, El Niño and La Niña, typically evolve over 12–18 months and are associated with distinct and different ocean–atmosphere circulation patterns in the core region of the central and eastern equatorial Pacific (McPhaden 2004). Typically for the two years spanning an El Niño event (e.g., 1982–1983, 1987–1988, 1997–1998), large areas of the tropical oceans have significantly warmer maximum SSTs than in ENSO-neutral years (Fig. 4.9a, b). Fig. 4.9b shows why, for example, many Caribbean bleaching events occur in the

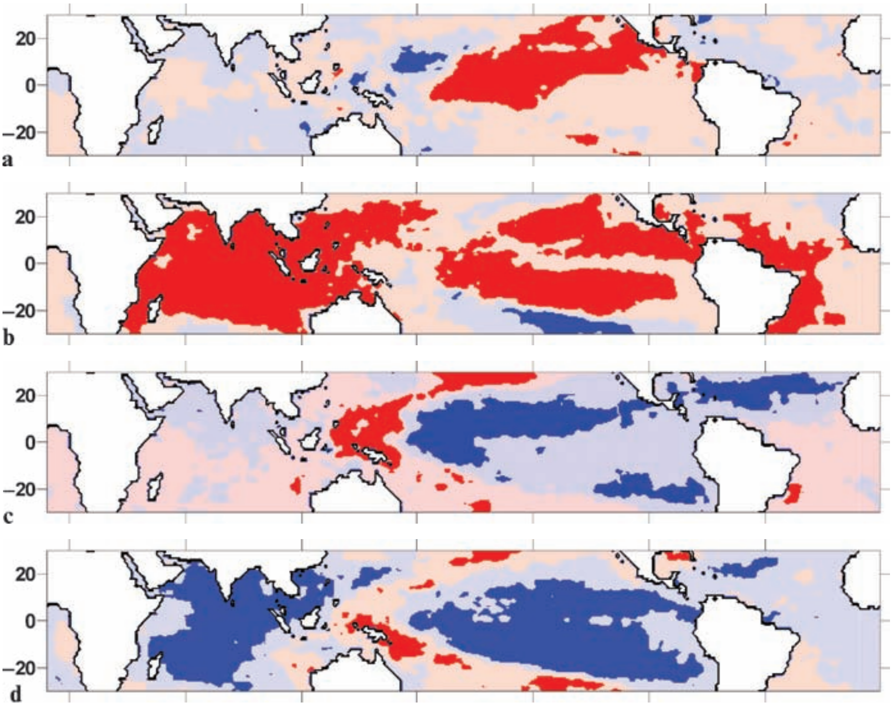


Fig. 4.9 Significantly (at 5% level) warmer (*red*) or cooler (*blue*) annual maximum SST difference: **a** El Niño year *t*, **b** El Niño year *t*+1, **c** La Niña year *t* and **d** La Niña year *t*+1. Average values calculated for 20 El Niño events, 20 La Niña events and tested for significant differences from 20 ENSO-neutral years. The groups of years were identified from the Troup (1965) SOI updated by the Australian Bureau of Meteorology

second year of an El Niño event. Conversely during the two years spanning a La Niña event, large areas of the tropical oceans have significantly cooler maximum SSTs than in ENSO-neutral years (Fig. 4.9c, d). An interesting exception is the region in the western equatorial Pacific lying along the South Pacific Convergence Zone where waters tend to be warmer during La Niña years and coral reefs experienced mass bleaching not in 1997–1998 but during the ensuing 1998–1999 La Niña (Wilkinson 2002). In general though, the risk of warmer than normal maximum SSTs and thus bleaching is greater during El Niño events for many of the world's coral reefs and this risk is much lower during La Niña and ENSO-neutral years. There is still debate as to whether the characteristics of recent ENSO events have changed (Trenberth and Stepaniak 2001) and how ENSO characteristics may change with continued global climate change (Philip and van Oldenborgh 2006). The important point for future mass bleaching on coral reef ecosystems is that even if temperature anomalies resulting from ENSO events remain within the range observed during the past 150 years, the warming of baseline maximum SSTs (Fig. 4.3b, 4.4, 4.6) increases the probability that waters overlying reefs will reach or exceed critical temperature thresholds for bleaching.

The ENSO system is not the only climatic pattern that influences ocean temperatures, and accordingly, the risk of coral bleaching. Oceanic SST variations also result from other longer-term modes including the Pacific Decadal Oscillation (Mantua et al. 1997) and the Atlantic Multidecadal Oscillation (AMO; Schlesinger and Ramankutty 1994), which show return periods on the order of 25 years and 65 years, respectively. These oscillations have typically been observed in periodic variations of temperature anomalies in the northern parts of their respective oceans. The Indian Ocean Dipole (Saji et al. 1999) is considered an aperiodic variation of SST anomalies between the eastern and western tropical Indian Ocean. Using an 18-year satellite time-series, Strong et al. (2006) observed a pattern shift in short-term SST trends during the latter half of the 1990s. Generally neutral trends across the Pacific Ocean transitioned to warming in the western Pacific and to cooling in the eastern Pacific; the tropical Indian Ocean moved from neutral to warming conditions; and warming trends in the northern and tropical Atlantic Ocean were enhanced. This pattern shift is likely a reflection of the superposition of short- and long-term climate variabilities.

Many authors have suggested that ocean temperature increases due to global climate change, especially in combination with natural variability such as ENSO, have and will continue to increase the frequency and severity of coral bleaching events (Williams and Bunkley-Williams 1990; Hoegh-Guldberg 1999; Eakin 2007). NOAA and NASA analyses revealed that global temperatures in 2005 surpassed 1998 as the warmest year on record (combined land and ocean global climate records; Shein 2006). This resulted in the most severe and widespread coral bleaching and mortality ever seen in the Caribbean (Eakin 2007; Wilkinson and Souter 2008). The anomalously warm North Atlantic temperatures that caused the 2005 Caribbean bleaching were only slightly related to ENSO and AMO. Trenberth and Shea (2006) used an attribution analysis to separate the anomaly in 2005 North Atlantic temperatures into its component climate patterns. They found that 0.45°C of the 0.9°C warming was due to the monotonic rise in global SSTs, 0.2°C due to after effects of the 2004–2005 mild El Niño and 0.1°C due to AMO. Donner et al. (2007) suggest that twentieth century anthropogenic warming, on top of the natural modes of variability, increased the probability that the Caribbean would experience the level of thermal stress observed in 2005 by an order of magnitude, compared with the natural modes alone. Their projections of future SST (including anthropogenic warming) suggest that, in the absence of acclimatization or adaptation by coral organisms, stress levels like those seen in 2005 will be experienced almost biannually by the 2030s.

4.4 Other Local Environmental Variables

Large-scale SST anomalies in the tropical oceans (Sect. 4.3.1) are the principal drivers of conditions that result in mass coral bleaching. At the local scale, the occurrence and intensity of bleaching can be highly variable both within a coral colony, between coral colonies, within a reef and between reefs in a region (Hoegh-Guldberg 1999). These variations are in addition to the differential susceptibility of different coral species to thermal stress (Marshall and Baird 2000). Other physical factors that operate locally can either enhance or suppress the impacts of higher-than-normal regional SSTs and thus the intensity of coral bleaching. Observations that corals often bleach more on their upper surface than at the sides clearly implicates light as an additional factor and frequently the local weather conditions that cause intense warming of the water column (low winds, low cloud amount, still waters; Skirving et al. 2006a) allow increased light penetration to the coral's surface (Coles and Jokiel 1978; Salm and Coles 2001). Increased cloudiness can mitigate bleaching even when SSTs are unusually warm (Mumby et al. 2001a). Lowered salinity due to a major flood event appears to have increased the intensity of coral bleaching on nearshore reefs of the central GBR in 1998 (Berkelmans and Oliver 1999). There can also be considerable local-scale variations in SSTs within and between reefs that can affect bleaching occurrence and intensity (Nadaoka et al. 2001; Berkelmans 2002; Berkelmans et al. 2004). Such local-scale SST variations can be related to water movements such as upwelling, mixing, tidal range and wave energy, shading and exposure that reduce the local thermal stress (Salm and Coles 2001; Skirving and Guinotte 2001; Skirving et al. 2006b). Although often small in scale, identification and enhanced protection of such bleaching resistant sites may be critical for recovery of adjacent bleaching-damaged coral populations (Marshall and Schuttenberg 2006; Skirving et al. 2006b).

4.5 Summary

We now have strong evidence of how global climate change due to the enhanced concentration of atmospheric greenhouse gases already has caused significant coral bleaching. This threat of future warming is so strong that coral bleaching has been highlighted among the greatest threats to ecosystems brought about by anthropogenic climate change (IPCC 2007b). Warming of the tropical oceans has raised the baseline SSTs where coral reefs live much closer to their upper thermal limits, so that weather conditions or interannual variability are more likely to raise SSTs above these limits than similar weather conditions did 100 years ago. The risk of unusually warm maximum SSTs also varies with the ENSO cycle, so that the risk of conditions conducive to bleaching further increases for much of the tropical oceans during ENSO events. This allows us to use El Niño conditions as an analogue for potential future climatic conditions. What remains is to determine if corals are capable of evolving physiological adaptations to thermal stress rapidly enough to cope with the combination of natural variability and climate change – a now ongoing, uncontrolled experiment that could result in the extinction of many corals.

Our ability to identify, monitor and predict SST conditions that can lead to coral bleaching has improved dramatically since the first reports of mass bleaching events in the early 1980s. This allows near-real-time monitoring and identification of potential bleaching conditions throughout the world's coral reefs. Of course, monitoring alone cannot prevent coral bleaching or mortality. It can, however, enable scientists and managers to be alert to bleaching and to document the intensity, impact and follow-on effects more comprehensively than was possible 10–20 years ago (Chap. 5). It also allows managers to take actions to help protect reefs at times when bleaching makes them more vulnerable to other stressors (Marshall and Schuttenberg 2006; Obura et al. 2006). Understanding linkages between the physical environment and biological processes on coral reefs improves our knowledge of the bleaching phenomenon, its ramifications and potential management responses. This helps managers develop and test management approaches to protect corals from mortality at the time of bleaching events. It also allows identification of "bleaching-resistant" corals, reefs and regions that should be targeted for enhanced protection. Resilient reefs may provide important refugia for coral reef organisms as climate continues to change and increasingly stress the world's reefs. The health of many of the world's coral reefs already has been severely compromised by local human-induced impacts. Climate change impacts at least add to local impacts and may act synergistically with them. In addition to the other consequences of a rapidly warming, enhanced greenhouse world (ocean acidification, more intense tropical storms, etc.), the observed increase in mass coral bleaching events does not bode well for the near- and long-term future of these vital ecosystems.

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