Spatial and temporal patterns of mass bleaching of corals in the Anthropocene

The window for safeguarding the world's coral reefs from anthropogenic climate change is rapidly closing

Terry P. Hughes[1], Kristen D. Anderson[1], Sean R. Connolly[1,2], Scott F. Heron[3,4,] , James T. Kerry[1], Janice M. Lough[1,5], Andrew H. Baird[1], Julia K. Baum[6], Michael L. Berumen[7], Tom C. Bridge[1,8], Danielle C. Claar[6], C. Mark Eakin[3], James P. Gilmour[9], Nicholas A.J. Graham[1,10], Hugo Harrison[1], Jean-Paul A. Hobbs[11], Andrew S. Hoey[1], Mia Hoogenboom[1,2], Ryan J. Lowe[12], Malcolm T. McCulloch[12], John M. Pandolfi[13], Morgan Pratchett[1], Verena Schoepf[12], Gergely Torda[1,5], Shaun K. Wilson[14]

[1]Australian Research Council (ARC) Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD 4811, Australia

[2]College of Marine & Environmental Sciences, James Cook University, Townsville, Queensland 4811, Australia

[3]Coral Reef Watch, U.S. National Oceanic and Atmospheric Administration, College Park, MD 20740, USA

[4]Marine Geophysical Laboratory, Physics Department, College of Science, Technology and Engineering, James Cook University, Townsville, QLD 4811, Australia

[5]Australian Institute of Marine Science, PMB 3, Townsville, Queensland 4810, Australia

[6]Department of Biology, University of Victoria, British Columbia, V8W 2Y2, Canada

[7]Red Sea Research Center, King Abdullah University of Science and Technology, Thuwal 23599-6900, Saudi Arabia

[8]Queensland Museum, 70-102 Flinders St, Townsville, QLD, 4810, Australia

[9]Australian Institute of Marine Science, Indian Ocean Marine Science Centre, UWA, WA 6009, Australia

[10]Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK

[11]Department of Environment and Agriculture, Curtin University, Perth, WA 6845, Australia

[12]ARC Centre of Excellence in Coral Reef Studies, UWA Oceans Institute, and School of Earth Sciences, University of Western Australia, Western Australia 6009, Australia

[13]ARC Centre of Excellence for Coral Reef Studies, School of Biological Sciences, University of Queensland, Brisbane, QLD 4072, Australia

[14]Department of Biodiversity, Conservation & Attractions, Kensington, Perth, WA 6151, Australia

Tropical reef systems are transitioning to a new era in which the interval between recurrent bouts of coral bleaching is too short for a full recovery of mature assemblages. We analyzed bleaching records at 100 globally-distributed reef locations from 1980 to 2016. The median return-time between pairs of severe bleaching events has diminished steadily since 1980, and is now only six years. As global warming has progressed, tropical sea surface temperatures are warmer now during current La Niña conditions than they were in El Niño events three decades ago. Consequently, as we transition to the Anthropocene, coral bleaching is occurring more frequently in all El Niño Southern Oscillation phases, increasing the likelihood of annual bleaching in coming decades.

The average surface temperature of our planet has risen by close to 1°C since the 1880s (*1*), and global temperatures in 2015 and 2016 were the warmest since instrumental records began in the 19th century (*2*). Recurrent regional-scale (>1000 km) bleaching and mortality of corals is a modern phenomenon caused by anthropogenic global warming (*3*-*10*). Bleaching prior to the 1980s was recorded only at a local scale of a few tens of kilometres, due to small-scale stressors such as freshwater inundation, sedimentation, or unusually cold or hot weather (*3*-*5*). The novelty of regional-scale bleaching is also evident from the growth bands of old Caribbean corals: synchronous distortions of skeletal deposition (stress bands) along a 400 km stretch of the Mesoamerican Reef are only found following recent hot conditions, confirming that regional-scale heat stress is a modern phenomenon caused by anthropogenic global warming (*10*). Bleaching occurs when the density of algal symbionts, or zooxanthellae (*Symbiodinium* spp.), in the tissues of a coral host diminishes due to environmental stress, revealing the underlying white skeleton of the coral (*8*). Bleached corals are physiologically and nutritionally compromised, and prolonged bleaching over several months leads to high levels of coral mortality (*11*, *12*). Global climate modelling and satellite observations also indicate that the thermal conditions for coral bleaching are becoming more prevalent (*13*, *14*) leading to predictions that localities now considered to be thermal refugia could disappear by mid-century (*15*).

Although several global databases of bleaching records are available (notably ReefBase, reefbase.org), they suffer from intermittent or lapsed maintenance, and from uneven sampling effort across both years and locations (*7*). The time-spans of five earlier global studies of coral bleaching range from 1870-1990 (*3*), 1960-2002 (*4*), 1973-2006 (*5*), 1980-2005 (*6*), and 1985-2010 (*7*). Here, we compiled *de novo* the history of recurrent bleaching from 1980-2016 for 100 globally-distributed coral reef locations in 54 countries, using a standardized protocol to examine patterns in the timing, recurrence and intensity of bleaching episodes, including the latest global bleaching event in 2015-2016 (Supplementary Table S1). This approach avoids the bias of continuous addition of new sites in open access databases, and retains the same range of spatial scales through time (Supplemental Figure S1). A bleaching record in our analysis consists of three elements: The location from 1-100, the year, and the binary presence or absence of bleaching. Our findings reveal that coral reefs have entered the distinctive human-dominated era characterized as the Anthropocene (*16*-*18*), in which the frequency and intensity of bleaching events is rapidly approaching unsustainable levels. At the spatial scale we examined (Supplementary Figure S1), the number of years between recurrent severe bleaching events has diminished five-fold in the past four decades, from 25-30 years in the early 1980's to once every 5.9 years in 2016. Across the 100 locations, we scored 300 bleaching episodes as severe, i.e. >30% of corals bleached at a scale of 10s to 100s of kilometres, and a further 312 as moderate (<30% of corals bleached). Our analysis indicates that coral reefs have moved from a period prior to 1980 when regional-scale bleaching was exceedingly rare or absent (*3*-*5*), to an intermediary phase beginning in the 1980s when global warming increased the thermal stress of strong El Niño events, leading to global bleaching events. Finally, in the past two decades many additional regional-scale bleaching events are also occurring outside of El Niño conditions, affecting more and more former spatial refuges and threatening the future viability of coral reefs.

Increasingly, climate-driven bleaching is occurring in all El Niño Southern Oscillation (ENSO) phases, because as global warming progresses, average tropical sea surface temperatures are warmer today under La Niña conditions than they were during El Niño events only three decades ago (Fig. 1). Since 1980, 58% of severe bleaching events have been recorded during four strong El Niño periods (in 1982-1983, 1997-1998, 2009-2010 and 2015-2016) (Fig. 2A), with the remaining 42% occurring during hot summers in other ENSO phases. Inevitably, the link between El Niño as the predominant trigger of mass bleaching (*3-5*) is diminishing as global warming continues (Fig. 1) and as summer temperature thresholds for bleaching are increasingly exceeded throughout all ENSO phases.

The 2015-2016 bleaching event affected 75% of the globally-distributed locations we examined (Fig. 2A, Fig. 3), and is therefore comparable in scale to the then-unprecedented 1997-1998 event, when 74% of the same 100 locations bleached. In both periods, sea surface temperatures were the warmest on record in all major coral reef regions (*2, 19*). As the geographic footprint of recurrent bleaching spreads, fewer and fewer potential refuges from global warming remain untouched (Fig. 2B), and only six of the 100 locations we examined have escaped severe bleaching so far (Fig. 2B, Supplementary Table S1). This result is conservative, due to type 2 errors in our analyses, where bleaching could have occurred but was not recorded.

Following the extreme bleaching recorded in 2015-16, the median number of severe bleaching events experienced across our study locations since 1980 is now three (Fig. 2C). Eighty-eight percent of the locations that bleached in 1997-1998 have since bleached severely at least once again. Since 1980, 31% of reef locations have experienced four or more (up to nine) severe bleaching events (Fig. 2C), as well as many moderate episodes (Supplementary Table S1). Globally, the annual risk of bleaching (both severe and more moderate events) has increased by a rate of approximately 3.9% per annum (Supplementary Fig. S2), from an expected 8% of locations in the early 1980s to 31% in 2016. Similarly, the annual risk of severe bleaching has also increased, at a slightly faster rate of 4.3% per annum, from an expected 4% of locations in the early 1980's to 17% in 2016 (Supplementary Fig. S2). This trend corresponds to a 4.6-fold reduction in estimated return-times of severe events, from once every 27 years in the early 1980s to every 5.9 years in 2016. Thirty-three percent of return-times between recurrent severe bleaching events since 2000 have been just one, two or three years (Fig. 2D).

Our analysis also reveals strong geographic patterns in the timing, severity and return-times of mass bleaching (Fig. 4). The Western Atlantic, which has warmed earlier than elsewhere (13, 19), began to experience regular bleaching early, with an average of 4.1 events per location prior to 1998, compared with 0.4 to 1.6 in other regions (Fig. 4, Supplementary Fig. S2). Furthermore, widespread bleaching (affecting >50% of locations) has now occurred seven times since 1980 in the Western Atlantic, compared to three times for both Australasia and the Indian Ocean, and only twice in the Pacific. Over the entire period, the number of bleaching events has been highest in the Western Atlantic, with an average of 10 events per location, 2-3 times more than other regions (Fig. 4).

In the 1980s, bleaching risk was highest in the Western Atlantic, followed by the Pacific, with the Indian Ocean and Australasia having the lowest bleaching risk. However, bleaching risk increased most strongly over time in Australasia and the Middle East, at an intermediate rate in the Pacific, and slowly in the Western Atlantic (Fig. 4, Supplementary Fig. S3B, Supplementary Tables S2 and S3). The return-times between pairs of severe bleaching events are declining in all regions (Supplementary Fig. S3C), with the exception of the Western Atlantic where most locations have escaped a major bleaching event from 2010 – 2016 (Fig. 2D).

We tested the hypothesis that the number of bleaching events that have occurred so far at each location is positively related to the amount of post-industrial warming of sea surface temperatures that has been experienced there (Supplementary Fig. S4). However, we found no significant relationship for any of the four geographic regions, consistent with each bleaching event being caused by a short–lived episode of extreme heat (*12*, *19*, *20*) that is superimposed on much smaller long-term warming trends. Hence, the long-term predictions of future average warming of sea surface temperatures (*13*) are also unlikely to provide an accurate projection of bleaching risk or the location of spatial refuges over the next century.

In coming years and decades, climate change will inevitably continue to increase the number of extreme heating events on coral reefs, and further drive down the return-times between them. Our analysis indicates that we are already approaching a scenario where every hot summer, with or without an El Niño event, has the potential to cause bleaching and mortality at a regional scale. The time between recurrent events is increasingly too short to allow a full recovery of mature coral assemblages, which generally takes 10-15 years for the fastest growing species and far longer for the full complement of life histories and morphologies of older assemblages (*21-24*). Areas that have so far escaped severe bleaching are likely to decline further in number (Fig.

2B), and the size of spatial refuges will diminish. These impacts are already underway with close to 1°C of global average warming. Hence, 1.5°C or 2°C of warming above pre-industrial conditions will inevitably contribute to further degradation of the world's coral reefs (*14*). The future condition of reefs, and the ecosystem services they provide to people, will depend critically on the trajectory of global emissions and on our diminishing capacity to build resilience to recurrent high-frequency bleaching through management of local stressors (*18*), before the next bleaching event occurs.

REFERENCES AND NOTES

1. D. L. Hartmann *et al*., in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker, Ed. (Cambridge University Press, 2013).
2. National Aeronautics and Space Administration (NASA). Global Analysis - 2016 year-to-date temperatures versus previous years (2016) https://www.ncdc.noaa.gov/sotc/global/2016/10/supplementary/page-2
3. P.W. Glynn, Coral reef bleaching: ecological perspectives. *Coral Reefs* **12**, 1-17 (1993).
4. G. M. Wellington, P. W. Glynn, in *Geological Approaches to Coral Reef Ecology*, R. B. Aronson, Ed. (Springer, Berlin, 2007).
5. J. K. Oliver, R. Berkelmans, C. M. Eakin, in *Ecological Studies: Analysis and Synthesis*, M. J. H. van Oppen, J. M. Lough, Eds. (2009).
6. J. A. Kleypas, G. Danabasoglu, J. M. Lough, Potential role of the ocean thermostat in determining regional differences in coral bleaching events. *Geophys. Res. Lett*. **35**, L03613, (2008), doi:10.1029/2007GL032257.
7. S. D. Donner, G. J. M. Rickbeil, S. F. Heron, A new high-resolution global mass coral bleaching database. *PLoS ONE* **12**, e0175490, (2017). doi.org/10.1371/journal.pone.0175490.
8. A. C. Baker, P. W. Glynn, B. Riegl, Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. *Estuar. Coast. Shelf Sci.* **80**, 435-471 (2008).
9. T. P. Hughes, *et al.*, Climate change, human impacts, and the resilience of coral reefs. *Science* **301**, 929-933 (2003).

10. J. E. Carilli, R. D. Norris, B. Black, S. M. Walsh, M. McField, Century-scale records of coral growth rates indicate that local stressors reduce coral thermal tolerance threshold. *Glob. Chang. Biol.* **16**, 1247-1257 (2010).
11. A. H. Baird, P. A. Marshall, Mortality, growth and reproduction in scleractinian corals following bleaching on the Great Barrier Reef. *Mar. Ecol. Prog. Ser.* **237**, 133-141 (2002).
12. M. D. Spalding, B. E. Brown, Warm-water coral reefs and climate change. *Science*, **350**, 769–771 (2015).
13. O. Hoegh-Guldberg *et al*., in *Climate Change 2014: Impacts, Adaptation and Vulnerability. Part B: Regional Aspects: Contribution of working group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker, Ed. (Cambridge University Press, 2013).
14. S. F. Heron, J.A. Maynard, R. van Hooidonk, C.M. Eakin, Warming trends and bleaching stress of the world's coral reefs 1864-2012. *Sci. Rep*. **6**, 38402 (2016).
15. R. van Hooidonk, J. A. Maynard and S. Planes. Temporary refugia for coral reefs in a warming world. *Nat. Clim. Chang.* **3**, 508-511 (2013).
16. P. J. Crutzen, in *Earth System Science in the Anthropocene,* E. Ehlers, T. Krafft, Eds. (Springer, 2006).
17. J. Rockström *et al.*, A safe operating space for humanity. *Nature* **461**, 472-475 (2009).
18. T. P. Hughes *et al*., Coral reefs in the Anthropocene. *Nature* **543**, 36-44 (2017).
19. J. M, Lough, 1997-98: Unprecedented thermal stress to coral reefs? *Geophys. Res. Lett.* **27**, 3901-3904 (2000).

20. T. P. Hughes *et al.*, Global warming and recurrent mass bleaching of corals. *Nature* **543**, 373-377 (2017).
21. H. Kayanne, S. Harii, Y. Ide, F. Akimoto, Recovery of coral populations after the 1998 bleaching on Shiraho Reef, in the southern Ryukyus, NW Pacific. *Mar. Ecol. Prog. Ser.* **239**, 93-103 (2002).
22. J. P. Gilmour, L. D. Smith, A. J. Heyward, A. H. Baird, M. S. Pratchett, Recovery of an isolated coral reef system following severe disturbance. *Science* **340**, 69-71 (2013).
23. P.W. Glynn *et al.*, Coral recovery in the Galapagos Islands: the northernmost islands (Darwin and Wenman). *Coral Reefs* **34**, 421-436 (2015).
24. T. R. McClanahan, Decadal coral community reassembly on an African fringing reef. *Coral Reefs* **33**, 939-950 (2014).
25. N. A. Rayner *et al.*, Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.* **108**, 4407, (2003), doi:10.1029/2002JD002670.
26. Tierney JE *et al*., Tropical sea surface temperatures for the past four centuries reconstructed from coral archives. *Paleoceanography* **30**, 226-252. (2015), doi:10.1002/2014PA002717.
27. M. D. Spalding, C. Ravilious, E. P. Green (2001) *World Atlas of Coral Reefs* (UNEP-WCMC, Cambridge, 2001)
28. D. Bates, M. Maechler, B. Bolker, S. Walker, Fitting Linear Mixed-Effects Models Using lme4. J. Stat. Soft. **67**, 1-48, (2015), doi:10.18637/jss.v067.i01.
29. W. N. Venables, B. D. Ripley, *Modern Applied Statistics with S* (Springer, New York, ed. 4, 2002)

ACKNOWLEDGEMENTS

Major funding for this research was provided by the Australian Research Council's Centre of Excellence Program (CE140100020). The contents of this manuscript are solely the opinions of the authors and do not constitute a statement of policy, decision or position on behalf of NOAA or the U.S. Government. Data reported in this paper are tabulated in the Supplementary Materials.

Supplementary Materials

Materials and Methods

Figures S1 to S4

Tables S1 to S3

References (*26*-*29*)

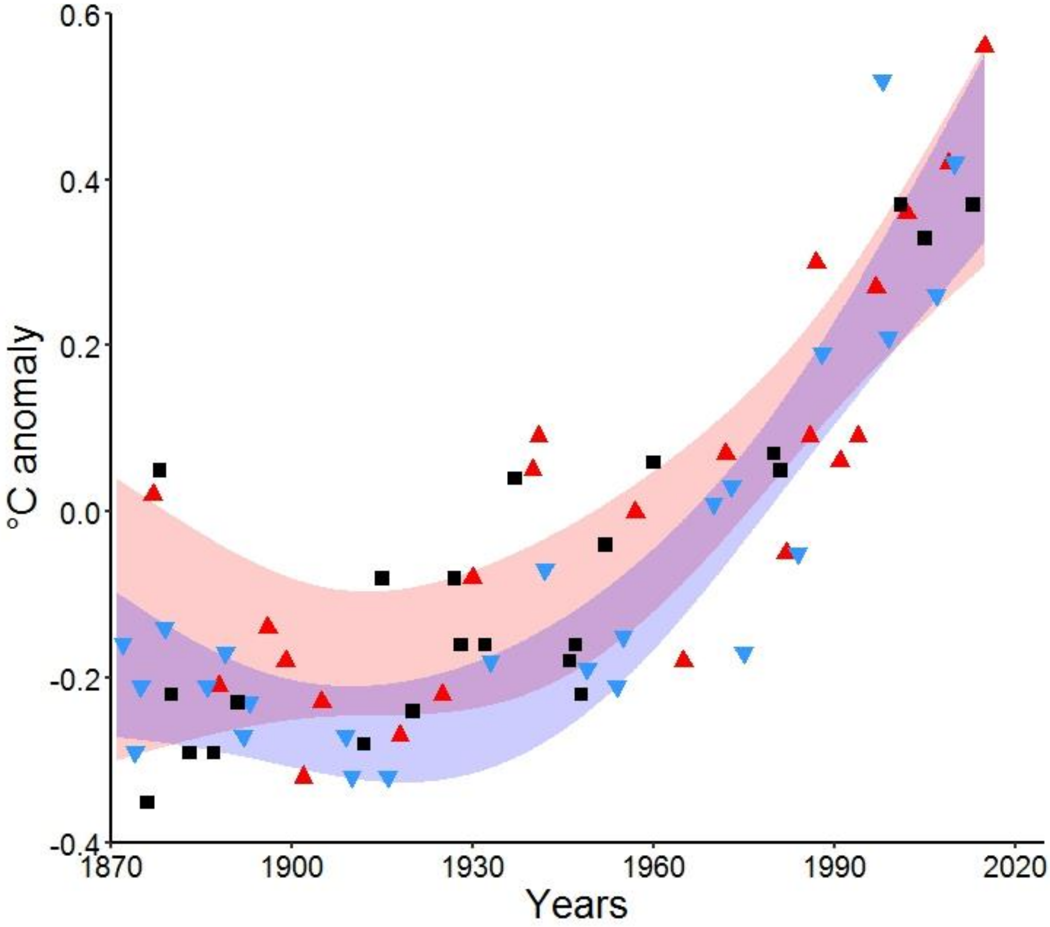

Fig. 1. Global warming throughout ENSO cycles. Sea surface temperature anomalies from 1871-2016, relative to a 1961-1990 baseline, averaged across 1,670 1-degree latitude by longitude boxes containing coral reefs between latitudes of 31^{o}N and 31^{o}S. Data points differentiate El Niño (red triangles), La Niña (blue triangles) and El Niño Southern Oscillation neutral periods (black squares). Ninety-five percent confidence intervals are shown for non-linear regression fits for years with El Niño and La Niña conditions (red and blue shading, respectively).

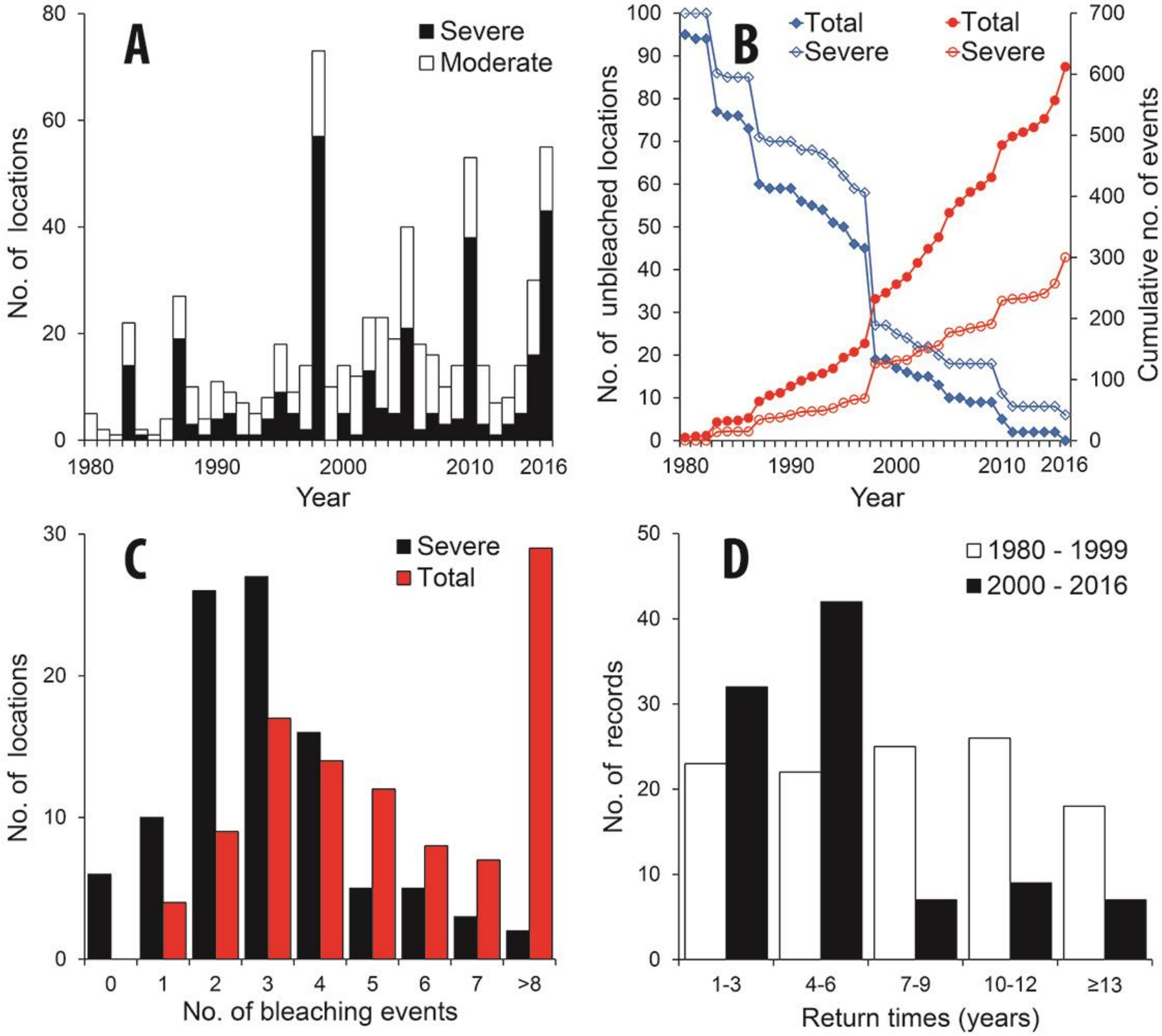

Fig. 2. Temporal patterns of recurrent coral bleaching. (**A**) Number of 100 pan-tropical locations that have bleached each year from 1980 to 2016. Black bars indicate severe bleaching affecting >30% of corals, and white bars depict moderate bleaching of <30% of corals. (**B**) Cumulative number of severe and total bleaching events since 1980 (red; right axis), and depletion of locations through time that remain free of any or severe bleaching (blue; left axis). (**C**) Frequency-distribution of the number of severe (black) and total bleaching events (red) per location. (**D**) Frequency distribution of return-times (number of years) between successive severe bleaching events from 1980-1999 (white bars) and 2000-2016 (black bars).

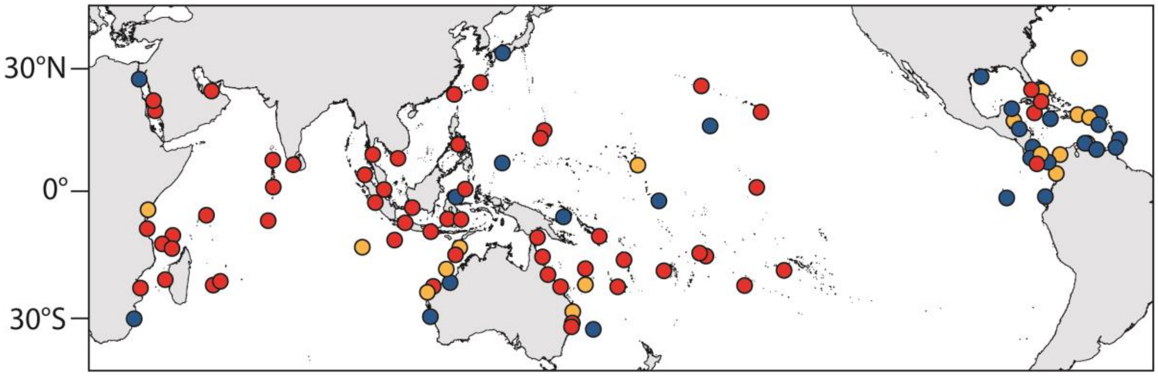

Fig. 3. The global extent of mass-bleaching of corals in 2015-2016. Symbols show 100 reef locations that were assessed: red – severe bleaching affecting >30% of corals; orange – moderate bleaching affecting <30% of corals; blue circles – no significant bleaching recorded. See Supplementary Table 1 for further details.

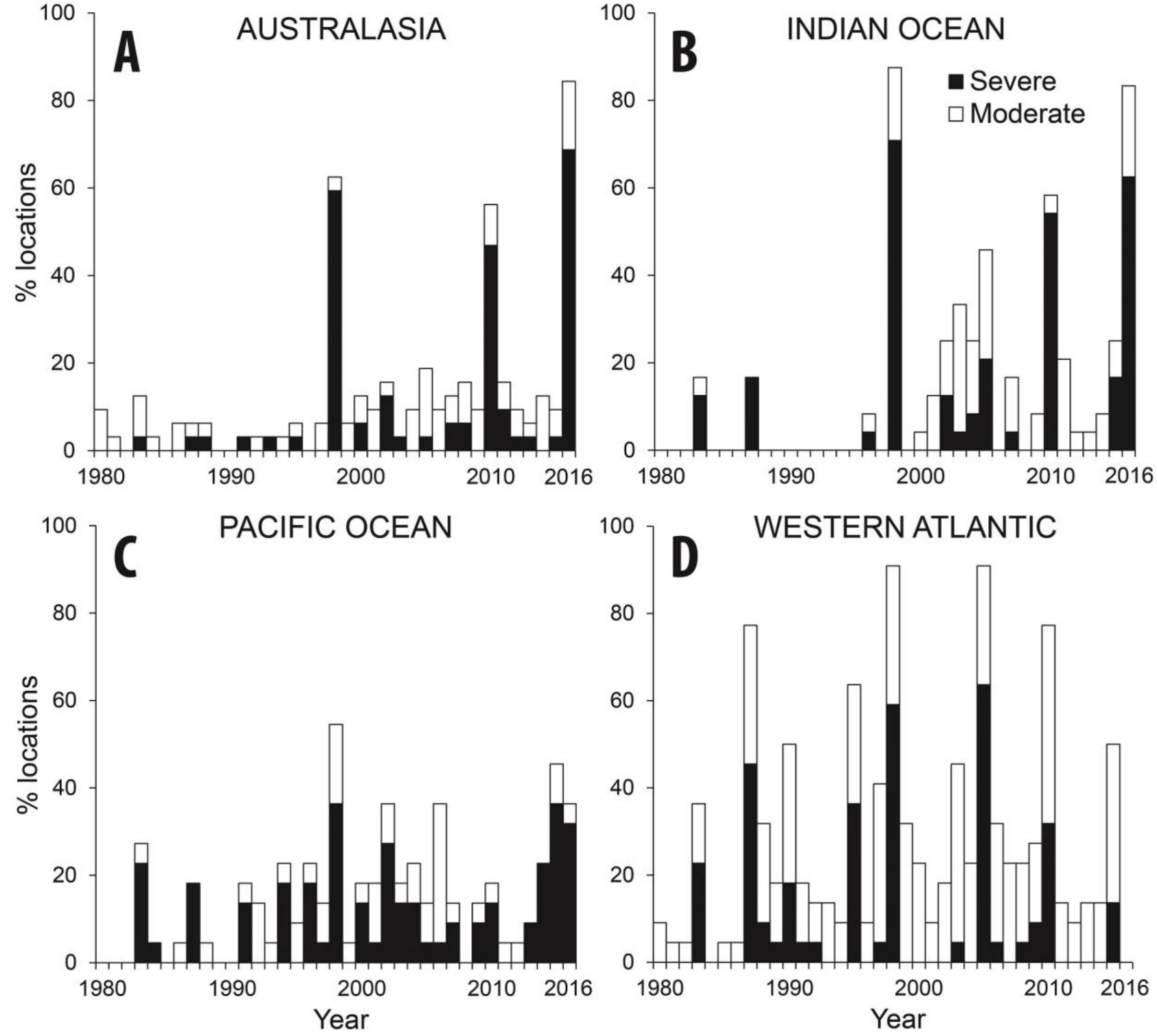

Fig. 4. Geographic variation in the timing and intensity of coral bleaching, from 1980-2016. **(A)** Australasia (32 locations). **(B)** Indian Ocean (24 locations). **(C)** Pacific Ocean (22 locations). **(D)** The Western Atlantic (22 locations). For each region, black bars indicate the percentage of locations that experienced severe bleaching, affecting >30% of corals. White bars indicate the percentage of locations per region with additional moderate bleaching affecting <30% of corals.

Supplementary Materials for

Spatial and temporal patterns of mass bleaching of corals in the Anthropocene

Terry P. Hughes, Kristen D. Anderson, Sean R. Connolly, Scott F. Heron, James T. Kerry, Janice M. Lough, Andrew H. Baird, Julia K. Baum, Michael L. Berumen, Tom C. Bridge, Danielle C. Claar, C. Mark Eakin, James P. Gilmour, Nicholas A.J. Graham, Hugo Harrison, Jean-Paul A. Hobbs, Andrew S. Hoey, Mia Hoogenboom, Ryan J. Lowe, Malcolm T. McCulloch, John M. Pandolfi, Morgan Pratchett, Verena Schoepf, Gergely Torda, Shaun K. Wilson

correspondence to: terry.hughes@jcu.edu.au

This PDF file includes:

- Materials and Methods
- Figs. S1 to S4
- Tables S1 to S3

Materials and Methods

Temperature Data, 1871-2016

We calculated the long-term amount of global warming throughout El Niño-Southern Oscillation (ENSO) phases (El Niño, La Niña and ENSO-neutral) for all 1,670 1-degree latitude by longitude boxes containing tropical coral reefs, between 31^{o}N to 31^{o}S. Monthly values of the Niño 3.4 SST index of ENSO were obtained from the HadISST data set (*25*) and the NOAA Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/indices/), from 1871-2016. The warming of the tropical oceans documented in the HadISST data set is also well-supported by tropical SST reconstructions (67% variance in common) developed from the skeletons of massive corals (*26*) which are not biased by data uncertainties in the instrumental SST records. We identified 23 El Niño periods when the index was more than one standard deviation above the mean; 24 La Niña episodes when the index was ≤ 1 SD below the mean; and 24 ENSO-neutral intervals when the index was ± 0.14 SD of the mean. For each of these three phases of ENSO cycles, thermal anomalies in maximum summer temperatures were compared to a 1961-1990 baseline (Fig. 1). Non-linear regressions of thermal anomalies versus year (Fig. 1) were produced in R (version 1.0.44), fitting generalized additive models (GAMs) to El Niño, ENSO-neutral and La Niña phases, using 3 splines (smoothing parameters).

To examine the relationship between the amount of global warming and the number of bleaching events per location, we also extracted monthly sea surface temperatures from the HadISST data set, for 1871-2016 (*25*), for a 1-degree latitude by longitude box centred on each of the 100 reef locations. The summer maximum temperature at each location was regressed against year to calculate the total amount of warming since the pre-industrial period. The level of warming at each location was then regressed against the number of severe (and total) bleaching events, separately for the locations in each of the four geographic regions (Fig. 4, Supplementary Tables S2 and S3). The results for severe and total bleaching events were virtually identical. Similarly, omitting high latitude reefs (sixteen locations north or south of 23.5° that have warmed more than average) did not affect the regression results.

Global analysis of coral bleaching, 1980-2016

We gathered information on coral bleaching for 100 well-studied locations, for each year between 1980 and September 2016. Because the number of locations in our analysis is fixed at 100, we avoided the potential bias in open access databases arising from the continuous addition through time of new sites, and of oversampling at well-studied or more accessible locations. Furthermore, the spatial scale of the locations we examined is fixed through time, allowing us to test for scale-dependency in the number of observed bleaching events. To constrain the size of more extensive reef systems, such as continental coastlines and large countries (e.g. Australia, Indonesia), we recorded bleaching at multiple locations (e.g. the northern, central and southern Great Barrier Reef, and separately for four major reef systems along the 3000 km coast of tropical and subtropical Western Australia). The size of each location is recorded in Supplementary Table S1 which presents the raw, binary data on bleaching records necessary to duplicate our results in Figures 2-4.

Each record was assessed using three sources: 349 publications that document bleaching events, our own observations at 70 of the locations, and communications with 43 colleagues who have expert knowledge of the history of specific locations (see sources cited for each location in Supplementary Table S1). The possibility of a type 2 error (a false negative) always exists in any analysis of this sort. Unlike any earlier compilation of bleaching records, we have sought to minimize this possibility by fixing the number of locations and compiling all of the available information for them. By making the Supplemental Table of 700 records available, we hope it will encourage any corrections and facilitate updates of future bleaching. We checked whether Reefbase (reference #258 in Supplemental Table S1) reports any additional bleaching events at our 100 study locations, up to 2010. This source accounts for 6 of our 613 bleaching records, of which 5 were minor. To compare locations, geographic regions and years, we standardized the severity of bleaching for each record into two categories, severe and more moderate, with roughly equal sample sizes. We defined bleaching as severe at each location if >30% of colonies bleached at replicate sites, at a scale of 10 to 100s of kilometres. We also recorded more moderate bleaching, defined as 1-30% of colonies affected at multiple sites. The thirty percent cut-off distinguished 300 severe versus 312 more moderate bleaching records at a global scale across the whole 1980-2016 period. We used the same 30% cut-off in our field studies of recurrent bleaching along the east and west coast of Australia, in the western Pacific and eastern Indian Ocean (*20*). Furthermore, mortality of corals increases steeply when more than 30% of corals are bleached (*11*).

To test for differences in the trajectory of bleaching events among geographic regions, we compared 22 locations in the Indian Ocean (including the Middle East), 32 in Australasia

(Australia, south-east Asia and the Coral Triangle), 24 in the Pacific, and 22 in the Western Atlantic. This classification also facilitated comparison with historical and projected changes in sea surface temperatures among major coral reef regions (*13,14,19*).

To test for scale-dependency in the frequency of bleaching, we plotted the number of bleaching records against the area of coral reefs at each of the 100 locations (*27*), as well as reef areas of regions that were larger, and individual reefs that were smaller in size than the 100 locations (Fig. SI). The larger regions were the Indian Ocean, Australasia, the Pacific, Western Atlantic, and the summed global total. The smaller individual reefs (n = 91) were all <10 sq km in size and located on the northern, central and southern Great Barrier Reef. Each of them bleached 0-3 times in three severe bleaching events from 1980-2016 (*20*). Across the full spectrum of reef areas, the number of severe bleaching records was strongly scale-dependent (Fig. S1, Adjusted R-squared = 0.610, $p < 0.0001$). However, there was no relationship between the number of bleaching events and the size of the 100 locations alone (severe bleaching events, $p = 0.952$; total number of bleaching events, $p = 0.415$)

Statistical analyses

We used a Generalized Linear Mixed Model (GLMM) with a binomial error structure to examine spatial and temporal trends in bleaching, treating the four geographic regions and year (1980-2016) as fixed effects, and location within region as a random effect. The error was modelled as binomial, for two analyses (based on unbleached versus bleached records, or severely bleached versus not severely bleached). For the unbleached versus bleached analysis, we fit the GLMM using maximum likelihood, as implemented by the function glmer() in the R library lme4 (*28*). For the severely bleached vs not severely bleached analysis, the maximum likelihood estimation failed to converge, so we used instead the penalized quasi-likelihood method implemented by the function glmmPQL() in the R library MASS (*29*). Time is measured as the number of years since 1980 (the start of the time series), and is an ordinal value. To facilitate ecological interpretation of the model's coefficients, the model has been parameterized such that the model's intercept, and the main effect of time, are fixed at zero. Thus, the fixed effect of region gives the log-odds of a location within that region bleaching in 1980, and the interaction between time and region gives the annual rate of change in the log-odds of bleaching for that region. A significant interaction between time and region indicates that the log-odds of bleaching changes significantly over time for that region.

To calculate the predicted cumulative number of bleaching events in each of the four geographic regions, we estimated the number of bleached reefs each year by summing the probability of bleaching across all locations within that region. The predicted cumulative number of bleaching events globally was calculated in the same fashion, by summing the predicted number of bleaching events across all regions. To estimate the rate of increase in bleaching risk per annum, we used the equation:

$$B(t) = B(0)e^{rt}$$

where $B(t)$ is the estimated frequency of bleaching events per location in year t, and r is the exponential rate of increase in bleaching frequency. After log-transformation, we have:

$$\ln(B(t)) = \ln\big(B(0)\big) + rt$$

We then used a linear model to fit the log bleaching frequencies (the left-hand side of the formula above) to the number of years since 1980 (i.e., t=0 in 1980).

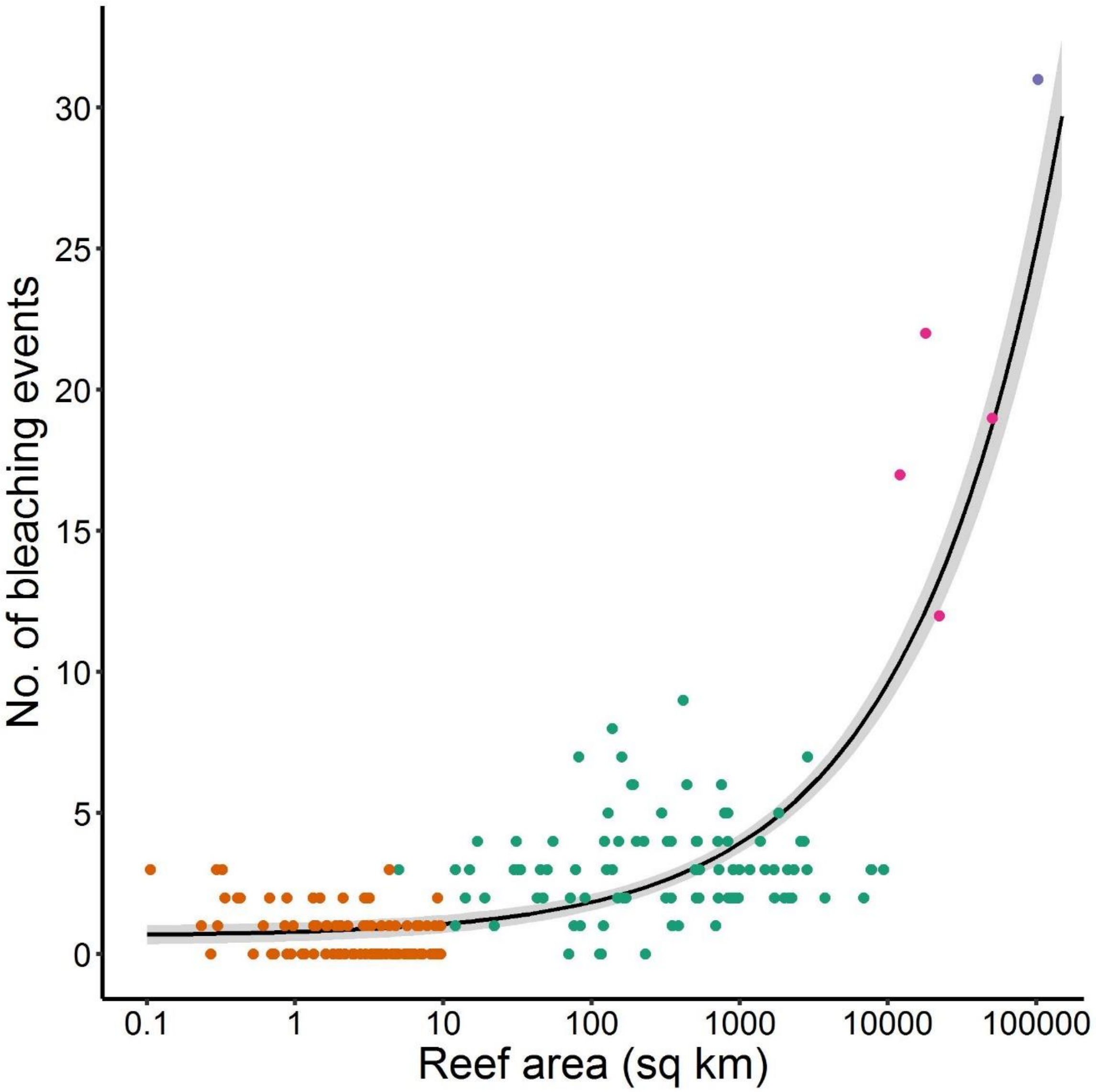

Fig. S1.

A test for scale-dependency in bleaching frequency, across a spectrum of location sizes. The orange symbols represent 91 individual reefs from the Great Barrier Reef, each smaller than 10 sq km in size. The green symbols are the 100 global locations (Fig. 3, Supplementary Table S1), the pink symbols are larger regions (the Indian Ocean, Australasia, the Pacific, and Western Atlantic) and the single purple symbol shows the global total area of coral reefs. The y-axis is the number of recorded severe bleaching events from 1980-2016. A linear regression for the 100 locations was not significant, either for severe or total number of bleaching events.

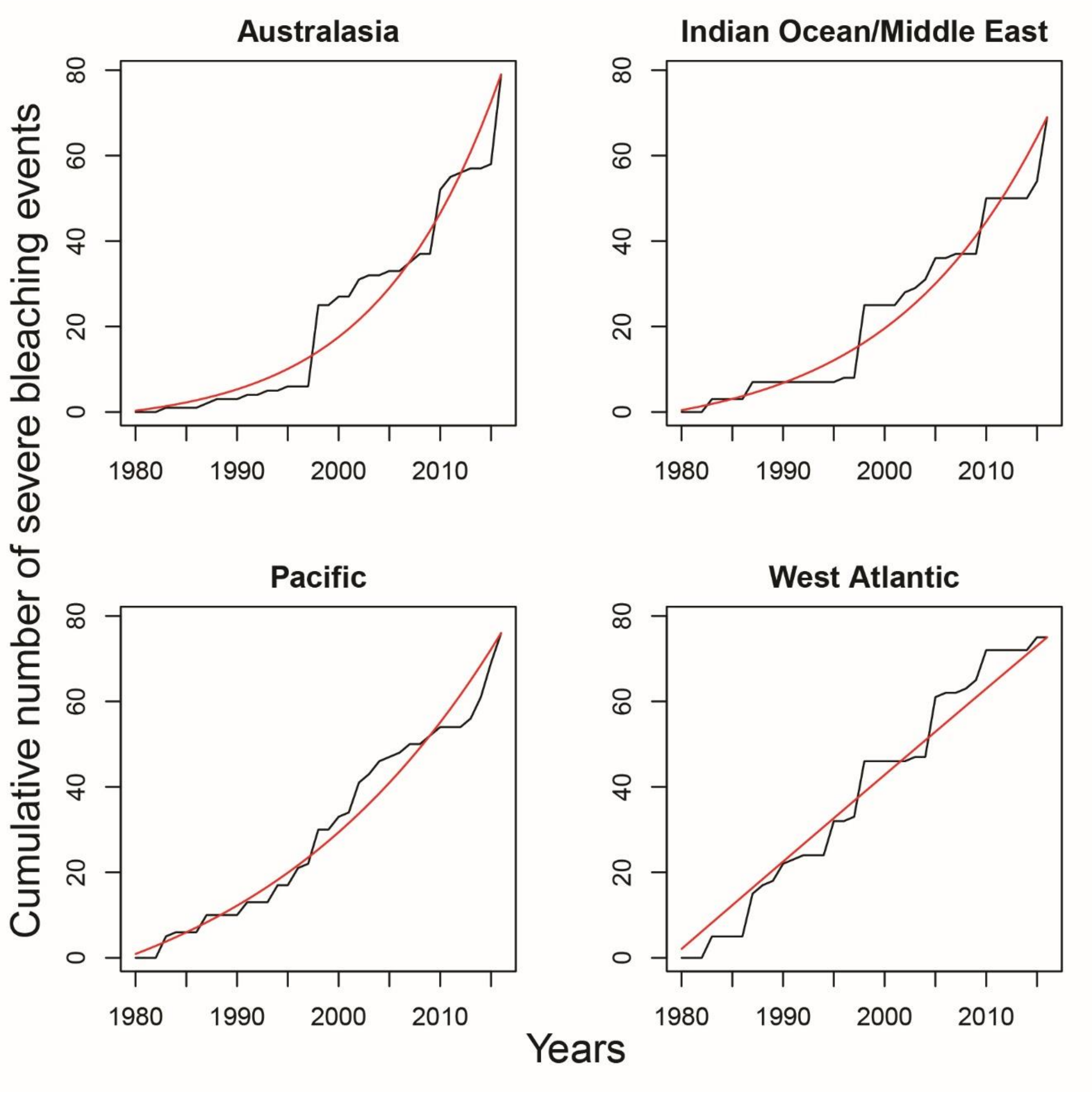
Australasia
Indian Ocean/Middle East
Pacific
West Atlantic
Cumulative number of severe bleaching events
Years
0
20
40
60
80
1980
1990
2000
2010

Fig. S2A

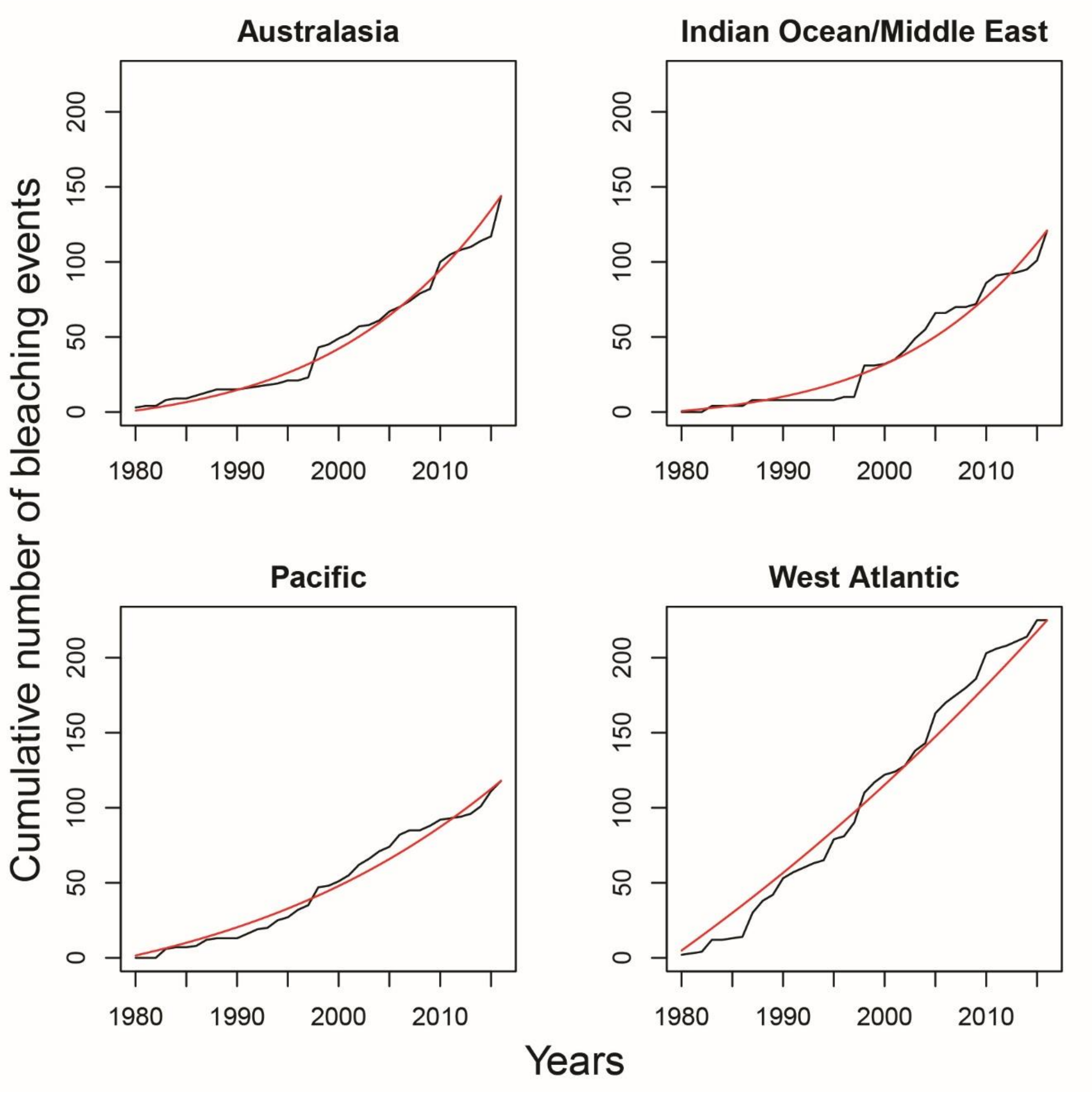

Fig. S2B

Global patterns of coral bleaching. The cumulative number of (A) severe and (B) total bleaching events for four geographic regions (Indian Ocean, Australasia, Pacific Ocean, and Western Atlantic). Each trajectory in black shows the total number of recorded events per region (n = 22-32 locations) and the fitted regression in red, calculated from the GLMM fits. See Fig. 2B for the global trajectory of severe and total bleaching events.

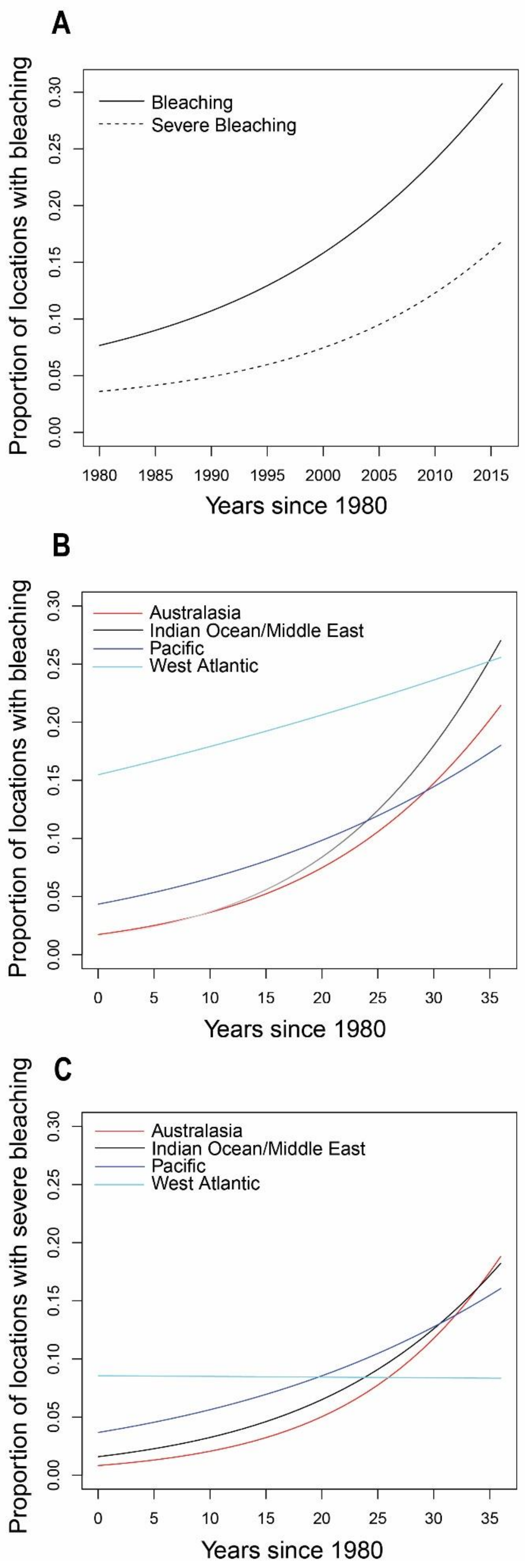
A
Proportion of locations with bleaching
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Bleaching
Severe Bleaching
1980
1985
1990
1995
2000
2005
2010
2015
Years since 1980
B
Proportion of locations with bleaching
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Australasia
Indian Ocean/Middle East
Pacific
West Atlantic
0
5
10
15
20
25
30
35
Years since 1980
C
Proportion of locations with severe bleaching
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Australasia
Indian Ocean/Middle East
Pacific
West Atlantic
0
5
10
15
20
25
30
35
Years since 1980

Fig. S3

Escalating frequency of bleaching. Proportion of locations that experienced bleaching each year since 1980. (A) total bleached and severely bleached for all locations, (B) bleached by region, and (C) severely bleached by region.

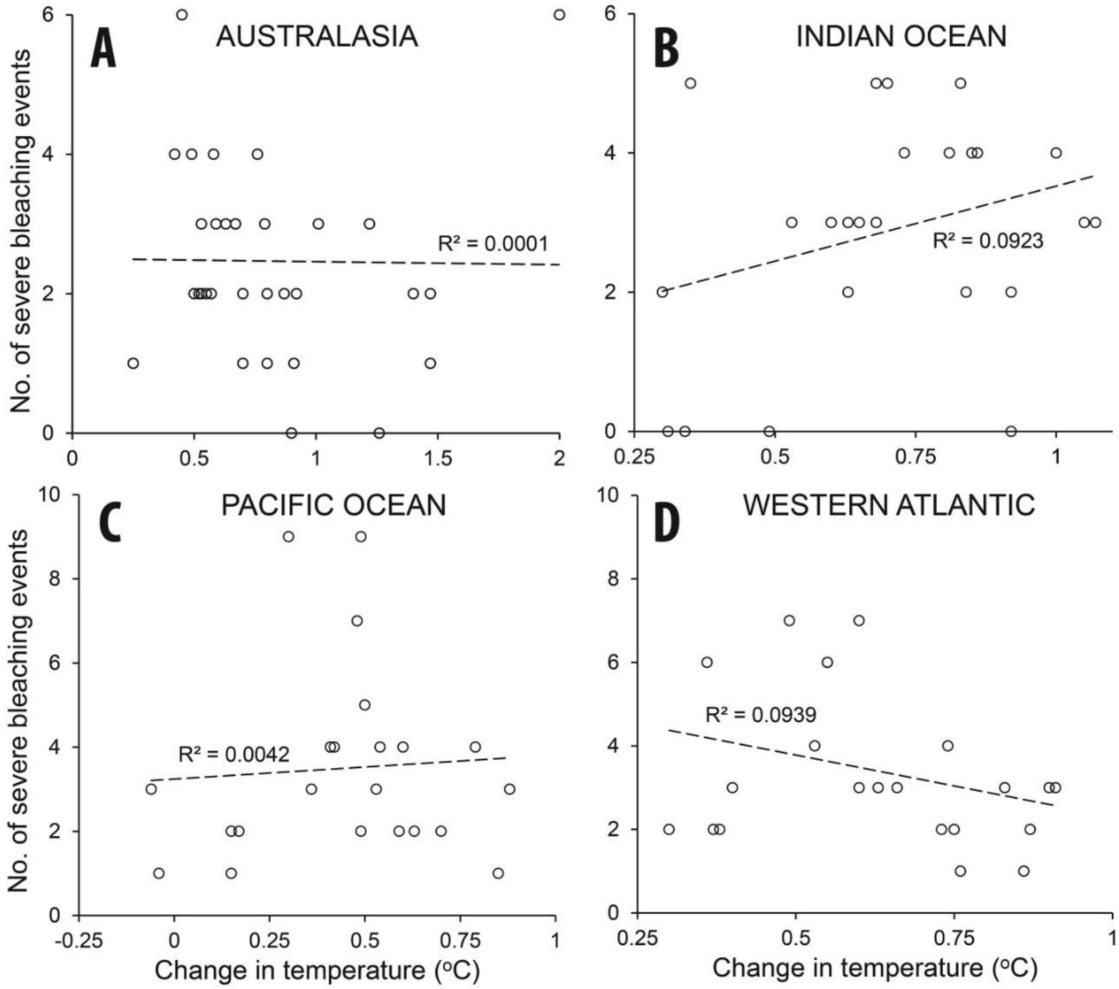

Fig. S4

Frequency of bleaching versus global warming. The relationship between the amount of global warming recorded since the pre-industrial period at each of 100 locations versus the number of observed bleaching events per location. Australasia (32 locations), the Indian Ocean (24 locations), the Pacific Ocean (22 locations), and the Western Atlantic (22 locations).

Table S1

Global bleaching database 1980 – 2016. Coral bleaching history from 1980 – 2016 at 100 fixed global locations. Latitude and longitude refer to centroids of locations. Bleaching events are recorded as either minor-moderate (M; 1-30% bleached) or severe (S; >30% bleached).

#	Location	Lat	Long	Size (km^2)	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	References (and Pers. Comm.)
Australasia																																										
1	Australia, Coral Sea Northern	16.5ºS	149.8ºE	1165																			S				S		M												S	334, 236, 237, 216, 19, 58, 280, 156, (JR), TB, HH
2	Australia, Coral Sea Southern	20.0ºS	153.0ºE	231																																					M	236, 58, 248, 156, TB, HH, MP, AH, AB
3	Australia, GBR Central	19.5ºS	148.5ºE	7735	M			M				M					M		M				S				S														S	63, 232, 173, 151, 36, 205, 35, 216, 156, AB, MP, MH, GT
4	Australia, GBR Northern	11.5ºS	145.3ºE	9319	M			M															S				S														S	63, 141, 35, 216, 156, AH, MP, AB, TH, GT
5	Australia, GBR Southern	23.5ºS	150.1ºE	6872																			S				S				M										M	369, 63, 35, 216, 156, MH, TH, JK, KA, TB, MP
6	Australia, Kimberly Coast	21.5ºS	115.4ºE	688																																					S	221, 281, 238, 156, (DW), (AL), (DB), (DW), (JF), (CP), (JB), (AH), (AM), (DO), VS
7	Australia, Lord Howe Island	31.5ºS	159ºE	12																										M					S	M	M		M			142, 84, 85, 156, AB, AH, MP, TH
8	Australia, Morton Bay	27.4ºS	153.5ºE	-																												M			M		M	M			M	156, (IB), (MB), JP
9	Australia, Ningaloo Reef	22.5ºS	113.7ºE	120																																S					M	58, 221, 87, 156, (DT), (GS), (PB), (TE), (RB), SW, RL
10	Australia, Pilbara (Dampier, Montebello, Onslow)	19.5ºS	119.9ºE	316																																S		S	M			221, 189, 260, 156, (DT), (MM), (RM), (RE), (RB), SW
11	Australia, Solitary Island	30.0ºS	153.3ºE	-																			S			M	M			M	M	M								M	S	339, 97, 58, 84, 76, 156, (MB), (WF), (SD), (HM), AB, JP
12	Australia, South West Rocks	30.5ºS	153.1ºE	2																										M											S	156, (WF), (SD), (HM), (MB)
13	Australia, Southwest (Shark Bay, Abrohlos, Rottnest)	29.0ºS	114.0ºE	385																																S						313, 221, 1, 291, 156, (TF), SW, RL
14	Australia, Torres Strait	9.0ºS	142.0ºE	3735																															S						S	28, 317, 156, (TS), AB, TH, JK
15	Indonesia, Aceh	4.8ºN	98.9ºE	344																															S						S	322, 133, 158, 157, AB
16	Indonesia, Bali/Lombok	8.5ºS	115.4ºE	152														S					S											M	S						S	305, 154, 61, 322, 158, 313, 157, 174, 164, AB
17	Indonesia, Central Sulawesi	0.5ºS	122.3ºE	170																			S												S						M	154, 61, 322, 157
18	Indonesia, Java	6.4ºS	108.9ºE	343				S															S												S						S	339, 44, 305, 61, 322, 158, 157
19	Indonesia, Kalimantan	2.9ºS	110.6ºE	14																			S												M						S	313, 157, 246

	Location	Lat	Long	Size (km^2)	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	References (and Pers. Comm.)
20	Indonesia, North Sulawesi/Manado	1.5ºN	124.8ºE	325																			S		S										S						S	154, 61, 322, 190, 157, TH, DB
21	Indonesia, South Sulawesi	5.6ºS	120.0ºE	90																															S						S	339, 322, 157, 138, 145
22	Indonesia, South-East Sulawesi/Wakatobi	5.7ºS	123.5ºE	715																			M												S						S	158, 157, 174
23	Indonesia, West/South Sumatra	1.8ºS	100.8ºE	899																			S												S						S	61, 322, 158, 157, 174, 200, 225
24	Japan, Kyushu	32.5ºN	130.5ºE	43																			S										M		S							179, 327, 180, 178, (JR)
25	Japan, Ryukyu Islands	26.5ºN	128.0ºE	993	M			M	M		M		M										S			M			M	M	M	S	M	M	M						S	175, 319, 339, 197, 278, 327, 178, 82, 153, 258, 346, 316, 156, AB
26	Malacca Strait	1.4ºN	103.1ºE	230																			S												S						S	305, 60, 62, 133, 157, AB
27	Papua New Guinea, Kimbe Bay	5.0ºS	151.0ºE	72																		M	S	M	M	M			M				S									339, 170, 41, 57, (MB), (GJ), TH, AB
28	Philippines, Central/Southern	9.4ºN	120.0ºE	7690		M														M		M	S	M	M					M			M		S				M	M	S	59, 21, 8, 322, 99, 258, 312, 252
29	Solomon Islands	9.7ºS	160.6ºE	2835																					S											M	S			S	M	195, 9, 57, 94, 256, 258, TH, AB
30	Taiwan, Southern	23.7ºN	121.0ºE	191							M	S	S										S									S	S	M					M		S	339, 297, 179, 180, 83, 188, 310, 64, 56
31	Thailand, Gulf of Thailand	10.0 ºN	99.8ºE	186												S				S			S					S							S						S	43, 340, 322, 313, 241, 347, 307, 219, 311
32	Vietnam, Con Dao Archipelago	14.3ºN	109.3ºE	17																			S							S					S						S	320, 129, 61, 124, 296, 321, 86
	Indian Ocean/ Middle East																																									
33	Australia, Ashmore Reef	12.3ºS	123.0ºE	70																			M					M							M						M	216, 149, 54, 156, JG
34	Australia, Christmas Island	10.5ºS	105.6ºE	5				S															S							M						M					S	37, 130, 301, 156, J-PH
35	Australia, Cocos Island	12.2ºS	96.8ºE	518																	M		M																M		M	216, 25, 156, (SE), (DM), J-PH
36	Australia, Rowley Shoals	17.4ºS	119.2ºE	113																										M											M	308, 156, (LS), (AH), JG
37	Australia, Scott Reef & Seringapatam Reef	14.0ºS	121.5ºE	150																			S													M		M			S	340, 292, 111, 156, JG
38	Chagos Archipelago (UK)	6.0ºS	72.ºE	1822																			S					S	S	M										S	S	288, 286, 255, 309, 17, 94
39	Comoros	11.5ºS	43.3ºE	518				S															S												S						S	7, 251, 73, 245, 74
40	Egypt, Red Sea, Hurghada	27.3ºN	33.8ºE	2240																									S	S		M										182, 218, 183, (MK), MB
41	India, Lakshadweep	8.3ºN	73.1ºE	827																			S				S					S			S						S	340, 23, 24, 255, 309, 231, 333, 187, 16, 219, 222

#	Location	Lat	Long	Size (km^2)	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	References (and Pers. Comm.)
42	Kenya	3.5ºS	40.0ºE	510								S											S					M		S		M			S						M	339, 230, 124, 208, 223, 73, 207, 74
43	La Reunion (France)	21.1ºS	55.5ºE	12				M				S											S			M			M	M				M		M					S	339, 340, 67, 324, 68, 7, 208, 284, 346, (PC), (LB)
44	Madagascar, Southwest	20.5ºS	46.5ºE	1374																			S			M	M	M		S					S						S	340, 124, 231, 73, 74
45	Maldives	1.9ºN	73.5ºE	2714								S											S					M	M			M			S					M	S	90, 340, 129, 255, 124, 283, 317, 42, 228, 335, 94, 346, (CP), MP
46	Mauritius (France)	20.3ºS	57.6ºE	720																			M				M	M	M	S				M	S						S	340, 322, 7, 209, 206, 38, 94
47	Mayotte (France)	12.5ºS	45.5ºE	296				S				S											S												S	M					S	339, 251, 6, 245, 207, 74, 75
48	Mozambique	21.9ºS	35.6ºE	2103																			S							S											S	230, 231, 285, 73, 74
49	Saudi Arabia, Red Sea, Al Lith	19.8ºN	39.9ºE	975																															S					S		88, 182, 106, 198, MB
50	Saudi Arabia, Red Sea, Thuwal	22.3ºN	39.1ºE	1705																			S												S					S		88, 182, 106, 198, 94, MB
51	Seychelles	4.7ºS	55.5ºE	1482																			S				M	M							S						S	340, 298, 7, 192, 132, 131, 242, (CM-P), (UE), NG
52	Seychelles, Aldabra	9.5ºS	46.3ºE	78																			S												S						S	7, 90, 287, 302, (KC-S), NG
53	South Africa, St Lucia	28.4ºS	32.4ºE	2																			M		M	M				M												73, 55, 262, 101, 282, 285, 74
54	Sri Lanka	7.3ºN	80ºS	122																			S				S		M	M					S					M	S	163, 254, 255, 124, 72, 93, 92, (NP), (CM)
55	Tanzania	7.9ºS	39.5ºE	2126																			S					M													S	230, 124, 73, 207, 74
56	United Arab Emirates, Arabian Gulf	24.5ºN	54.4ºE	129																	S		S				S								S	M	M		M	S	M	110, 261, 262, 259, 199, 263, 66, 289, (JB), MB
Pacific																																										
57	American Samoa	14.3ºS	170.7ºW	45															S				M			M	S	M	M	M	M									S		128, 129, 2, 80, 123, 39, 57, 346, (DB), TH
58	Colombia (Pacific)	5.1ºN	77.4ºW	19				S															S																	M		117, 115, 339, 328, 243, (FZ)
59	Commonwealth of the Northern Mariana Islands	15.2ºN	145.8ºE	82															M	M		M	S			M		S			M				S			S	S	S	S	2, 123, 57, 194, 94, 70
60	Cook Island	21.3º	159.8ºW	255												S			S				M		S						M			M							S	128, 81, 152, 57, 273, 98
61	Costa Rica (Pacific)	8.7ºN	83.9ºW	55				S				S				S	M						S																			135, 115, 134, 108, 161, 162, (JC)
62	Ecuador (mainland)	0.5ºN	80.4ºW	-																			S																			116, 243, (FR)
63	Fiji, Southeast & Southwest	17.7ºS	178.ºE	2325																					S		S				M										S	306, 81, 152, 195, 196, 57, 346, 94

#	Location	Lat	Long	Size (km^2)	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	References (and Pers. Comm.)
64	French Polynesia, Society Islands	17.7ºS	149.4ºW	416					S			S				S			S			M	M			M	S	S				S		S							S	63, 339, 275, 128, 113, 276, 129, 124, 331, 240, 4, 57, 249, 318, 94, TH, MP
65	Galapagos	0.5ºS	90.8ºW	126				S				S											S																			115, 63, 116, 201, 203, 118, (FR)
66	Guam	13.4ºN	144.5ºE	138															S		S										S	S			M	M	M	S	S	S	S	239, 2, 247, 48, 57, 194, 94, 70, 144
67	Hawaii (main islands)	19.5ºN	155.5ºW	788							M	S	M								S								S						M				S	S		169, 104, 168, 103, 57, 304, 194, 346, 94, 26, 264
68	Hawaii (North West Islands)	25.5ºN	171.4ºW	2567																							S		S		M								S	S		5, 104, 105, 168, 177, 194, 94
69	Johnston Atoll (USA)	16.3ºN	169.5ºE	76																	S																					65, 168, (BV-A)
70	Kiribati, Gilbert Islands	1.5ºS	176.5ºE	1718																									S					S								89, 51, (SD)
71	Kiribati, Kiritimati (Christmas Island)	1.9ºN	157.5ºE	164																		S																		S		129, 276, 94, JB, DC
72	New Caledonia, Southwest	21.5ºS	165.6ºE	833				M													S		M																		S	339, 337, 57, 120, 50, 346, 94
73	Palau	7.5ºN	134.5ºE	510																	M		S	M											S							40, 46, 2, 122, 123, 121, 57, 326, (YG)
74	Panama (Gulf of Chiriqui)	8.1ºN	82.0ºW	50				S															S																	S		115, 116, 337, 243, 213, 94, 211
75	Panama (Gulf of Panama)	8.5ºN	79.1ºE	84				S									M			M																						115, 116, 243, 211
76	Republic of the Marshall Islands	11.5ºN	166.8ºE	2005													M	M									S	M	M	M	M								S	M		239, 2, 32, 57, 215, 94, 147
77	Samoa (Western)	13.6ºS	172.4ºW	201																			S		S		S													S		339, 2, 94
78	Vanuatu	15.2ºS	167.2ºE	711																						S	S			S	M	M									S	256, 57, 257, 127
	West Atlantic																																									
79	Bahamas	24.5ºN	77.8ºW	2236				M				S			M	M	M	M	M	M			S							M		M			M					M		339, 191, 20, 333, 212, 202, 341, 95, 45, 159, 229
80	Barbados	13.2ºN	59.5ºW	31								S											S							S	M				S				M			233, 234, 95, 159, 226, 235, (NH)
81	Belize	17.5ºN	88.1ºW	877																S	M	M	S	M	M			M		M		M	M		M					M		113, 303, 224, 210, 186, 22, 49, 341, 52, 95, 172, 159, 33, 185
82	Bermuda	32.2ºN	64.7ºW	530				M					S		M	S	M			M		M	M		M			M		M								M		M		69, 339, 220, 113, 339, 343, 171, 341, 95, 293, 345, 34, 159, 167
83	Bonaire	12.2ºN	68.3ºW	22								M								S			M							M					M					M		339, 341, 299, 45, 159, 229

#	Location	Lat	Long	Size (km^2)	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	References (and Pers. Comm.)
84	British Virgin Islands	18.4ºN	64.6ºW	138								S											S							S												181, 339, 155, 341, 95, 159
85	Cayman Islands	19.3ºN	81.3ºW	188								S	M							S			S	M	M		M	M	M	S		M		S	M					S		146, 339, 340, 129, 343, 62, 341, 95, 325, 45, 323, 159, 229
86	Columbia (Caribbean)	9.6ºN	75.9ºW	922				S				M	M		M					M		M	M	M				M	M	S				M	M					M		114, 348, 339, 294, 295, 339, 108, 328, 268, 269, 95, 329, 31, 159, (VP)
87	Costa Rica (Caribbean)	10.2ºN	83.1ºW	15				S									S			S			M												M							78, 114, 108, 160, 77, 159, (AR S)
88	Cuba	22.ºN	78.8ºW	2854				S						M	M			M	M	S		M	S			M				S				S	S	M	M	M	M	S		343, 10, 341, 95, 12, 13, 159, 11, 14
89	Curacao	12.2ºN	69.0ºW	47								S			S						M		M												M							214, 339, 27, 341, 330, 159, (MJAV)
90	Dominican Republic	18.9ºN	69.6ºW	518								S			M													M	M	S	S			M	M					M		339, 340, 341, 95, 159, 229
91	Florida Keys	24.8ºN	80.9ºW	750	M			S		M		S		M	S							S	S	M	M			M	M	M	M	M				M			M	S		100, 53, 143, 91, 279, 202, 341, 95, 333, 159, 204, 29, 229, 112, 339
92	Gulf of Mexico (Texas Flower Gardens)	27.9ºN	93.8ºW	3								M		M	M	M						M	M				M	M		S	M		S		M							339, 137, 53, 18, 150, 341, 95, 166, 159, 165
93	Honduras	16.1ºN	86.8ºW	831								S								S		M	S							S				M	M							136, 339, 184, 184, 139, 124, 274, 52, 102, 159, 185, 265
94	Jamaica	18.0ºN	77.3ºW	439							M	S	M	S	S	M				M			S	M	M			M		S			M		S							125, 109, 126, 113, 343, 171, 341, 95, 79, 159, TH
95	Mexico (Yucatan)	19.8ºN	87.4ºW	532									M							S		M	S					M	M	S	M	M	M	M		M						339, 184, 300, 341, 95, 159, 148, 176, 185 (AR-S)
96	Panama (Caribbean)	9.3ºN	82.0ºW	501				S					S							M		M					M			S										M		114, 339, 108, 95, 159, 227, 193, 213
97	Puerto Rico	18.3ºN	66.5ºW	159	M	M	M	M				S	M		S					S			S	M		M		S		S					S					M		339, 119, 191, 342, 53, 107, 341, 95, 45, 159, 229
98	St Croix & US Virgin Islands	17.7ºN	64.8ºW	33								M	M		M			M					S	M						S	M				S							339, 181, 250, 53, 270, 18, 202, 341, 217, 271, 95, 272, 96, 159
99	Tobago	11.2ºN	60.7ºW	32								M											S				M			S			M		S		M	M				339, 290, 140, 201, 95, 159, 15, 47
100	Venezuela	11.2ºN	66.9ºW	349								M								M			M							M	M				S							191, 267, 266, 30, 159

Personal Communications List: Aldabra: KC-S=K. Chong-Seng; Arabian Gulf: JB=J. Burt; Barbados: NH=N. Hassell; Cocos Island: SE= S. Evans, DM= D. McKinney; Columbia Pacific: FZ= F. Zapata; Columbia Caribbean: VP=V. Pizarro, Coral Sea North: JR= J. Rumney; Costa Rica (Caribbean): AR-S= A. Rivera-Sosa; Costa Rica Pacific: JC= J. Cortés; Curacao: MJAV=M.J.A Vermeij; Ecuador (Mainland) and Galapagos: FR=F. Rivera; Gilbert Islands: SD=Simon Donner; Japan Northern: JR= J. Reimer; Johnston Atoll: BV-A=B. Vargas-Angel; Kimberly Coast WA: DW=D. Williams, AL=A. Lewis, DB=D. Barrow, DW=D. Woods, JF=J. French, CP=C. Piggot, JB=J Brown, AH=A. Halford, AM=A. McCarthy, DO=D. Oades; La Reunion: PC=P. Chabanet , LB=L. Bigot; Ningaloo: DT=D. Thomson, GS=G. Shedrawi, PB=P. Barnes, TE=T. Edgecombe; Palau: PICRC= Palau International Coral Reef Centre; Papua New Guinea: MB= M. Bonin, GJ=G. Jones; Pilbara: DT= D. Thomson, MM=M. Morhing, RM=R. Marshall, RE=R. Evans; Red Sea (Hurghada Egypt):MK=M. Khalil; Rowley Shoals, WA: LS= L. Smith, AH=A. Halford; Seychelles: CM-P= C. Mason-Parker, UE= U. Engelhardt; Sri Lanka: NP= N. Perera, CM=C. Manfrino; SW Western Australia: TF=T. Foster

Bibliography for Supplementary Table 1

1) Abdo, D. A., Bellchambers, L. M. & Evans, S. N. Turning up the heat: Increasing temperature and coral bleaching at the high latitude coral reefs of the Houtman Abrolhos Islands. *Plos One* **7**, e43878 (2012).
2) Abraham, T. *et al.* in *Status of coral reefs of the world: 2004* (Wilkinson, C. ed.) 381-409 (Australian Institute of Marine Science, 2004).
3) Adjeroud, M. *et al.* Detecting the effects of natural disturbances on coral assemblages in French Polynesia: A decade survey at multiple scales. *Aquatic Living Resources* **18**, 111-123 (2005).
4) Adjeroud, M. *et al.* Recurrent disturbances, recovery trajectories, and resilience of coral assemblages on a South Central Pacific reef. *Coral Reefs* **28**, 775-780 (2009).
5) Aeby, G. S., Kenyon, J. C., Maragos, J. E. & Potts, D. C. First record of mass coral bleaching in the Northwestern Hawaiian Islands. *Coral Reefs* **22**, 256-256 (2003).
6) Afrol News. Coral deaths reach Mayotte, Comoros, http://www.afrol.com/articles/36792 (2010).
7) Ahamada, S. *et al.* in *Status of Coral Reefs of the World: 2004* Vol. 1 (Wilkinson, C.ed.) 189-211 (Australian Institute of Marine Science, 2004).
8) Alave, K. L. Philippines scientists note massive bleaching of coral reefs. http://www.pressreader.com/philippines/philippine-daily-inquirer/20100906/textview (2010).
9) Albert, S. *et al.* Building social and ecological resilience to climate change in Roviana, Solomon Islands. (The University of Queensland, Brisbane, 2010).
10) Alcolado, P. *et al.* in *Latin American Coral Reefs* (Cortes, J. ed.) 53-75 (Elsevier Science, 2003).
11) Alcolado, P. M. Reporte de blanqueamiento de corales del año 2014 en Cuba. (Instituto de Oceanologia, 2015).
12) Alcolado, P. M. & Castellanos, S. Reporte de blanqueamiento de corales del año 2010 en Cuba. (Instituto de Oceanologia, 2011).
13) Alcolado, P. M. & Iglesias, S. C. Reporte de blanqueamiento de corales del año 2011 en Cuba. (Instituto de Oceanologia, 2012).
14) Alcolado, P. M. & Rey-Villiers, N. Reporte de blanqueamiento de corales del año 2015 en Cuba. (Instituto de Oceanologia, 2016).
15) Alemu I, J. B. & Clement, Y. Mass Coral Bleaching in 2010 in the Southern Caribbean. *PLoS ONE* **9**, e83829 (2014).
16) Ali, M. H., Jasper, B. & Vivekanandan, E. in *Climate Change and Island and Coastal Vulnerability* (eds J. Sundaresan *et al.*) 239-249 (Springer Netherlands, 2013).
17) Amos, J. Bleaching 'devastates' Chagos Marine Reserve. http://www.bbc.com/news/science-environment-36473928 (2016).
18) Andrews, K. *et al.* in *Status of Coral Reefs of the World: 2004* (Wilkinson, C. ed.) 431-450 (Australian Institute of Marine Science, 2004).
19) Andrews, Z., Clement, A.-l. & Hill, J. Reef Check Australia–GBR Project Report. (Reef Check Australia, 2007).
20) Anthony, S. L. *Scleractinian coral mortality and color change on central Bahamian reefs: 1991-1995*, University of Texas, (1997).
21) Arceo, H. O., Quibilan, M. C., Aliño, P. M., Lim, G. & Licuanan, W. Y. Coral bleaching in Philippine reefs: Coincident evidences with mesoscale thermal anomalies. *Bulletin of Marine Science* **69**, 579-593 (2001).
22) Aronson, R., Precht, W., Toscano, M. & Koltes, K. The 1998 bleaching event and its aftermath on a coral reef in Belize. *Marine Biology* **141**, 435-447 (2002).
23) Arthur, R., Done, T. J. & Marsh, H. Benthic recovery four years after an El Nino-induced coral mass mortality in the Lakshadweep atolls. *Current Science* **89**, 694-699 (2005).
24) Arthur, R., Done, T. J., Marsh, H. & Harriott, V. Local processes strongly influence post-bleaching benthic recovery in the Lakshadweep Islands. *Coral Reefs* **25**, 427-440 (2006).
25) Australian Government. *Pulu Keeling National Park: Managament Plan 2015-2025* (Director of National Parks, Canberra, 2015).
26) Bahr, K. D., Jokiel, P. L. & Rodgers, K. S. The 2014 coral bleaching and freshwater flood events in Kāne‘ohe Bay, Hawai‘i. *PeerJ* **3**, e1136 (2015).
27) Bak, R. P. M., Nieuwland, G. & Meesters, E. H. Coral reef crisis in deep and shallow reefs: 30 years of constancy and change in reefs of Curacao and Bonaire. *Coral Reefs* **24**, 475-479 (2005).
28) Bainbridge, S. & Berkelmans, R. The use of climatologies and Bayesian models to link observations to outcomes; an example from the Torres Strait. *Environmental Science-Processes & Impacts* **16**, 1041-1049 (2014).
29) Barnes, B. B. *et al.* Prediction of coral bleaching in the Florida Keys using remotely sensed data. *Coral Reefs* **34**, 491-503, (2015).
30) Bastidas, C. *et al.* Massive hard coral loss after a severe bleaching event in 2010 at Los Rogues, Venezuela. *Revista De Biologia Tropical* **60**, 29-37 (2012).
31) Bayraktarov, E., Pizarro, V., Eidens, C., Wilke, T. & Wild, C. Bleaching susceptibility and recovery of Colombian Caribbean corals in response to water current exposure and seasonal upwelling. *PLoS ONE* **8**, e80536 (2013).
32) Beger, M. *et al.* in *The state of coral reef ecosystems of the United States and Pacific freely associated states* (Waddell, J. E. & Clarke, A. M. eds.) 387-417 (NOAA Technical Memorandum NOS NCCOS 73, NOAA/NCCOS Center for Coastal Monitoring and Assessment’s Biogeography Team, 2008).
33) Belize Audubon Society. *2015 Annual Report*. (Belize Audubon Society, Belize City, Belize, 2015).
34) Bell, J. Fire coral bleached by warm water. http://www.royalgazette.com/article/20130827/NEWS/130829740 (2013).
35) Berkelmans, R., De'ath, G., Kininmonth, S. & Skirving, W. J. A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns, and predictions. *Coral Reefs* **23**, 74-83 (2004).

36) Berkelmans, R. & Oliver, J. K. Large-scale bleaching of corals on the Great Barrier Reef. *Coral Reefs* **18**, 55-60 (1999).

37) Berry, P. in *Survey of the marine fauna of Christmas Island, Indian Ocean.* Vol. 59 (Berry, P. F. & Wells, F. E. eds.) 75-78 (Records of the Western Australian Museum Supplement, 2000).

38) Bhagooli, R. & Taleb-Hossenkhan, N. Thermal spatial heterogeneity and coral bleaching: implications for habitat refuges. *Proc. 12th Intl. Coral Reef Symp. Cairns, Australia*, 9-13 (2012).

39) Birkeland, C. *et al.* in *Coral Reefs of the USA* (Riegl, B. M. & Dodge, R. E. eds.) 741-765 (Springer Netherlands, 2008).

40) Birkeland, C. E. *et al.* in *Status of coral reefs of the world: 2000* (Wilkinson, C. ed.) 199-217 (Australian Institute of Marine Science, 2000).

41) Bonin, M. C., Munday, P. L., McCormick, M. I., Srinivasan, M. & Jones, G. P. Coral-dwelling fishes resistant to bleaching but not to mortality of host corals. *Marine Ecology Progress Series* **394**, 215-222 (2009).

42) Bowermaster, J. Warming seas continue to plague coral reefs in Maldives. National Geographic, voices.nationalgeographic.com/2011/10/24/coral-reefs-in-maldives-hit-by-second-bleaching-event/ (2011).

43) Brown, B. E., Dunne, R. P. & Chansang, H. Coral bleaching relative to elevated seawater temperature in the Andaman Sea (Indian Ocean) over the last 50 years. *Coral Reefs* **15**, 151-152 (1996).

44) Brown, B. E. & Suharsono. Damage and recovery of coral reefs affected by El Niño related seawater warming in the Thousand Islands, Indonesia. *Coral Reefs* **8**, 163-170 (1990).

45) Bruckner, A. Factors contributing to the regional decline of *Montastraea annularis* (complex). *Proc. 12th Int. Coral Reef Symp., Cairns, Australia*, 1-5 (2012).

46) Bruno, J. F., Siddon, C. E., Witman, J. D., Colin, P. L. & Toscano, M. A. El Nino related coral bleaching in Palau, Western Caroline Islands. *Coral Reefs* **20**, 127-136 (2001).

47) Buglass, S. *A study on the recovery of Tobago's coral reefs following the 2010 mass bleaching event.* (The University of British Columbia, Vancouver, 2014).

48) Burdick, D. *et al.* in *The state of coral reef ecosystems of the United States and Pacific freely associated states* (Waddell, J. E. & Clark, A. eds.) 465-509 (NOAA Technical Memorandum NOS NCCOS 73, NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team, 2008).

49) Burke, C. D. *et al.* Coral mortality, recovery and reef degradation at Mexico Rocks Patch Reef Complex, Northern Belize, Central America: 1995–1997. *Hydrobiologia* **530**, 481-487 (2004).

50) Carassou, L., Leopold, M., Guillemot, N., Wantiez, L. & Kulbicki, M. Does herbivorous fish protection really improve coral reef resilience? A case study from New Caledonia (South Pacific). *PLoS ONE* **8**, e60564 (2013).

51) Carilli, J., Donner, S. D. & Hartmann, A. C. Historical temperature variability affects coral response to heat stress. *Plos One* **7**, (2012).

52) Carilli, J. E., Norris, R. D., Black, B., Walsh, S. M. & McField, M. Century-scale records of coral growth rates indicate that local stressors reduce coral thermal tolerance threshold. *Global Change Biology* **16**, 1247-1257 (2010).

53) Causey, B. *et al.* in *Status of Coral Reefs of the World: 2000* (Wilkinson, C. ed.) 239-259 (Australian Institute of Marine Science, 2000).

54) Ceccarelli, D. M., Richards, Z. T., Pratchett, M. S. & Cvitanovic, C. Rapid increase in coral cover on an isolated coral reef, the Ashmore Reef National Nature Reserve, north-western Australia. *Marine and Freshwater Research* **62**, 1214-1220 (2011).

55) Celliers, L. & Schleyer, M. H. Coral bleaching on high-latitude marginal reefs at Sodwana Bay, South Africa. *Marine Pollution Bulletin* **44**, 1380-1387 (2002).

56) Chih-hsuan, K. & Chen, C. Kenting National Park sees worst coral bleaching in 17 years. http://focustaiwan.tw/news/asoc/201607280005.aspx (2016).

57) Chin, A. *et al. Status of coral reefs of the Pacific and outlook: 2011.* 1-260 (Global Coral Reef Monitoring Network, 2011).

58) Chin, A. *et al.* in *Status of Coral Reefs of the World: 2008* (Wilkinson, C. ed.) 159-176 (Australian Institute of Marine Science, 2008).

59) Chou, L. M. in *Status of Coral Reefs of the World*: 2000 (Wilkinson, C. ed.) 117-129 (Australian Institute of Marine Science, 2000).

60) Chou, L. M. *Country Report: Singapore*. Report of the International Coral Reef Initiative (2001).

61) Chou, L. M., Tuan, V., Yeemin, T. & Cabanban, A. in *Status of coral reefs of the World: 2002.* (Wilkinson, C. ed.) 123-152 (GCRMN Report, Australian Institute of Marine Science, 2002).

62) Coelho, V. R. & Manfrino, C. Coral community decline at a remote Caribbean island: marine no-take reserves are not enough. *Aquatic Conservation: Marine and Freshwater Ecosystems* **17**, 666-685 (2007).

63) Coffroth, M. A., Lasker, H. R. & Oliver, J. K. in *Elsevier Oceanography Series* Vol. Volume 52 (Glynn, P. W., ed.) 141-182 (Elsevier, 1990).

64) Cohen, A. Expedition to Dongsha Atoll. http://dongsha2014.blogspot.com.au/p/bleaching-gallery.html (2014).

65) Cohen, A. L., Lobel, P. S. & Tomasky, G. L. Coral bleaching on Johnston Atoll, Central Pacific Ocean. *The Biological Bulletin* **193**, 276 (1997).

66) Coles, S. L. & Riegl, B. M. Thermal tolerances of reef corals in the Gulf: A review of the potential for increasing coral survival and adaptation to climate change through assisted translocation. *Marine pollution bulletin* **72**, 323-332 (2013).

67) Conand, C., Lame 2, M., Quod, I.-P., Conand, F. & Turquet, J. Bleaching in a Western Indian Ocean island, La Reunion: a multiscale approach. *Proceedings of the 9th International Coral Reef Symposium, Bali, Indonesia* **2**, 23-27 (2000).

68) Conand, F., Marsac, F., Tessier, E. & Conand, C. A ten-year period of daily sea surface temperature at a coastal station in Reunion Island, Indian ocean (July 1993-April 2004): Patterns of variability and biological responses. *Western Indian Ocean Journal of Marine Science* **6**, 1-16 (2007).

69) Cook, C. B., Logan, A., Ward, J., Luckhurst, B. & Berg, C. J. Elevated temperatures and bleaching on a high latitude coral reef: the 1988 Bermuda event. *Coral Reefs* **9**, 45-49 (1990).
70) Coral Reef Watch Twitter. More bleaching reported in Guam and Saipan. Severe beaching expected until October. https://twitter.com/CoralReefWatch/status/760545243649433601 (2016).
71) CORDIO. Coral reef degradation in the Indian Ocean. 1-209 (Stockholm University, Sweden, 2000).
72) CORDIO. Coral reef degradation in the Indian Ocean. (University of Kalmar, Sweden, 2005).
73) CORDIO. Western Indian Ocean: Regional coral bleaching alert. 1-6 (CORDIO/IUCN working group on Climate Change and Coral Reefs, Western Indian Ocean Regional Bleaching Warning Network; 27 April 2010, 2010).
74) CORDIO. Western Indian Ocean-Regional coral bleaching alert. (Coastal Oceans Research and Development in the Indian Ocean, 2016).
75) CORDIO. Mayotte bleaching 2016. http://cordioea.net/mayotte-bleaching/ (2016).
76) Cornish, R. Investigation into coral bleaching damage to begin along New South Wales coastline, http://www.abc.net.au/news/2016-04-13/investigation-into-coral-bleaching-damage-along-nsw-coast/7322438 (2016).
77) Cortés, J., Jimenez, C. E., Fonseca, A. C. & Alvarado, J. J. Status and conservation of coral reefs in Costa Rica. *Rev. Biol. Trop* **58 (Suppl. 1)**, 33-50 (2010).
78) Cortés, J., Murillo, M. M., Guzmán, H. M. & Acuña, J. Pérdida de zooxantelas y muerte de corales y otros organismos arrecifales en el Caribe y Pacífico de Costa Rica. *Rev. Biol. Trop* **32**, 227-231 (1984).
79) Crabbe, M. J. C. Coral Ecosystem Resilience, Conservation and Management on the Reefs of Jamaica in the Face of Anthropogenic Activities and Climate Change. *Diversity* **2**, 881 (2010).
80) Craig, P., DiDonato, G., Fenner, D. & Hawkins, C. in *The state of coral reef ecosystems of the United States and pacific freely associated states* Vol. NOAA Technical Memorandum NOS NCCOSS, 11 (Waddell, J. E. ed.) 312-337 (NOAA/National Centers for Coastal Ocean Science, 2005)
81) Cumming, R. *et al.* Mass coral bleaching in the Fiji Islands, 2000. *Proceedings of the Ninth International Coral Reef Symposium, Bali, 23-27 October 2000* **2**, 1161-1167 (2002).
82) Dadhich, A. P., Nadaoka, K., Yamamoto, T. & Kayanne, H. Detecting coral bleaching using high-resolution satellite data analysis and 2-dimensional thermal model simulation in the Ishigaki fringing reef, Japan. *Coral Reefs* **31**, 425-439 (2012).
83) Dai, C. F. in *Status of Coral Reefs in East Asia Seas Region: 2010* (Chou, L. M. ed.) 79-88 (Global Coral Reef Monitoring Network, Ministry of the Environment, 2010).
84) Dalton, S. J. & Carroll, A. G. Monitoring coral health to determine coral bleaching response at high latitude eastern Australian reefs: an applied model for a changing climate. *Diversity* **3**, 592-610 (2011).
85) Dalton, S. J. *et al.* Determining the resilience capacity of Lord Howe Island coral community to successive coral bleaching event: Symbiont shuffling potential and recovery. 53 (National Marine Science Centre, Southern Cross University, Coffs Harbour, 2013).
86) Dantri International News. Mass coral bleaching found in Con Dao Islands. http://www.dtinews.vn/en/news/021/45686/mass-coral-bleaching-found-in-con-dao-islands.html (2016).
87) Depczynski, M. *et al.* Bleaching, coral mortality and subsequent survivorship on a west Australian fringing reef. *Coral Reefs* **32**, 233-238 (2013).
88) DeVantier, L. & Pilcher, N. The Status of Coral Reefs in Saudi Arabia–2000. *PERSGA Technical Series Report, Jeddah*, 1-45 (2000).
89) Donner, S. D., Kirata, T. & Vieux, C. Recovery from the 2004 coral bleaching event in the Gilber Islands, Kiribati. *Atoll Research Bulletin*, 1-25 (2010).
90) Downing, N., Buckley, R., Stobart, B., LeClair, L. & Teleki, K. Reef fish diversity at Aldabra Atoll, Seychelles, during the five years following the 1998 coral bleaching event. *Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences* **363**, 257-261 (2005).
91) Downs, C. A. *et al.* Oxidative stress and seasonal coral bleaching. *Free Radical Biology and Medicine* **33**, 533-543 (2002).
92) Economynext. Mass bleaching of Sri Lanka coral reefs. http://www.economynext.com/Mass_bleaching_of_Sri_Lanka_coral_reefs-3-5226.html (2016).
93) Environment News Service (ENS). Corals bleached and dying in overheated South Asian Waters. http://www.ens-newswire.com/ens/aug2010/2010-08-16-02.html (2010).
94) Eakin, C. M. *et al.* Global coral bleaching 2014-2017: Status and an appeal for observations. *Reef Encounters* **31,** 20-26 (2016).
95) Eakin, C. M. *et al.* Caribbean Corals in Crisis: Record Thermal Stress, Bleaching, and Mortality in 2005. *Plos One* **5**, e13969 (2010).
96) Edmunds, P. J. Decadal-scale changes in the community structure of coral reefs of St. John, US Virgin Islands. *Marine Ecology Progress Series* **489**, 107-123 (2013).
97) Edgar, R., Malcolm, H. & Dalton, S. Coral bleaching in the Solitary Islands Marine Park, NSW. *Technical data report. NSW Marine Parks Authority, Coffs Harbour, Australia* (2003).
98) Ewart, R. Coral bleaching event in Cook Islands hurting struggling pearl oyster industry, http://www.abc.net.au/news/2016-02-17/coral-bleaching-event-in-cook-islands-hurting/7175766 (2016).
99) Fabro, K. A. S. El Nino triggers coral bleaching in parts of Tubbataha Reef. http://cnnphilippines.com/regional/2015/09/15/El-Ni%C3%B1o-triggers-coral-bleaching-in-parts-of-Tubbataha-Reef.html (2015).
100) Fitt, W. K., Spero, H. J., Halas, J., White, M. W. & Porter, J. W. Recovery of the coral *Montastrea annularis* in the Florida Keys after the 1987 Caribbean “bleaching event”. *Coral Reefs* **12**, 57-64 (1993).
101) Floros, C. D., Samways, M. J. & Armstrong, B. Taxonomic patterns of bleaching within a South African coral assemblage. *Biodivers. Conserv.* **13**, 1175-1194 (2004).
102) FORCE Project. *Summary of the Bay Islands, Honduras Surveys October 2010*. (Future of Reefs in a

Changing Environment (FORCE), A European Union 7th Framework Programme Project, Grant Agreement 244161, 2010).

103) Friedlander, A. *et al.* in *The state of coral reef ecosystems of the United States and Pacific freely associated states. NOAA Technical Memorandum NOS NCCOS 73* (eds J.E. Waddell & A.M. Clarke) 222-269 (NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team, 2008).

104) Friedlander, A. *et al.* in *Status of Coral Reefs of the World*: 2004 (Wilkinson, C. ed.) 411-430 (Australian Institute of Marine Science, 2004).

105) Friedlander, A. *et al.* in *The state of coral reef ecosystems of the United States and Pacific freely associated states* (Waddell, J. E. & Clarke, A. M. eds.) 263-301(NOAA Technical Memorandum NOS NCCOS 73, NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team, 2008).

106) Furby, K. A., Bouwmeester, J. & Berumen, M. L. Susceptibility of central Red Sea corals during a major bleaching event. *Coral Reefs* **32**, 505-513, doi:10.1007/s00338-012-0998-5 (2013).

107) García-Sais, J. *et al.* in *The state of coral reef ecosystems of the United States and Pacific Freely Associated States* (eds J.E. Waddell & A.M. Clarke) 75-116 (2008).

108) Garzon-Ferreira, J. *et al.* in *Status of Coral Reefs of the World: 2000* (Wilkinson, C. ed.) 331-348 (Australian Institute of Marine Science, 2000).

109) Gates, R. D. Seawater temperature and sublethal coral bleaching in Jamaica. *Coral Reefs* **8**, 193-197 (1990).

110) George, D. & John, D. High sea temperatures along the coast of Abu Dhabi (UAE), Arabian Gulf- Their impact upon corals and macroalgae. *Reef Encounters* **25**, 21-23 (1999).

111) Gilmour, J. P., Smith, L. D., Heyward, A. J., Baird, A. H. & Pratchett, M. S. Recovery of an Isolated Coral Reef System Following Severe Disturbance. *Science* **340**, 69-71 (2013).

112) Gintert, B. et al. Image mosaics before, during and after the 2014 mass coral bleaching at Cheeca Rocks, Florida Keys reveal high resilience of a Caribbean coral reef. Proceedings of the 13th International Coral Reef Symposium, Honolulu, Abstract Book, 119 (2016).

113) Gleeson, M. W. & Strong, A. E. Satellite monitoring of the Earth's surface and atmosphere applying MCSST to coral reef bleaching. *Advances in Space Research* **16**, 151-154 (1995).

114) Glynn, P. W. Widespread coral mortality and the 1982-83 El Nino Warming Events. *Environmental Conservation* **11**, 133-146 (1984).

115) Glynn, P. W. Coral mortality and disturbances to coral reefs in the Tropical Eastern Pacific. *Elsevier Oceanography Series* **52**, 55-126 (1990).

116) Glynn, P. W., Mate, J. L., Baker, A. C. & Calderon, M. O. Coral bleaching and mortality in Panama and Ecuador during the 1997-1998 El Nino-Southern oscillation event: Spatial/temporal patterns and comparisons with the 1982-1983 event. *Bulletin of Marine Science* **69**, 79-109 (2001).

117) Glynn, P. W., Prahl, H. v. & Guhl, F. Coral reefs of Gorgona Island, Colombia, with special reference to corallivores and their influence on community structure and reef development. *An. Inst, Inv, Mar, Punta de betin* **12**, 185-214 (1982).

118) Glynn, P. W., Riegl, B., Purkis, S., Kerr, J. M. & Smith, T. B. Coral reef recovery in the Galápagos Islands: the northernmost islands (Darwin and Wenman). *Coral Reefs* **34**, 421-436 (2015).

119) Goenaga, C. & Canals, M. Island-wide coral bleaching in Puerto Rico. *Caribbean Journal of Science* **26**, 171-175 (1990).

120) Goiran, C. & Shine, R. Decline in sea snake abundance on a protected coral reef system in the New Caledonian Lagoon. *Coral Reefs* **32**, 281-284 (2013).

121) Golbuu, Y., Isechal, A. L., Idechong, J. W. & van Woesik, R. Spatial variability of coral bleaching in Palau during a regional thermal stress event in 2010. *Report to the Nature Conservancy* (2011).

122) Golbuu, Y. *et al.* Palau's coral reefs show differential habitat recovery following the 1998-bleaching event. *Coral Reefs* **26**, 319-332, doi:10.1007/s00338-007-0200-7 (2007).

123) Goldberg, J. *et al.* in *Status of Coral Reefs of the World: 2008* Vol. 1 (Wilkinson, C. ed.) 199-212 (Australian Institute of Marine Science, 2008).

124) Goldberg, J. & Wilkinson, C. in *Status of coral reefs of the world*: 2004 (Wilkinson, C. ed) 67-92 (Australian Institute of Marine Science, 2004).

125) Goreau, T. J. Coral bleaching in Jamaica. *Nature* **343**, 417-417 (1990).

126) Goreau, T. J. Bleaching and reef community change in Jamaica: 1951–1991. *American Zoologist* **32**, 683-695 (1992).

127) Goreau, T. J. Vanuatu Biorock Workshop June 9-18, 2016. Global Coral Reef Alliance, http://www.globalcoral.org/vanuatu-biorock-workshop-june-9-18-2016/ (2016).

128) Goreau, T. J. & Hayes, R. L. A survey of coral reef bleaching in the south central Pacific during 1994. (U.S. Department of State, 1994).

129) Goreau, T. J., McClanahan, T., Hayes, R. & Strong, A. Conservation of coral reefs after the 1998 global bleaching event. *Conservation Biology* **14**, 5-15, doi:10.1046/j.1523-1739.2000.00011.x (2000).

130) Government of Western Australia. *Case study: monitoring coral bleaching on Christmas Island*. (Department of Fisheries, Hillarys, W.A., 2012).

131) Graham, N. A. J., Jennings, S., MacNeil, M. A., Mouillot, D. & Wilson, S. K. Predicting climate-driven regime shifts versus rebound potential in coral reefs. *Nature* **518**, 94-97 (2015).

132) Graham, N. A. J., McClanahan, T. R., Letourneur, Y. & Galzin, R. Anthropogenic stressors, inter-specific competition and ENSO effects on a mauritian coral reef. *Environmental Biology of Fishes* **78**, 57-69 (2007).

133) Guest, J. R. *et al.* Contrasting patterns of coral bleaching susceptibility in 2010 suggest an adaptive response to thermal stress. *PLoS ONE* **7**, e33353 (2012).

134) Guzman, H. M. & Cortes, J. Cocos Island (Pacific of Costa Rica) coral reefs after the 198283 El Nifto disturbance. *Rev. Biol. Trop* **40**, 309-324 (1992).

135) Guzmán, H. M., Cortés, J., Richmond, R. H. & Glynn, P. W. Efectos del fenómeno de" El Niño Oscilación

Sureña" 1982/83 en los arrecifes coralinos de la Isla del Caño, Costa Rica. *Revista de Biología Tropical/International Journal of Tropical Biology and Conservation* **35**, 325-332 (1987).

136) Guzman, H. & Guevara, C. Massive mortality of zooxanthelate reef organisms during the 1995 bleaching in Cayos Cochinos, Honduras. *Revista de Biologia Tropical* **46**, 165-173 (1998).

137) Hagman, D. K. & Gittings, S. R. Coral bleaching on high latitude reefs at the Flower Garden Banks, NW Gulf of Mexico. *Proceedings of the 7th International Coral Reef Symposium* **1**, 38-43 (1992).

138) Hajramurni, A. Bulukumba coral reefs threatened with extinction. http://www.thejakartapost.com/news/2016/03/18/bulukumba-coral-reefs-threatened-with-extinction.html (2016).

139) Harborne, A. R., Afzal, D. C. & Andrews, M. J. Honduras: Caribbean Coast. *Marine Pollution Bulletin* **42**, 1221-1235 (2001).

140) Harding, S., van Bochove, J.-W., Day, O., Gibson, K. & Raines, P. Continued degradation of Tobago's coral reefs linked ot the prevalence of coral disease following the 2005 mass coral bleaching event. *Proceedings of the 11th International Coral Reef Symposium*, 738-741 (2008).

141) Harriott, V. J. Mortality rates of scleractinian corals before and during a mass bleaching event. *Marine ecology progess series* **21**, 81-88 (1985).

142) Harrison, P., Dalton, S. & Carroll, A. Extensive coral bleaching on the world’s southernmost coral reef at Lord Howe Island, Australia. *Coral Reefs* **30** (2011).

143) Harvell, D., Kim, K., Quirolo, C., Weir, J. & Smith, G. Coral bleaching and disease: contributors to 1998 mass mortality in *Briareum asbestinum* (Octocorallia, Gorgonacea). *Hydrobiologia* **460**, 97-104 (2001).

144) Harvey, C. ‘I cried…right into my mask’: Scientists sat Guam’s reefs have bleached four years straight. https://www.washingtonpost.com/news/energy-environment/wp/2016/08/03/i-cried-right-into-my-mask-these-coral-reefs-have-seen-a-devastating-four-years-of-bleaching/?utm_term=.ed0b39134784 (2016).

145) Hasrul. Oakar Unhas: Peningkatan Suhu Panas Ancam Terumbu Karang. http://makassar.tribunnews.com/2016/03/18/pakar-unhas-peningkatan-suhu-panas-ancam-terumbu-karang (2016).

146) Hayes, R. L. & Bush, P. G. Microscopic observations of recovery in the reef-building scleractinian coral, *Montastrea annularis*, after bleaching on a Cayman reef. *Coral Reefs* **8**, 203-209 (1990).

147) Hess, D. Marshall Islands coral bleaching update. RICE University Coral Reefs Blog, http://coralreefs.blogs.rice.edu/2016/03/16/marshall-islands-coral-bleaching-update/ (2016).

148) Hernandez-Arana, H., Lopez-Adame, H. & Vega-Zepeda, A. An overview of the coral bleaching event in the central and southern Mexican Caribbean in 2011. *Reef Encounters* **29**, 32-33 (2014).

149) Heyward, A., Radford, B., Burns, K., Colquhoun, J. & Moore, C. Montara Surveys: Final report on Benthic Surveys at Ashmore, Cartier and Seringapatam Reefs. (Report prepared by the Australia Institute of Marine Science for PTTEP Australasia (Ashmore Cartier) Pty. Ltd, 2010).

150) Hickerson, E. L., Schmahl, G. P., Robbart, M., Precht, W. F. & Caldow, C. in *The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008* (eds J.E. Waddell & A.M. Clarke) 189-218 (NOAA Technical Memorandum NOS NCCOS 73. NOAA/NCCOS Center for Coastal Monitoring and Assessment’s Biogeography Team, 2008).

151) Hoegh-Guldberg, O., Berkelmans, R. & Oliver, J. Coral bleaching: implications for the Great Barrier Reef Marine Park. *Proceedings of The Great Barrier Reef Science, Use and Management Conference, 25–29 November, 1996, Townsville, Australia*, 210-224 (1997).

152) Hoffmann, T. C. Coral reef health and effects of socio-economic factors in Fiji and Cook Islands. *Marine Pollution Bulletin* **44**, 1281-1293 (2002).

153) Hongo, C. & Yamano, H. Species-specific responses of corals to bleaching events on anthropogenically turbid reefs on Okinawa Island, Japan, over a 15-year period (1995-2009). *Plos One* **8**, e60952 (2013).

154) Hopley, D. & Suharsono. *in Status of Coral Reefs of the World: 2000* (Wilkinson, C. ed.) (Australian Institute of Marine Science, 2000).

155) Howell, C., Petrovic, C., Baily, T. & Hastings, M. International coral reef Initiative country report: British Virgin Islands regional ICRI workshop for the tropical Americas and the Caribbean Cancun, Mexico June 12-14, 2002. 1-7 (Island Resources Foundation, British Virgin Islands, 2002).

156) Hughes, T. P. Catastrophes, phase-shifts, and large-scale degradation of a Caribbean coral reef *Science* **265**, 1547-1551 (1994).

157) Indonesia’s National Coral Bleaching Monitoring Network. Coral Bleaching Indonesia. Indonesia Ministry of Marine and Fisheries, https://www.facebook.com/CoralBleachingIndonesia/photos/pcb.273055436363174/273054889696562/?type=3&theater (2016).

158) International Coral Reef Initiative. Indonesia-Global mass bleaching of coral reefs in 2010. (ICRI Secretariat, Japan) http://www.icriforum.org/news/2010/08/indonesia-global-mass-bleaching-coral-reefs-2010 (2010)

159) Jackson, J. B. C., Donovan, M. K., Cramer, K. L. & Lam, W. *Status and Trends of Caribbean Coral Reefs: 1970-2012*. (Global Coral Reef Monitoring Network, IUCN, 2014).

160) Jiménez, C. Bleaching and mortality of reef organism during a warming event in 1995 on the Caribbean coast of Costa Rica. *Revista de biología tropical* **49**, 233-238 (2001).

161) Jimenez, C. & Cortes, J. Effects of the 1991-92 El Nino on scleractinian corals of the Costa Rican central Pacific coast. *Revista De Biologia Tropical* **49**, 239-250 (2001).

162) Jiménez, C., Cortés, J., León, A. & Ruíz, E. Coral bleaching and mortality associated with the 1997-98 El Niño in an upwelling environment in the eastern Pacific (Gulf of Papagayo, Costa Rica). *Bulletin of Marine Science* **69**, 151-169 (2001).

163) Jinendradasa, S. S. & Ekaratne, S. Post-bleaching changes in coral settlement at the Hikkaduwa Nature Reserve in Sri Lanka. *Proc. 9th Int. Coral Reef Symp., Bali, Indonesia*, 1-4 (2000).

164) Johan, O. & Kusumah, G. Inilah Fenomena Penyakit yang Muncul Sebagai Lanjutan Pemutihan Karang yang

Terjadi. https://www.mongabay.co.id/2016/10/02/inilah-fenomena-penyakit-yang-muncul-sebagai-lanjutan-pemutihan-karang-yang-terjadi/ (2016).

165) Johnston, M. A. *et al.* Long-term monitoring at East and West Flower Garden Banks: 2015 Anual Report., 86 (U.S. Department of Commerce, national Oceanic and Atmospheric Administration, Flower Farden Banks National Marine Sanctuary, Glaveston, TX, 2016).

166) Johnston, M. A. *et al.* Long-term monitorning at the East and West Flower Garden Banks National Marine Sanctuary, 2009-2010. (U.S. Dept. of Interior, Nureau of Ocean Energy Management, Gulf of Mexico OCS Region, New Orleans, Louisiana, 2013).

167) Johnston-Barnes, O. Bermuda escapes coral bleaching problem. The Royal Gazette, http://www.royalgazette.com/article/20151202/NEWS07/151209947 (2015).

168) Jokiel, P. L. & Brown, E. K. Global warming, regional trends and inshore environmental conditions influence coral bleaching in Hawaii. *Global Change Biology* **10**, 1627-1641 (2004).

169) Jokiel, P. L. & Coles, S. L. Response of Hawaiian and other Indo-Pacific reef corals to elevated temperature. *Coral Reefs* **8**, 155-162 (1990).

170) Jones, G. P., McCormick, M. I., Srinivasan, M. & Eagle, J. V. Coral decline threatens fish biodiversity in marine reserves. *Proceedings of the National Academy of Sciences of the United States of America* **101**, 8251-8253 (2004).

171) Jones, L. *et al.* in *Status of Coral Reefs of the World: 2004* (Wilkinson, C. ed.) 451-472 (Australian Institute of Marine Science, 2004).

172) Jones, N., Ateweberhan, M., Chapman, J., Humber, F. & Gough, C. Bacalar Chico Marine Reserve 2010: a survey of the coral reefs in Bacalar Chico Marine Reserve, Belize. (Blue Ventures Conservation Report, Blue Ventures, London, 2011).

173) Jones, R. J., Berkelmans, R. & Oliver, J. K. Recurrent bleaching of corals at Magnetic Island (Australia) relative to air and seawater temperature. *Marine Ecology Progress Series* **158**, 289-292 (1997).

174) Jong, H. N. Coral destruction shifts to eastern Indonesia. http://www.thejakartapost.com/news/2016/02/12/coral-destruction-shifts-eastern-indonesia.html (2016).

175) Kawaguti, S. & Matsuno, A. A new species of the Coronatae, Scyphozoa, from the Japan Sea. *Atorella japonica*, 15-21 (1981).

176) Kemp, D. W., Hernandez-Pech, X., Iglesias-Prieto, R., Fitt, W. K. & Schmidt, G. W. Community dynamics and physiology of *Symbiodinium spp.* before, during, and after a coral bleaching event. *Limnology and Oceanography* **59**, 788-797 (2014).

177) Kenyon, J. C. *et al.* Mass coral bleaching on high-latitude reefs in the Hawaiian Archipelago. *Proceedings of the 10th International Coral Reef Symposium*, 631-643 (2006).

178) Kimura, K. in *Status of Coral Reef in East Asia Seas Region: 2010*. 89-107 (Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, 2010).

179) Kimura, T. *et al.* in *Status of Coral Reefs of the World: 2004* Vol. 1 (Wilkinson, C. ed) 277-301 (Australian Institute of Marine Science, 2004).

180) Kimura, T., Dai, C. F., Park, H.-S., Hui, H. & Ang, P. O. in *Status of Coral Reefs of the World* (ed C Wilkinson) 145-158 (Australian Institute of Marine Science, 2008).

181) Kohler, S. T. & Kohler, C. C. Dead bleached coral provides new surfaces for dinoflagellates implicated in ciguatera fish poisonings. *Environmental Biology of Fishes* **35**, 413-416 (1992).

182) Kotb, M. *et al.* in *Status of Coral Reefs of the World: 2004* Vol. 1 (Wilkinson, C. ed.) 137-139 (Australian Institute of Marine Science, 2004).

183) Kotb, M. M. *et al.* Status of coral reefs in the Red Sea and Gulf of Aden region. *Status of coral reefs of the world*, 67-78 (2008).

184) Kramer, P., Kramer, P. R., Arias-González, E. & Mcfield, M. in *Status of Coral Reefs of the World: 2000* (Wilkinson, C. ed.) 289-313 (Australian Institute of Marine Science, 2000).

185) Kramer, P. *et al.* Report card for the Mesoamerican Reef. (Healthy Reefs Initiative, www.healthyreefs.org, 2015).

186) Kramer, P. A. & Kramer, P. R. Transient and lethal effects of the 1998 coral bleaching event on the Mesoamerican reef system. *Proceedings of the 9th International Coral Reef Symposium, Bali, Indonesia* **2**, 1-7 (2000).

187) Krishnan, P. *et al.* Elevated sea surface temperature during May 2010 induces mass bleaching of corals in the Andaman. *Current Science* **100**, 111-117 (2011).

188) Kuo, C. Y. *et al.* Recurrent disturbances and the degradation of hard coral communities in Taiwan. *Plos One* **7**, e44364 (2012).

189) Lafratta, A., Fromont, J., Speare, P. & Schönberg, C. H. L. Coral bleaching in turbid waters of north-western Australia. *Marine and Freshwater Research*, -, doi:http://dx.doi.org/10.1071/MF15314 (2016).

190) Lalamentik, L. T., Sompie, D. E., Runtukahu, F., Kojansow, J. W. & Rondonuwu, A. B. Coral bleaching in Ratatotok Peninsula and its surrounds area, South-East Minahasa, North Sulawesi Province, Indonesia (A 15 years monitoring data). Proceedings of the 13th International Coral Reef Symposium, Honolulu, Abstract Book, 187 (2016).

191) Lang, J. C. *et al.* Spatial and temporal variability during periods of “recovery” after mass bleaching on Western Atlantic coral reefs. *American Zoologist* **32**, 696-706 (1992).

192) Ledlie, M. H. *et al.* Phase shifts and the role of herbivory in the resilience of coral reefs. *Coral Reefs* **26**, 641-653 (2007).

193) Levitan, D. R., Boudreau, W., Jara, J. & Knowlton, N. Long-term reduced spawning in *Orbicella* coral species due to temperature stress. *Marine Ecology Progress Series* **515**, 1-10 (2014).

194) Liu, G. *et al.* Reef-Scale Thermal Stress Monitoring of Coral Ecosystems: New 5-km Global Products from NOAA Coral Reef Watch. *Remote Sensing* **6**, 11579 (2014).

195) Lovell, E. *et al.* in *Status of Coral Reefs of the World: 2004* (Wilkinson, C ed.) (Australian Institute of Marine Science, 2004).
196) Lovell, E. R. & Sykes, H. Rapid recovery from bleaching events-Fiji Coral Reef Monitoring Network assessment of hard coral cover from 1999-2007. *Proceedings of the 11th International Coral Reef Symposium* **2**, 836-840 (2008).
197) Loya Y *et al.* Coral bleaching: the winners and the losers. *Ecology Letters* **4**, 122-131 (2001).
198) Lozano-Cortes, D. *et al.* Coral bleaching in Saudi Arabia affecting both the Res Sea and Arabian Gulf. *Reef Encounters* **31**, 50-52 (2016).
199) Maghsoudlou, A., Araghi, P. E., Wilson, S., Taylor, O. & Medio, D. in *Status of coral reefs of the world: 2008* (Wilkinson, C. ed.) 79-90 (Australian Institute of Marine Science, 2008).
200) Mahbub, A. Coral bleaching in Alarming State. http://en.tempo.co/read/news/2016/04/13/206762338/Coral-Bleaching-in-Alarming-State (2016).
201) Mallela, J. & Crabbe, M. J. C. Hurricanes and coral bleaching linked to changes in coral recruitment in Tobago. *Marine Environmental Research* **68**, 158-162 (2009)
202) Manzello, D. P., Berkelmans, R. & Hendee, J. C. Coral bleaching indices and thresholds for the Florida Reef Tract, Bahamas, and St. Croix, US Virgin Islands. *Marine Pollution Bulletin* **54**, 1923-1931 (2007).
203) Manzello, D. P. *et al.* Galápagos coral reef persistence after ENSO warming across an acidification gradient. *Geophysical Research Letters* **41**, 9001-9008, (2014).
204) Manzello, D. P., Enochs, I. C., Kolodziej, G. & Carlton, R. Coral growth patterns of *Montastraea cavernosa* and *Porites astreoides* in the Florida Keys: The importance of thermal stress and inimical waters. *Journal of Experimental Marine Biology and Ecology* **471**, 198-207 (2015).
205) Marshall, P. A. & Baird, A. H. Bleaching of corals on the Great Barrier Reef: differential susceptibilities among taxa. *Coral Reefs* **19**, 155-163 (2000).
206) Matton-Moorgawa, Bhagooli, R. & Rughooputh, S. D. D. V. Thermal stress physiology and mortality responses in scleractinian corals of Mauritius. *Proc. 12th Int. Coral Reef Symp., Cairns, Australia*, 1-6 (2012).
207) McClanahan, T. R., Ateweberhan, M., Darling, E. S., Graham, N. A. & Muthiga, N. A. Biogeography and change among regional coral communities across the Western Indian Ocean. *PloS one* **9**, e93385 (2014).
208) McClanahan, T. R. *et al.* Western Indian Ocean coral communities: bleaching responses and susceptibility to extinction. *Marine Ecology Progress Series* **337**, 1-13 (2007).
209) McClanahan, T. R., Maina, J., Moothien-Pillay, R. & Baker, A. C. Effects of geography, taxa, water flow, and temperature variation on coral bleaching intensity in Mauritius. *Marine Ecology Progress Series* **298**, 131-142 (2005).
210) McField, M. D. Coral response during and after mass bleaching in Belize. *Bulletin of Marine Science* **64**, 155-172 (1999).
211) McGillis,W. Changes in coral metabolism during the 2015 El Niño in eastern Panama, Abstract from 2016 Ocean Science Meetings, https://agu.confex.com/agu/os16/preliminaryview.cgi/Paper92258.html (2016).
212) McGrath, T. A. & Smith, G. W. Comparisons of the 1995 and 1998 coral bleaching events on the patch reefs of San Salvador Island, Bahamas. *Revista De Biologia Tropical* **51**, 67-75 (2003).
213) McGraw, B. Rising sea water temperatures causing coral bleaching in Seca Islands, Panama. http://www.thefishsite.com/articles/2195/rising-sea-water-temperatures-due-to-el-nio-causing-coral-bleaching-in-seca-islands-chiriqui-bay-pacific-panama/ (2016).
214) Meesters, E. H. & Bak, R. P. M. Effects of coral bleaching on tissue regeneration potential and colony survival. *Marine Ecology Progress Series* **96**, 189-198 (1993).
215) Mellgard, P. Uncertain over Paris climate talks, Marshall Islanders prepare for the worst. http://www.huffingtonpost.com/entry/marshall-islands-climate-change_us_565f5337e4b079b2818cf643 (2015).
216) Miller, I. & Sweatman, H. in *Status of Coral Reefs of the World: 2004* Vol. 2 (Wilkinson, C. ed.) 303-335 (Australian Institute of Marine Science, 2004).
217) Miller, J. *et al.* Coral disease following massive bleaching in 2005 causes 60% decline in coral cover on reefs in the US Virgin Islands. *Coral Reefs* **28**, 925-937 (2009).
218) Mohammed, T. A. E.-A. A. & Mohamed, M. A. E.-W. Some ecological factors affecting coral reef assemblages off Hurghada, Red Sea, Egypt. *Egyptian Journal of Aquatic Research* **31**, 133-142 (2005).
219) Mondal, T., Raghunathan, C. & Venkataraman, K. Coral bleaching in Andaman Sea–an indicator for climate change in Andaman and Nicobar Islands. *INDIAN J. MAR. SCI* **43** (2014).
220) Montgomery, R. & Strong, A. Coral bleaching threatens oceans, life. *Eos* **75**, 145-147 (1994).
221) Moore, J. A. Y. *et al.* Unprecedented mass bleaching and loss of coral across 12 degrees of latitude in Western Australia in 2010-11. *Plos One* **7**, e51807 (2012).
222) Mongabay News. Heart wrenching: India's coral reef experiencing widespread bleaching, scientist says. https://news.mongabay.com/2016/05/indias-coral-reefs-experiencing-catastrophic-bleaching-heart-wrenching-scientist-says/ (2016).
223) Montano, S., Seveso, D., Galli, P. & Obura, D. O. Assessing coral bleaching and recovery with a colour reference card in Watamu Marine Park, Kenya. *Hydrobiologia* **655**, 99-108 (2010).
224) Mumby, P. J. Bleaching and hurricane disturbances to populations of coral recruits in Belize. *Marine Ecology Progress Series* **190**, 27-35 (1999).
225) National Geographic Indonesia. Kala Terumbu Karang Sumatera Barat Memutih. http://nationalgeographic.co.id/berita/2016/04/kala-terumbu-karang-sumatera-barat-memutih (2016).
226) National News Barbados. Govt seeking $9m to rescue reefs. http://www.nationnews.com/nationnews/news/61607/govt-seeking-usd9m-rescue-reefs (2015).
227) Neal, B. P. *et al.* When depth is no refuge: cumulative thermal stress increases with depth in Bocas del Toro, Panama. *Coral Reefs* **33**, 193-205 (2014).
228) NOAA. 2014-15 Bleaching event continues, June 2015 update.

http://coralreefwatch.noaa.gov/satellite/analyses_guidance/global_bleaching_update_20150602.php (2015).

229) NOAA. Caribbean Coral Reef Watch. http://www.weather.gov.dm/images/docs/Caribbean-CRW-Vol1_Issue_7_Dec_2015.pdf (2015).

230) Obura, D. in *Status of Coral Reefs of the World: 2002* (Wilkinson, C. ed.) (Australian Institute of Marine Science, 2002).

231) Obura, D. O., Tamelander, J., Linden, O. (Eds) Ten years after bleaching - facing the consequences of climate change in the Indian Ocean, CORDIO Status Report 2008. (Coastal Oceans Research and Development in the Indian Ocean/Sida-SAREC, Mombasa, 2008).

232) Oliver, J. Recurrent seasonal bleaching and mortality of corals on the Great Barrier Reef. *Proceedings of the Fifth International Coral Reef Congress, Tahiti* **4**, 201-206 (1985).

233) Oxenford, H. A., Roach, R. & Brathwaite, A. Large scale coral mortality in Barbados: a delayed response to the 2005 bleaching episode. *Proceedings of the 11th International Coral Reef Symposium*, 1-5 (2008).

234) Oxenford, H. A. *et al.* Quantitative observations of a major coral bleaching event in Barbados, Southeastern Caribbean. *Climatic Change* **87**, 435-449 (2008).

235) Oxenford, H. A. & Vallès, H. Transient turbid water mass reduces temperature-induced coral bleaching and mortality in Barbados. *PeerJ* **4**, e2118 (2016).

236) Oxley, W. W., Ayling, T. A., Cheal, A. A. & Thompson, A. A. Marine Surveys undertaken in the Coringa-Herald National Nature Reserve, March-April 2003. (Australian Institute of Marine Science, Townsville, 2003).

237) Oxley, W. W., Emslie, M. M., Muir, P. P. & Thompson, A. A. Marine Surveys undertaken in the Lihou Reef National Nature Reserve, March 2004. Produced for Department of the Environment and Heritage. (Australian Institute of Marine Science, Townsville, 2004).

238) Parke, E. First coral bleaching found on WA Kimberly coast, http://www.abc.net.au/news/2016-04-11/first-coral-bleaching-found-on-wa-kimberley-coast/7315960 (2016).

239) Paulay, G. & Benayahu, Y. Patterns and consequences of coral bleaching in Micronesia (Majuro and Guam) in 1992-1994. *Micronesica* **32**, 109-124 (1999).

240) Penin, L., Adjeroud, M., Schrimm, M. & Lenihan, H. S. High spatial variability in coral bleaching around Moorea (French Polynesia): patterns across locations and water depths. *Comptes Rendus Biologies* **330**, 171-181 (2007).

241) Phongsuwan, N. & Chansang, H. Repeated coral bleaching in the Andaman Sea, Thailand, during the last two decades. *Phuket Mar Biol Cent Res Bull* **71**, 19-41 (2012).

242) PHYS.ORG. Seychelles reefs hit hard, but 'pockets of resistance' give hope. http://phys.org/news/2016-05-seychelles-reefs-hard-pockets-resistance.html (2016).

243) Plass-Johnson, J. G. *et al.* in *Environmental Indicators* (Armon, R. H. & Hänninen, O eds.) 117-146 (Springer Netherlands, 2015).

244) Podestá, G. P. & Glynn, P. W. The 1997-98 El Niño event in Panama and Galápagos: an update of thermal stress indices relative to coral bleaching. *Bulletin of Marine Science* **69**, 43-59 (2001).

245) Poh, W. P. in *Encyclopedia of the World's Coastal Landforms.* 1097-1110 (Springer, 2010).

246) Pontianakpost.com. Pemutihan Karang Ancam Kalbar http://www.pontianakpost.com/pemutihan-karang-ancam-kalbar (2016).

247) Porter, V. *et al.* Status of the coral reef ecosystems of Guam. (University of Guam Marine Laboratory Technical Report no. 113, 2005).

248) Pratchett, M. S. *et al.* Elizabeth and Middleton Reef reserves marine survey 2011. (James Cook University, Townsville, 2011).

249) Pratchett, M. S., McCowan, D., Maynard, J. A. & Heron, S. F. Changes in bleaching susceptibility among corals subject to ocean warming and recurrent bleaching in Moorea, French Polynesia. *PLoS ONE* **8**, e70443 (2013).

250) Quinn, N. J. & Kojis, B. L. Subsurface seawater temperature variation and the recovery of corals from the 1993 coral bleaching event in waters off St. Thomas, U.S. Virgin Islands. *Bulletin of Marine Science* **65**, 201-214 (1999).

251) Quod, J.-P. & Bigot, L. in *Coral reef degradation in the Indian Ocean* (Souter, D. Obura, & O. Linden, eds) 108-113 (CORDIO, 2011).

252) Raymundo, L. & Maypa, A. Recovery of the Apo Island Marine Reserve, Philippines, 2 years after the El Niño bleaching event. *Coral Reefs* **21**, 260-261, doi:10.1007/s00338-002-0237-6 (2002)

253) Rajasuriya, A. Status of Coral Reefs in the Northern, Western and Southern Coastal Waters of Sri Lanka. *Ten Years after bleaching-facing the consequences of climate change in the Indian Ocean. CORDIO Status Report*, 11-22 (2008).

254) Rajasuriya, A. *et al.* in *Status of Coral Reefs of the World 2000* (Wilkinson, C. ed.) 95-114 (Australian Institute of Marine Science, 2000).

255) Rajasuriya, A., Zahir, H., Venkataraman, K., Islam, Z. & Tamelander, J. in *Status of Coral Reefs of the World: 2004* Vol. 1 (Wilkinson, C ed.) 213-234 (Australian Institute of Marine Science, 2004).

256) Raubani, J. J. J. in *South-West Pacific status of coral reefs report 2007* (Whippy-Morris, C. ed.)167-203 (Coral Reef Initiatives for the Pacific, 2009).

257) Red Cross Climate Centre. Record February global temperature shocks scientists, impacts Pacific Fisheries. http://www.climatecentre.org/news/705/record-february-global-temperature-shocks-scientists-impacts-pacific-fisheries (2016).

258) ReefBase. A global information system for coral reefs. http://www.reefbase.org (2016).

259) Rezai, H., Wilson, S., Claereboudt, M. & Riegl, B. in *Status of Coral Reefs of the World* Vol. 1 (Wilkinson, C. ed.)155-170 (Australian Institute of Marine Science, 2004).

260) Ridgway, T. *et al.* Temporal patters of coral cover in the offshore Pilbara, Western Australia. *Mar Biol* **163:182**, doi:0.1007/s00227-016-2956-1 (2016).

261) Riegl, B. Effects of the 1996 and 1998 positive sea-surface temperature anomalies on corals, coral diseases

and fish in the Arabian Gulf (Dubai, UAE). *Marine biology* **140**, 29-40 (2002).

262) Riegl, B. Climate change and coral reefs: different effects in two high-latitude areas (Arabian Gulf, South Africa). *Coral reefs* **22**, 433-446 (2003).

263) Riegl, B. M., Purkis, S. J., Al-Cibahy, A. S., Abdel-Moati, M. A. & Hoegh-Guldberg, O. Present limits to heat-adaptability in corals and population-level responses to climate extremes. *Plos One* **6**, e24802 (2011).

264) Ritson-Williams, R., & Gates, R. Processes driving coral resilience to bleaching. Proceedings of the 13th International Coral Reef Symposium, Honolulu, Abstract Book, 287 (2016).

265) Rivera-Sosa, A., Muniz-Castillo, A. C., McField, M. & Arias-Gonzalez, J. E. Coral bleaching in Tela, Honduras and the Mesoamerica reef region. Proceedings of the 13th International Coral Reef Symposium, Honolulu, Abstract Book, 288 (2016).

266) Rodríguez, S., Cróquer, A., Bone, D. & Bastidas, C. Severity of the 1998 and 2005 bleaching events in Venezuela, southern Caribbean. *Revista de biología tropical* **58**, 189-196 (2010).

267) Rodríguez-Ramírez, A. *et al.* in *Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005* (eds C Wilkinson & D Souter) 105-114 (Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre, 2008).

268) Rodriguez-Ramirez, A. *et al.* Status of coral reefs of Columbia in 2003. *Proceedings of the 10th International Coral Reef Symposium*, 976-981 (2006).

269) Rodríguez-Ramírez, A. *et al.* Recent dynamics and condition of coral reefs in the Colombian Caribbean. *Revista de Biología Tropical* **58**, 107-131 (2010).

270) Rogers, C. S. & Beets, J. Degradation of marine ecosystems and decline of fishery resources in marine protected areas in the US Virgin Islands. *Environmental Conservation* **28**, 312-322 (2001).

271) Rogers, C. S., Muller, E., Spitzack, T. & Miller, J. Extensive coral mortality in the US Virgin Islands in 2005/2006: A review of the evidence for synergy among thermal stress, coral bleaching and disease. *Caribbean Journal of Science* **45**, 204-214 (2009).

272) Rogers, C. S. & Muller, E. M. Bleaching, disease and recovery in the threatened scleractinian coral *Acropora palmata* in St. John, US Virgin Islands: 2003–2010. *Coral Reefs* **31**, 807-819 (2012).

273) Rongo, T. & van Woesik, R. The effects of natural disturbances, reef state, and herbivorous fish densities on ciguatera poisoning in Rarotonga, southern Cook Islands. *Toxicon* **64**, 87-95 (2013).

274) Rowlands, G. P., Purkis, S. J. & Riegl, B. M. The 2005 coral bleaching event Roatan (Honduras): Use of psuedoinvariant features (PIFSs) in satellite assessments. *Journal of Spatial Science* **53**, 99-112 (2008).

275) Salvat, B. The 1991 bleaching event in the Society islands, French Polynesia. *Proceedings of the 7th International Coral Reef Symposium, Guam* **1**, 73 (1993).

276) Salvat, B. in *Status of Coral Reefs of the World: 2000* Vol. 2 (Wilkinson, C. ed.) 181-198 (Australian Institute of Marine Science, 2000).

277) Sandin, S. A. *et al.* Baselines and degradation of coral reefs in the Northern Line Islands. *PLoS ONE* **3**, e1548 (2008).

278) Sano, M. Short-term effects of a mass coral bleaching event on a reef fish assemblage at Iriomote Island, Japan. *Fisheries Science* **70**, 41-46 (2004).

279) Santavy, D. L., Summers, J. K., Engle, V. D. & Harwell, L. C. The condition of coral reefs in South Florida (2000) using coral disease and bleaching as indicators. *Environ. Monit. Assess.* **100**, 129-152 (2005).

280) Schiller, A., Ridgway, K. R., Steinberg, C. R. & Oke, P. R. Dynamics of three anomalous SST events in the Coral Sea. *Geophysical Research Letters* **36**, (2009).

281) Scheopf, V. Perspective: local coral reefs battle bleaching conditions, Science Network Australia, http://www.sciencewa.net.au/topics/perspectives/item/4149-perspective-local-coral-reefs-battle-bleaching-conditions (2016).

282) Schleyer, M. H., Kruger, A. & Celliers, L. Long-term community changes on a high-latitude coral reef in the Greater St Lucia Wetland Park, South Africa. *Marine Pollution Bulletin* **56**, 493-502 (2008).

283) Schuhmacher, H., Loch, K., Loch, W. & See, W. R. The aftermath of coral bleaching on a Maldivian reef - a quantitative study. *Facies* **51**, 80-92 (2005).

284) Scopélitis, J. *et al.* Changes of coral communities over 35 years: Integrating *in situ* and remote-sensing data on Saint-Leu Reef (la Réunion, Indian Ocean). *Estuarine, Coastal and Shelf Science* **84**, 342-352 (2009).

285) Sebastian, C. R., Sink, K. J., McClanahan, T. R. & Cowan, D. A. Bleaching response of corals and their *Symbiodinium* communities in southern Africa. *Marine Biology* **156**, 2049-2062 (2009).

286) Sheppard, C., Harris, A. & Sheppard, A. Archipelago-wide coral recovery patterns since 1998 in the Chagos Archipelago, central Indian Ocean. *Marine Ecology Progress Series* **362**, 109-117 (2008).

287) Sheppard, C. & Obura, D. Corals and reefs of Cosmoledo and Aldabra atolls: Extent of damage, assemblage shifts and recovery following the severe mortality of 1998. *J. Nat. Hist.* **39**, 103-121 (2005).

288) Sheppard, C. R. C. Predicted recurrences of mass coral mortality in the Indian Ocean. *Nature* **425**, 294-297 (2003).

289) Shuail, D. *et al.* Local bleaching thresholds established by remote sensing techniques vary among reefs with deviating bleaching patterns during the 2012 event in the Arabian/Persian Gulf. *Marine Pollution Bulletin* **105**, 654-659 (2016).

290) Singh, B. Climate-related global changes in the southern Caribbean: Trinidad and Tobago. *Global and Planetary Change* **15**, 93-111 (1997).

291) Smale, D. A. & Wernberg, T. Ecological observations associated with an anomalous warming event at the Houtman Abrolhos Islands, Western Australia. *Coral Reefs* **31**, 441-441 (2012).

292) Smith, L. D., Gilmour, J. P. & Heyward, A. J. Resilience of coral communities on an isolated system of reefs following catastrophic mass-bleaching. *Coral Reefs* **27**, 197-205 (2008).

293) Smith, S. R. *et al.* in *Coral Reefs of the United Kingdom Overseas Territories* (Charles Sheppard, R. C. ed.)173-188 (Springer Netherlands, 2013).

294) Solano, P., David, O., Navas Suárez, G. & Moreno-Forero, S. K. Blanqueamiento coralino de 1990 en el Parque Nacional Natural Corales del Rosario (Caribe, colombiano). *Boletín de Investigaciones Marinas y Costeras-INVEMAR* **22**, 97-111 (1993).

295) Solano, P. & David, O. Corales, formaciones arrecifales y blanqueamiento de 1987 en Bahía Portete (Guajira, Colombia). *Boletín de Investigaciones Marinas y Costeras-INVEMAR* **23**, 149-163 (1994).

296) Son, T. P. H., Tan, C. K. & Ransi, V. Remote sensing for coral mapping and monitoring of coral bleaching in coastal waters of Vietnam. *Proc. of the first joint PI Symposium of ALOS Data Nodes for ALOS Science Program in Kyoto*, 1-4 (2007).

297) Soong, K., Dai, C. & Lee, C. Status of Pratas Atoll in South China Sea. *Proceedings of the 4th Conference on the Protected Areas of East Asia*, 739-742 (2002).

298) Spencer, T., Teleki, K. A., Bradshaw, C. & Spalding, M. D. Coral bleaching in the southern Seychelles during the 1997–1998 Indian Ocean warm event. *Marine Pollution Bulletin* **40**, 569-586 (2000).

299) Steneck, R. S., Arnold, S. & DeBey, H. *Status and trends of Bonaire's coral reefs 2011 & cause for grave concerns.* 1-116 (University of Maine, School of Marine Sciences, Darline Marine Center, Walpole, ME 04573 National Marine Fisheries Service, Silver Spring, MD, 2011).

300) Steneck, R. S. & Lang, J. C. Status of Coral Reefs in the Western Atlantic: Results of Initial Surveys, Atlantic and Gulf Rapid Reef Assessment (Agrra) Program-Part 17-Mexico. Rapid assessment of Mexico's Yucatan reef in 1997 and 1999: pre- and post-1998 mass bleaching and hurricane Mitch (stony corals, algae and fishes) *Atoll Res Bull* **496**, 1-24 (2003).

301) Stewart, A. Rising sea temperatures cause massive coral bleaching off Christmas Island, researchers say, http://www.abc.net.au/news/2016-05-06/coral-bleaching-strikes-christmas-island/7390500 (2016).

302) Stobart, B., Teleki, K., Buckley, R., Downing, N. & Callow, M. Coral recovery at Aldabra Atoll, Seychelles: five years after the 1998 bleaching event. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* **363**, 251-255 (2005).

303) Stout, M. Coral reef bleaching found in Belize for the first time. (NOAA Coral Health and Monitoring Program, http://www.publicaffairs.noaa.gov/pr95/nov95/noaa95-80.html, 1995)

304) Sudek, M., Aeby, G. S. & Davy, S. K. Localized bleaching in Hawaii causes tissue loss and a reduction in the number of gametes in *Porites compressa*. *Coral Reefs* **31**, 351-355 (2012).

305) Suharsono. Bleaching event followed by mass mortality of corals in 1998 in Indonesia waters. *Proc. 9th JSPS Joint Sem. Mar. Fish. Sci.*, 179-187 (1999).

306) Sulu, R. *et al.* in *Status of Coral Reefs of the World* (Wilkinson, C. ed.) (Australian Institute of Marine Science, 2002).

307) Sutthacheep, M. *et al.* Impacts of the 1998 and 2010 mass coral bleaching events on the Western Gulf of Thailand. *Deep-Sea Research Part Ii-Topical Studies in Oceanography* **96**, 25-31 (2013).

308) Sweatman, H. *et al.* in *Status of Coral Reefs of the World: 2002* (Wilkinson, C. ed.)163-180 (Australia Institute of Marine Science, 2002).

309) Tamelander, J. & Rajasuriya, A. in *Status of coral reefs of the world: 2008* (Wilkinson, C. ed.) 119-130 (Global Coral Reef Monitoring Network and Reef and Rainforest Research Center, 2008).

310) Tew, K. S. *et al.* A continuous, real-time water quality monitoring system for the coral reef ecosystems of Nanwan Bay, Southern Taiwan. *Marine Pollution Bulletin* **85**, 641-647 (2014).

311) Thai PBS. Coral reef bleaching in Gulf shocking. http://englishnews.thaipbs.or.th/coral-reef-bleaching-gulf-shocking/ (2016).

312) The University of the Philippines Marine Science Institute. Bleaching Watch. http://www.msi.upd.edu.ph/?page_id=3250 (2016). Report of the 2016 Philippines Coral Bleaching Event, Abrina et al., in prep.

313) This Study

314) Thomas, C. & Heron, S. South-East Asia coral bleaching rapid response: final report. *Townsville, Queensland: CSIRO*, 20 (2011).

315) Thomson, D. P., Bearham, D., Graham, F. & Eagle, J. V. High latitude, deeper water coral bleaching at Rottnest Island, Western Australia. *Coral Reefs* **30**, 1107-1107 (2011).

316) Tkachenko, S. The northernmost coral frontier of the Maldives: The coral reefs of Ihavandippolu Atoll under long-term environmental change. *Marine Environmental Research* **82**, 40-48 (2012).

317) Top News. Okinawa, Japan, coral reefs due to rising sea temperatures mass bleaching. http://www.top-news.top/news-12303375.html (2016).

318) Torres Strait Regional Authority (TSRA). Torres Strait Climate Change Strategy 2014–2018. 1-36 (Report prepared by the Land and Sea Management Unit, 2014).

319) Trapon, M. L., Pratchett, M. S. & Penin, L.Comparative effects of different disturbances in coral reef habitats in Moorea, French Polynesia. *Journal of Marine Biology* **2011**, doi:10.1155/2011/807625 (2011).

320) Tsuchiya, M., Yanagiya, K. & Nishihira, M. Mass mortality of the sea urchin Echinometra mathaei(Blainville) caused by high water temperature on the reef flats in Okinawa, Japan. *Galaxea. Nishihara* **6**, 375-385 (1987).

321) Tuan, V. S. The corals at Con Dao Achipelago (South Vietnam): Before, during and after the bleaching event in 1998. *Proceedings of the Ninth International Coral Reef Symposium* **2**, 895-899 (2002).

322) Tun, K. *et al.* in *Status of Coral Reef in East Asia Seas Region: 2010*. 9-28 (Global Coral Reef Monitoring Network and Reef and Rainforest Research Center, Townsville, Australia, 2010).

323) Turner, J. *et al.* in *Coral Reef Degradation in the Indian Ocean. Status Reports and Project Presentation 2000* (Souter, D., Obura, D. & Linden, O., eds.) 94-107 (CORDIO, 2000).

324) Turner, J. R. *et al.* in *Coral Reefs of the United Kingdom Overseas Territories* (Sheppard, R. C. C. ed.) 69-88 (Springer Netherlands, 2013).

325) Turquet, J. *et al.* in *Coral Reef Degradation in the Indian Ocean. Status Report 2002* (Linden, O., Souter, D., Wilhelmsson, D., & Obura, D. eds.) 177-178 (CORDIO, 2002).

326) van Hooidonk, R. J. *et al.* Coral bleaching at Little Cayman, Cayman Islands 2009. *Estuarine Coastal and Shelf Science* **106**, 80-84 (2012).
327) van Woesik, R. *et al.* Climate-change refugia in the sheltered bays of Palau: analogs of future reefs. *Ecology and Evolution* **2**, 2474-2484 (2012).
328) van Woesik, R., Irikawa, A. & Loya, Y. *Coral bleaching: Signs of change in southern Japan*. (Springer-Verlag Berlin, 2004).
329) Vargas-Ángel, B., Zapata, F. A., Hernández, H. & Jiménez, J. M. Coral and coral reef responses to the 1997/98 El Niño event on the Pacific coast of Colombia. *Bulletin of Marine Science* **69**, 111-132 (2001).
330) Vega-Sequeda, J., Navas-Camacho, R., Gómez-Campo, K. & López-Londoño, T. Instalación y evaluación de dos nuevas estaciones de monitoreo de arrecifes coralinos en el Caribe colombiano. *Boletín de Investigaciones Marinas y Costeras-INVEMAR* **40**, 203-211 (2011).
331) Vermeij, M. J. A. The current state of Curacao's coral reefs. 1-34 (Carmabi Foundation, University of Amsterdam, 2012).
332) Vieux, C. *et al.* in *Status of Coral Reefs of the World: 2004* Vol. 2 (Wilkinson, C. ed.) 363-380 (Australian Institute of Marine Science, 2004).
333) Vivekanandan, E., Hussain Ali, M., Jasper, B. & Rajagopalan, M. Thermal thresholds for coral bleaching in the Indian seas. *Journal of the Marine Biological Association of India* **50**, 209-214 (2008).
334) Wagner, D. E., Kramer, P. & van Woesik, R. Species composition, habitat, and water quality influence coral bleaching in southern Florida. *Marine Ecology Progess Series* **408**, 65-78 (2010).
335) Wakeford, M. Assessment of bleaching at Flinders Reef, Coral Sea. (Australian Institute of Marine Science, Townsville, 2002).
336) Walsh, M. Coral bleaching hits the Maldives in the Indian Ocean, http://www.abc.net.au/news/2016-06-02/coral-bleaching-hits-the-maldives-in-the-indian-ocean/7468090 (2016).
337) Wantiez, L. Coral reefs of New Caledonia in 2006: status report and monitoring network. *Rev. Ecol.-Terre Vie* **63**, 117-132 (2008).
338) Wellington, G. M. & Glynn, P. W. in *Geological Approaches to Coral Reef Ecology*. 342-385 (Springer, 2007).
339) Williams, E. H. J. & Bunkley-Williams, L. The world-wide coral reef bleaching cycle and related sources of coral mortality. *Atoll Res Bull* **335**, 1-71 (1990).
340) Wilkinson, C. The 1997-1998 mass bleaching event around the world. 15-38 (Australian Institute of Marine Science, Townsville, Australia, 1998).
341) Wilkinson, C. *et al.* Ecological and socioeconomic impacts of 1998 coral mortality in the Indian Ocean: An ENSO Impact and a warning of future change? *Ambio* **28**, 188-196 (1999).
342) Wilkinson, C. & Souter, D. *Status of Caribbean Coral Reefs After Bleaching and Hurricanes in 2005*. (Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre, 2008).
343) Winter, A., Appeldoorn, S. R., Bruckner, A., Williams Jr., H. E. & Goenaga, C. Sea surface temperatures and coral reef bleaching off La Parguera, Puerto Rico (northeastern Caribbean Sea). *Coral Reefs* **17**, 377-382 (1998).
344) Woodley, J. D. *et al.* in *Status of Coral Reefs of the World: 2000* (Wilkinson, C. ed.) 261-285 (Australian Institute of Marine Science, 2000).
345) XL Caitlin Seaview Survey. Coral bleaching in Bermuda. http://catlinseaviewsurvey.com/news/30-09-2013/coral-bleaching-in-bermuda (2013).
346) XL Caitlin Seaview Survey. The 3rd Global Bleaching Event-2014/2016. www.globalcoralbleaching.org/ (2016).
347) Yamano, H. Coral reefs in a changing world-climate change and land based pollution issues and conservation strategies. *International Workshop on Eco-city and Biodiversity* **Session 2: Biodiversity**, 1 (2014).
348) Yeemin, T. *et al.* Impacts of coral bleaching, recovery and management in Thailand. *Proc. 12th Int. Coral Reef Symp., Cairns, Australia* (2012).
349) Zea, S. & Duque Tobon, F. Bleaching of reef organisms in the Santa Marta region, Colombia: 1987 Caribbean-wide event. *TRIANEA (Act. Cient. Tecn., INDERENA)* **3**, 37-51 (1989).

Table S2.

Bleaching probability since 1980. Results of a generalized linear mixed model fit by maximum likelihood (Laplace Approximation) showing the bleaching probability (bleached or not bleached) for different regions, and for years since 1980.

Region and years	**Estimate**	**Std. Error**	**z value**	**Pr(>|z|)**
Australasia	-3.675661	0.26823	-13.703	**2.00e-16**
Indian Ocean/Middle East	-3.776389	0.309041	-12.220	**2.00e-16**
Pacific	-2.728397	0.259412	-10.518	**2.00e-16**
West Atlantic	-1.335086	0.194862	-6.851	**7.31e-12**
Years since 1980 (Australasia)	0.076119	0.009823	7.749	**9.26e-15**
Years since 1980 (Indian Ocean/Middle East)	0.087404	0.011227	7.785	**6.96e-15**
Years since 1980 (Pacific)	0.043760	0.009936	4.404	**1.06e-05**
Years since 1980 (West Atlantic)	0.017479	0.007540	2.318	**0.0204**

Table S3

Bleaching severity probability since 1980. Results of a generalized linear model fit by maximum likelihood with simple random effects structure via Breslow and Clayton's PQL algorithm, showing probability of bleaching status (severe or not severe) for different regions, and for years since 1980.

Region and years	**Estimate**	**Std. Error**	**t-value**	**p-value**
Australasia	-4.685643	0.3691068	-12.694545	**0.0000**
Indian Ocean/Middle East	-4.025899	0.3511802	-11.463911	**0.0000**
Pacific	-3.172498	0.2872635	-11.043858	**0.0000**
West Atlantic	-2.276737	0.2360508	-9.645112	**0.0000**
Years since 1980 (Australasia)	0.092086	0.0134598	6.841573	**0.0000**
Years since 1980 (Indian Ocean/Middle East)	0.072645	0.0133423	5.444755	**0.0000**
Years since 1980 (Pacific)	0.044698	0.0116927	3.822747	**0.0001**
Years since 1980 (West Atlantic)	-0.000773	0.0110730	-0.069850	0.9443