Coral Reefs (2009) 28:841–850
DOI 10.1007/s00338-009-0522-8

REPORT

Sea-surface temperature and thermal stress in the Coral Triangle over the past two decades

E. L. Peñaflor · W. J. Skirving · A. E. Strong · S. F. Heron · L. T. David

Received: 8 January 2009 / Accepted: 5 June 2009 / Published online: 25 June 2009

Abstract Increasing ocean temperature has become one of the major concerns in recent times with reports of various related ecological impacts becoming commonplace. One of the more notable is the increased frequency of mass coral bleaching worldwide. This study focuses on the Coral Triangle region and utilizes the National Oceanic and Atmospheric Administration-Coral Reef Watch (NOAA-CRW) satellite-derived sea surface temperature (SST) and Degree Heating Weeks (DHW) products to investigate changes in the thermal regime of the Coral Triangle waters between 1985 and 2006. Results show an upward trend in SST during this period with an average rate of 0.2°C/decade. However, warming within this region is not uniform, and the waters of the northern and eastern parts of the Coral Triangle are warming fastest. Areas in the eastern part have experienced more thermal stress events, and these stress events appear to be more likely during a La Niña.

Keywords Coral Triangle · SST · Thermal stress · ENSO

Introduction

The Coral Triangle (CT) is the center of the highest coastal marine biodiversity in the world (Allen and Werner 2002). This region, located in the heart of the Indo-Pacific, includes the countries such as the Philippines, Indonesia, and Papua New Guinea (Fig. 1) and is home to more than 500 species of corals (Green and Mous 2004). Studies have also shown that the waters around Indonesia and the Philippines possess the highest reef fish endemism (Mora et al. 2003) and that the Philippines is also considered the global center of marine fish biodiversity (Carpenter and Springer 2005). As a bio-region, the CT, known also as the "East Indies Triangle" (Briggs 2005, 2007) and the "Indo-Malay-Philippines Archipelago" (Carpenter and Springer 2005), has become one of the most important target areas in marine biodiversity research.

Reports have shown, however, that species diversity and abundance in many parts of this region have been greatly threatened by both man-made and natural stresses (Burke et al. 2002; Wilkinson 2004). Specifically, studies have highlighted the alarming decline in coral cover in this region (Bruno and Selig 2007; Carpenter et al. 2008). The decline has been attributed to numerous contributing factors (Edinger et al. 1998; Fox et al. 2003) including the effect of increasing sea surface temperature (SST) over recent years (Carpenter et al. 2008).

The effect of SST increase has a wide range of effects on the marine ecosystem. Studies have shown that warm temperature anomalies have led to a reduction in primary production and a decrease in fish catch (Barber and Chavez 1986; McGowan et al. 1998). Another visible effect related to elevated SST is the resultant mass coral bleaching and related mortality (Hoegh-Guldberg 1999; Wilkinson 2004), which led to a decline in reef fish population in some areas (Pratchett et al. 2006), and may trigger coral disease outbreaks (Bruno et al. 2007). A pronounced increase in SST and coral bleaching such as that predicted for the coming decades (IPCC 2007; Hoegh-Guldberg et al. 2007) could

Communicated by Geology Editor Dr. Bernhard Riegl

E. L. Peñaflor (✉) · L. T. David
Marine Science Institute, University of the Philippines, Diliman, Quezon City 1101, Philippines
e-mail: elpenaflor@yahoo.com

W. J. Skirving · A. E. Strong · S. F. Heron
NOAA NESDIS Coral Reef Watch, E/RA31, SSMC1, 1335 East-West Highway, 20910 Silver Spring, MD, USA

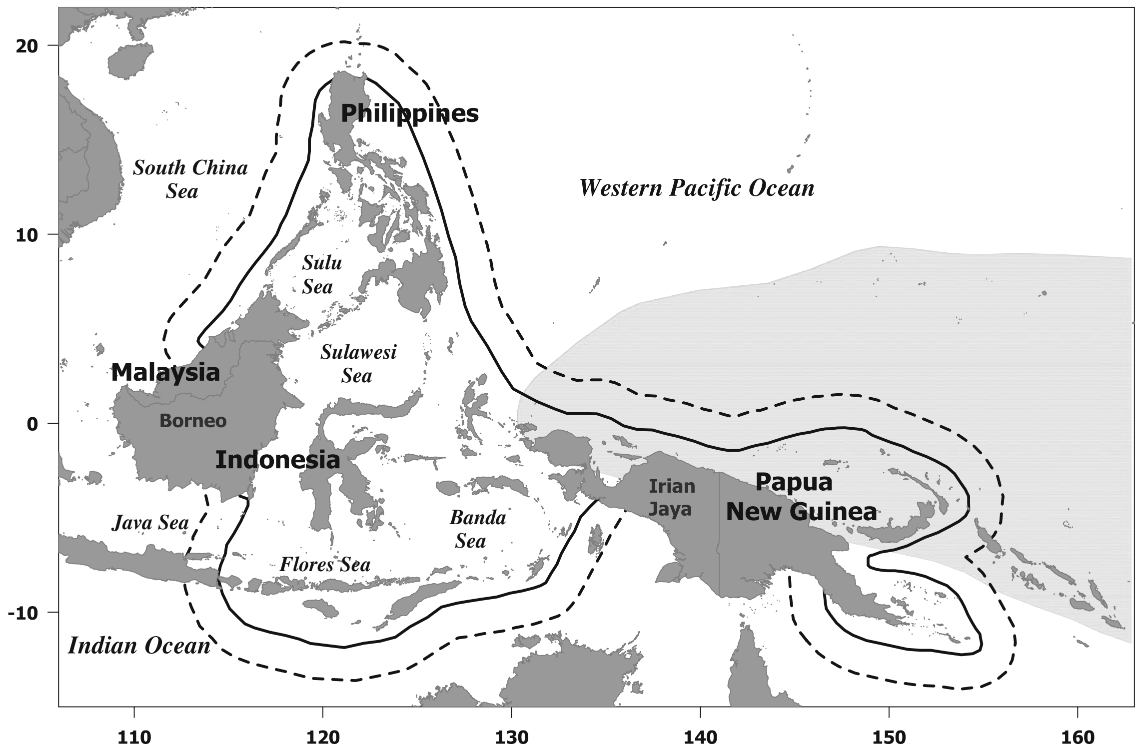


Fig. 1 Map of the Coral Triangle region. *Solid line* depicts border after Green and Mous (2004) and J. E. N. Veron (pers. comm.). The broken line represents the 200-km buffer zone extension used in this study. The *gray polygon* near Papua New Guinea represents the western end of the western Pacific warm pool (after Kleypas et al. 2008)

therefore lead to a significant depletion of the CT's already stressed marine resources.

The CT as a whole is known to experience a pronounced increase in SST during phases of ENSO (El Niño Southern Oscillation), which is a fluctuation between unusually warm and cold conditions in the tropical Pacific that typically recur with a period of 2–7 years (McPhaden et al. 2006). A good example of this was during the 1997–1998 ENSO when intense warming led to the widespread occurrences of coral bleaching in this region (Wilkinson 1998; Oliver et al. 2009). Bleaching in corals can be triggered when the thermal condition is as little as 1°C higher than the mean summer maximum (Berkelmans and Willis 1999; Jokiel and Brown 2004).

In order to monitor the presence of large-scale thermal stress, the National Oceanic and Atmospheric Administration's (NOAA)-Coral Reef Watch (CRW) developed a suite of satellite products based on the NOAA 0.5° (approximately 50 km) resolution Advanced Very High Resolution Radiometer (AVHRR) twice-weekly SST product. This CRW suite of satellite products has been successfully used to predict and monitor bleaching events all over the world (Liu et al. 2003; Skirving et al. 2006b; Strong et al. 2006).

Beyond this near real-time warning of bleaching occurrence, it is important to investigate how the SST and thermal stress have changed over time and in space in one of the most ecologically important regions in the world. To date, no study has been published that provides details of the long-term changes in spatial and temporal SST and thermal stress levels for the CT. This article will use a hindcast version of the NOAA CRW satellite product suite to examine the changes in SST and bleaching-level thermal stress within the Coral Triangle for the period 1985 to 2006.

Materials and methods

This study utilized the gap-filled, 0.5° resolution, biweekly SST product developed by the NOAA's CRW over the period 1985–2006. This product is based on the AVHRR Pathfinder SST data (http://pathfinder.nodc.noaa.gov) and was derived by CRW mimicking the methodology of the CRW near real-time product (Eakin et al. 2009).

The study area was extended beyond the CT boundary (Green and Mous 2004; verified by J. E. N. Veron, pers. comm. with WJS) by including a 200-km buffer zone to ensure that the analyses would not suffer from edge effects. Only data from this "buffered CT" (Fig. 1) were included in the study.

The SST data were then used to determine annual averages and ranges for the entire region. The annual average maximum and minimum for the entire region were calculated based on monthly SST averages. The trends in SST within the Coral Triangle were also calculated on a pixel by pixel basis by fitting a linear regression to the 22 years of biweekly SST data. Moreover, a spatial clustering of the entire SST data was also performed on the monthly means of each pixel, grouping pixels with similar SST signatures. The analysis made use of a web-based software, designed for geospatial clustering, called “Deluxe Integrated System for Clustering Operations” (DISCO) (http://fangorn.colby.edu/disco-devel). The clustering is based on k-means method, a popular clustering algorithm known for its speed and simplicity (Arthur and Vassilvitskii 2007). Several iterations of randomly seeded runs were performed to determine the consistency of pixel classification. As *k*-means requires the number of clusters as input, DISCO also provides means to estimate the optimal number of clusters in a given dataset. An article that describes the background of this online tool is downloadable at the URL cited above. The development of DISCO and its applications have been highlighted in Buddemeier et al. (2008).

An analysis using 0.5° resolution HotSpot and Degree Heating Weeks (DHW) was then conducted to determine the thermal stress levels and frequency of bleaching-level stress within the study area. The HotSpot anomaly, which is derived by subtracting a pixel’s SST by its maximum monthly mean SST climatology, is an index that indicates the current intensity of thermal stress for a given location. The SST climatology is constant in time but differs in each of the pixels (Liu et al. 2003). DHW, on the other hand, computes the cumulative thermal stress by accumulating HotSpot values greater than or equal to one. This is performed over a running 12-week period. Both are anomaly products derived from satellite sea surface temperatures. It is assumed that the surface anomaly products are approximately representative of conditions experienced by corals at depth. This is a reasonable assumption since the absolute temperatures at depth are likely to trend in the same direction as those on the surface during a coral bleaching event due to a lack of wind-driven mixing (Skirving et al. 2006a). A full description of these products is presented in Skirving et al. (2006b) and Strong et al. (2006).

In this analysis, a pixel-by-pixel calculation of the thermal stress frequency and annual thermal stress levels of reef pixels (1985–2006) were determined. The former highlighted areas within the study area with high occurrences of thermal stress events while the latter was used to compare the interannual changes in thermal stress level in reef locations. Data from the World Resources Institute’s

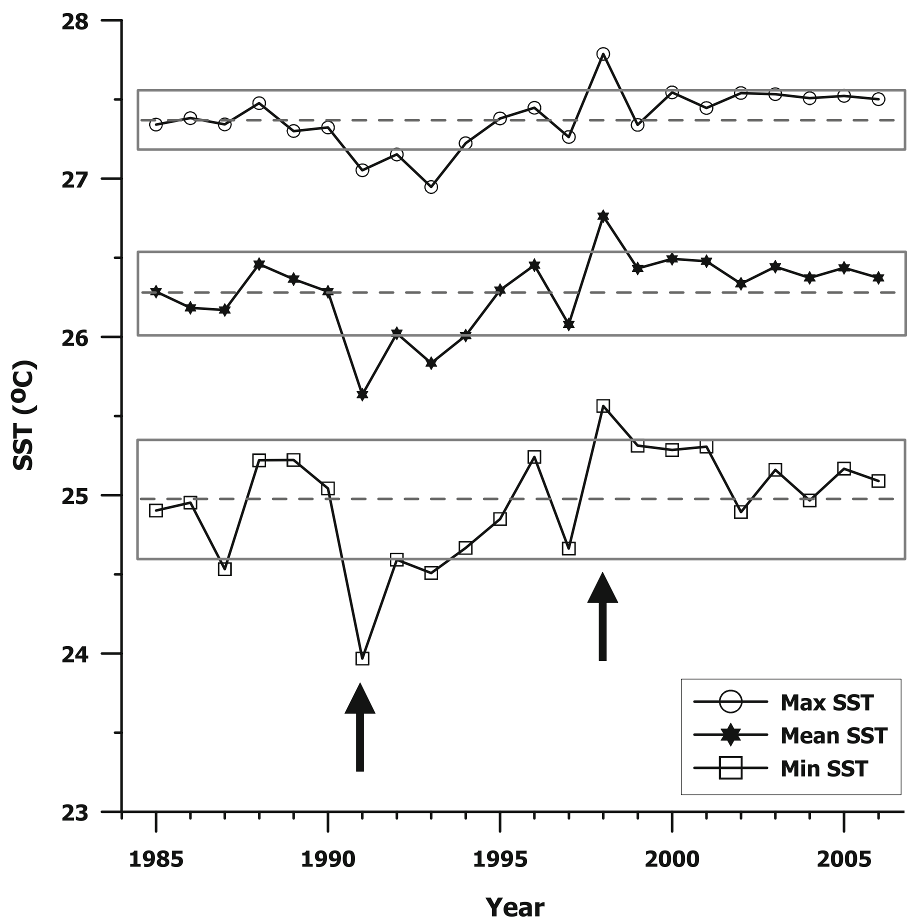


Fig. 2 Average sea surface temperatures (annual maximum, mean, and minimum) for the entire study area for the period 1985–2006. *Arrows* indicate Mt. Pinatubo eruption (1991) and strong El Niño/La Niña events (1998). *Boxes* indicate one standard deviation around 1985–2006 mean (in *broken, horizontal line*)

Reefs at Risk (http://www.wri.org) were utilized to determine the reef locations within the study area. A mask was then created to select pixels in the satellite products with reef sites, deemed "reef-pixels". All reef-pixels were then divided into clusters, as previously defined. The thermal stress level was calculated by determining the maximum DHW of that pixel within the duration of a stress event. A stress event is defined in this study to begin when DHW first has a value greater than 0 and end just before HotSpot goes below the value of 1. The event year is defined as the year when the stress event started. For example, if a stress event in a certain reef-pixel started in 1997 and ended in 1998 then the DHW value will be attributed to 1997. For some reef-pixels with multiple stress events in a year, only the event with the highest DHW value was considered. The per-pixel thermal stress frequency, on the other hand, was calculated by counting all the number of events reaching DHW > 0 and DHW ≥ 4. Occurrences of multiple stress events within a year were therefore considered in this part of the analysis.

The ecological impact of the thermal stress at particular DHW values is well established (Skirving et al. 2006b; Strong et al. 2006). DHW values greater than zero indicate the existence of thermal stress (regardless of severity) while DHW values of 4 and greater indicate the existence of sufficient thermal stress to produce significant levels of coral bleaching.

Results and discussion

The annual averages show that the entire region as a whole has experienced a slight increase in SST (maximum, average, and minimum) over the period 1985–2006 (Fig. 2). This trend seems to have stabilized since 2000. There are two noteworthy years. During 1991, the region experienced a drastic decrease in SST as a result of the Mt. Pinatubo eruption in the Philippines. The effects of this cooling are evident for 2–3 years after the eruption. Conversely, the region experienced dramatic warming in 1998. This warming resulted in widespread bleaching in many parts of this region (Wilkinson 1998; ReefBase [http://www.reefbase.org]). Interestingly, temperatures during 1997 were remarkably low considering the dramatic warming in 1998. This seesaw in SST was due to the occurrence of a very strong El Niño in 1997 and a very strong La Niña in 1998.

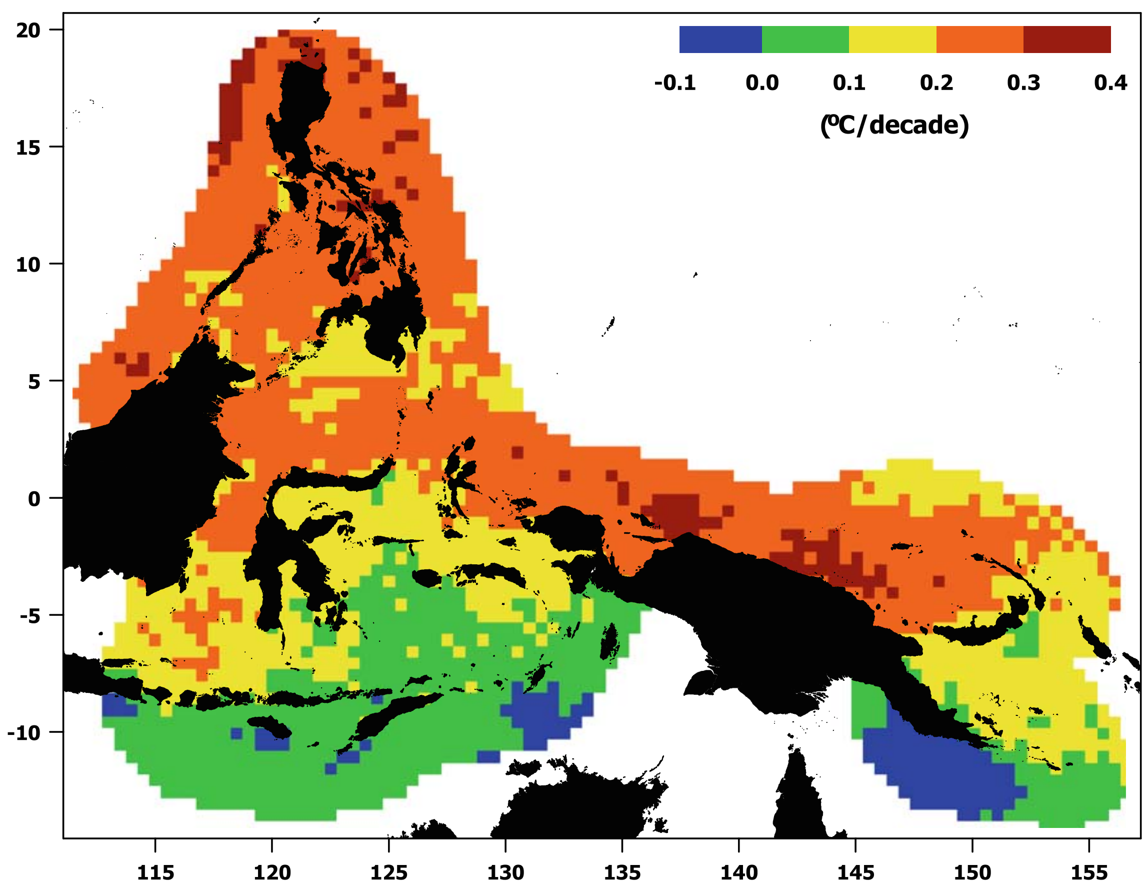


Fig. 3 Trends in sea surface temperature within each 0.5° × 0.5° pixel for the period 1985–2006 calculated from biweekly data

The contrasting differences in SST during these years are due to the temperature and geographic extent of the western Pacific warm pool (WPWP, SST > 28°C) that oscillates during ENSO events (Kawahata and Gupta 2004). This warm pool of surface water, which is normally located in the western equatorial Pacific, spreads eastward as the trade winds in the western and central equatorial Pacific weaken during an El Niño and shifts to the west of average location during a La Niña as trade winds intensify (McPhaden 1999; Kawahata and Gupta 2004). Normally, these easterly trade winds create a warm surface water pool in the western Pacific while upwelling cold water occurs on the eastern side (McPhaden et al. 2006). The weakening, or relaxation, of the trade winds during an El Niño leads to an ocean relaxation process as well, resulting in a shallower thermocline and cooler than normal temperature in the west Pacific and a deeper thermocline and warmer than normal temperature in the east Pacific (Enfield 2001). Consequently, in the CT region, an El Niño has a relative cooling effect while a La Niña is accompanied by warming.

The trends in SST within the Coral Triangle show that on average, the region's SST increased at a rate of 0.2°C/decade over the period 1985-2006 (Fig. 3). This value is comparable with the trends in many other tropical seas (Hoegh-Guldberg 1999). The SST trends varied spatially across the region with higher warming rates around the Philippines and north of Irian Jaya and Papua New Guinea, as compared to the southernmost CT areas (below 5S) where rates were much lower. Investigating the SST trends in an area can be valuable in explaining the occurrences of mass bleaching events because of the strong correlation between SST and bleaching events (Hoegh-Guldberg 1999). Studies have also shown that a rapid increase in SST has been a major factor in many large-scale coral bleaching occurrences in recent decades (Berkelmans et al. 2004; Lough et al. 2006).

Clustering analysis allows further examination of the SST scenarios within the region, and indicated 12 distinct sub-regions (clusters). Annual mean SST's were calculated for each of the clusters to determine the temporal changes in SST of these areas (Fig. 4). The majority of the clusters had greater number of warmer-than-average years in the latter 11 years, which explained the SST trends shown in Fig. 3. The pronounced increase in SST in 1998 was also

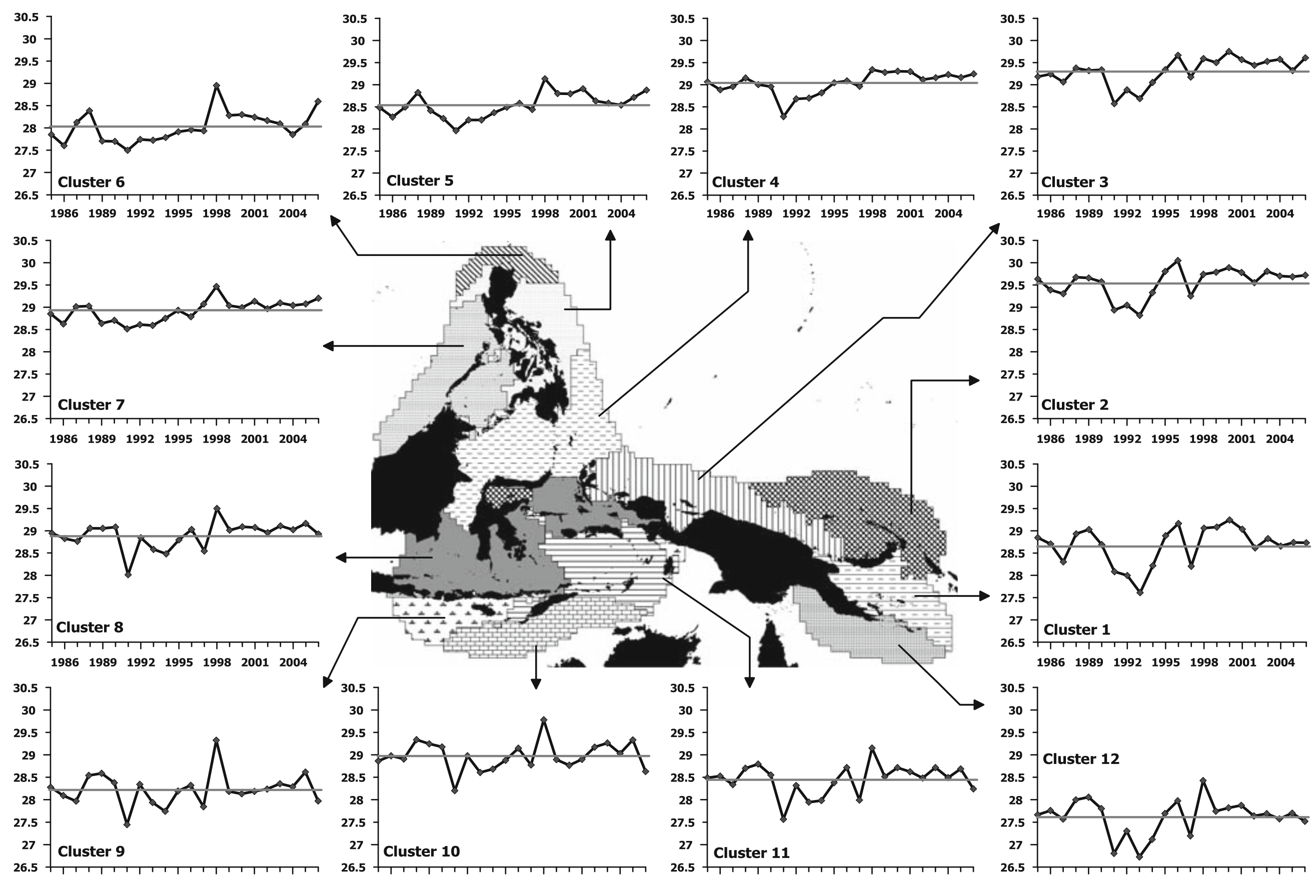


Fig. 4 The Coral Triangle divided into 12 clusters. *Graphs* show the annual mean SST for each cluster with *horizontal line* indicating the mean of the biweekly SST for all years

evident in many of the clusters. Northern clusters showed a consistent positive slope but with less frequent annual fluctuations. Corals located in these areas are more likely to be susceptible to future bleaching unless they develop mechanisms to cope with expected rapid increases in SST. The caveat to this statement is that corals in these areas could also have more time to reestablish due to the infrequency of stress events. The southern clusters, on the other hand, had smaller positive trends in SST but exhibited frequent pronounced fluctuations. The fluctuations may indicate that these areas frequently undergo temperature changes and it is possible that marine organisms in these areas (e.g., corals) have adapted to cope with more variable temperatures (more eurythermal). It has also been pointed out that high variability in temperature may help corals to better acclimate or adapt to an increase in temperature (McClanahan et al. 2007).

The trends in SST, however, are not the whole story as the length of time that corals are exposed to thermal stress is as important as the temperature reached. While the relatively slow SST increase in the southern sub-region could be interpreted to mean that coral reefs in this part of the CT have been subjected to less long-term thermal stress levels than in other areas of the region, this may not necessarily the case. The DHW product provides the metric to investigate trends in thermal stress.

An analysis of the thermal stress event frequency in this region (Fig. 5) revealed more thermal stress (DHW > 0) events and more occurrences of bleaching-level thermal stress (DHW $\geq$ 4) during 1996–2006 than during 1985–1995. Results also indicated the emergence of multiple stress events within a single year (DHW > 0) during the latter 11 years. The multiple stress events were most prominent in areas nearest to the WPWP.

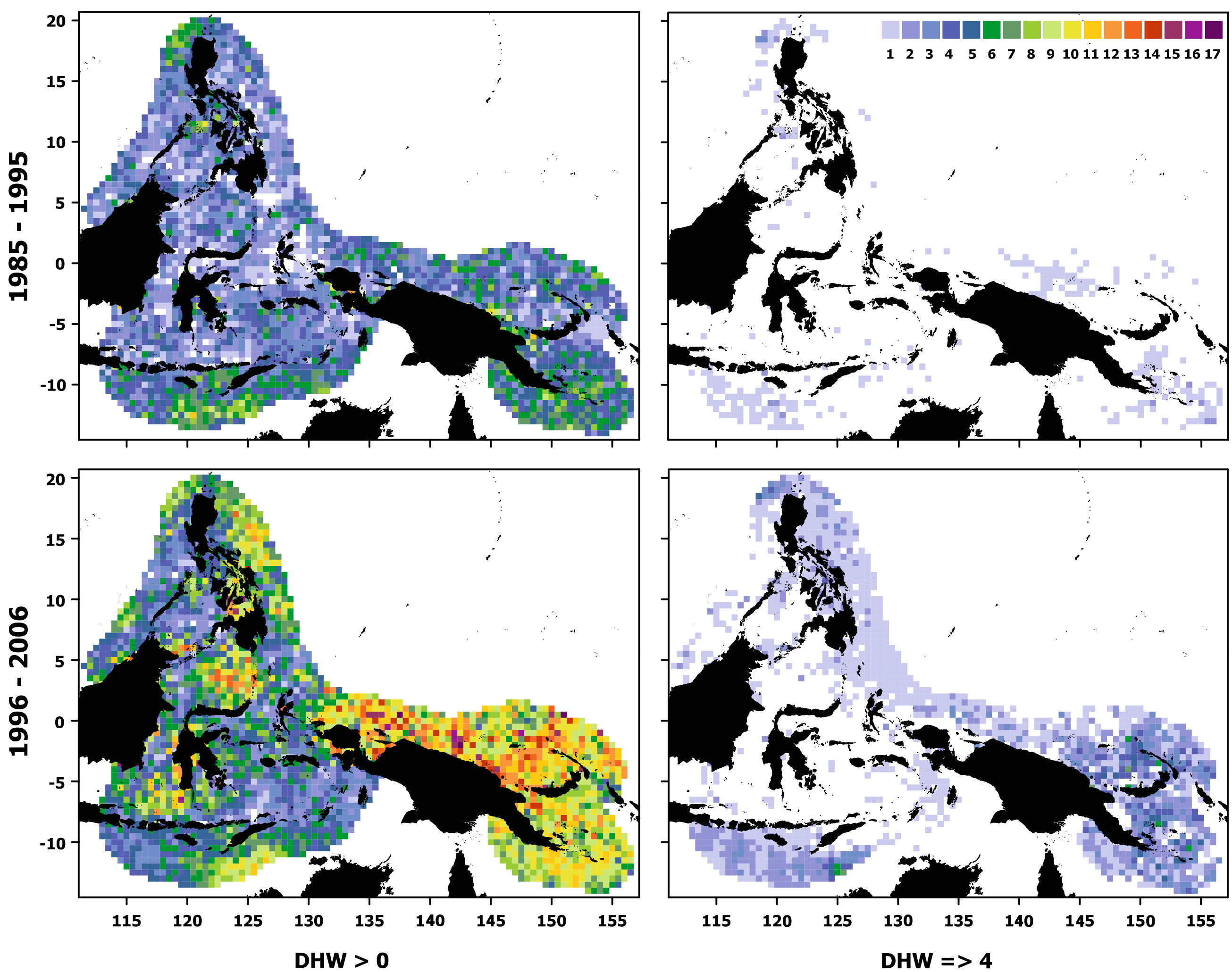


Fig. 5 Maps of the return frequency of thermal stress events reaching two thresholds, DHW > 0 (*left*) and DHW $\geq$ 4 (*right*). Upper images show the frequency of stress event occurrences from 1985 to 1995 while lower images depict years from 1996 to 2006. Some pixels show multiple event occurrences within a year, indicated by values greater than 11

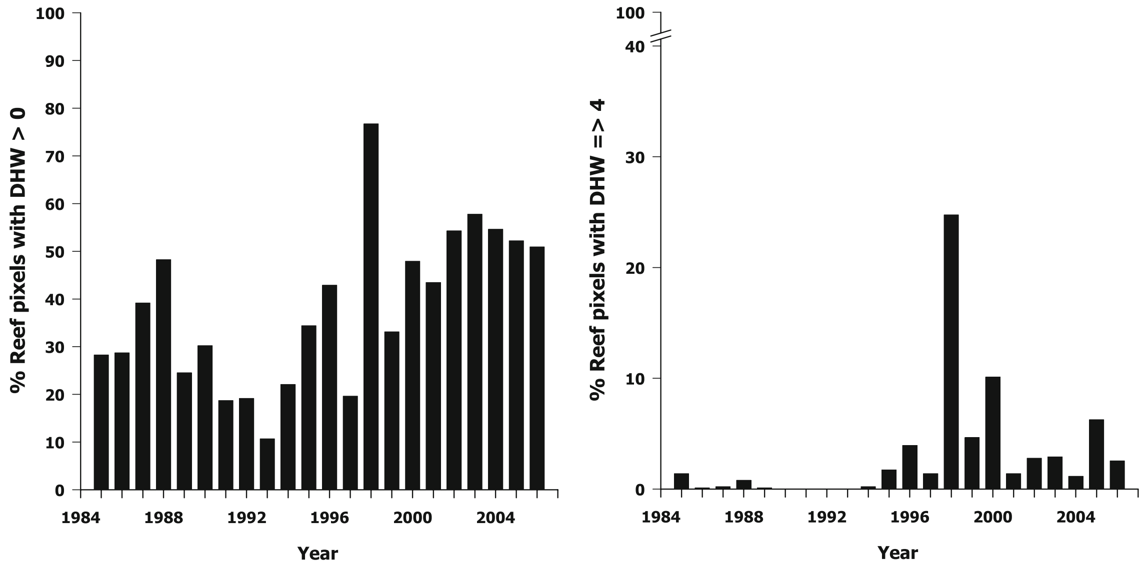


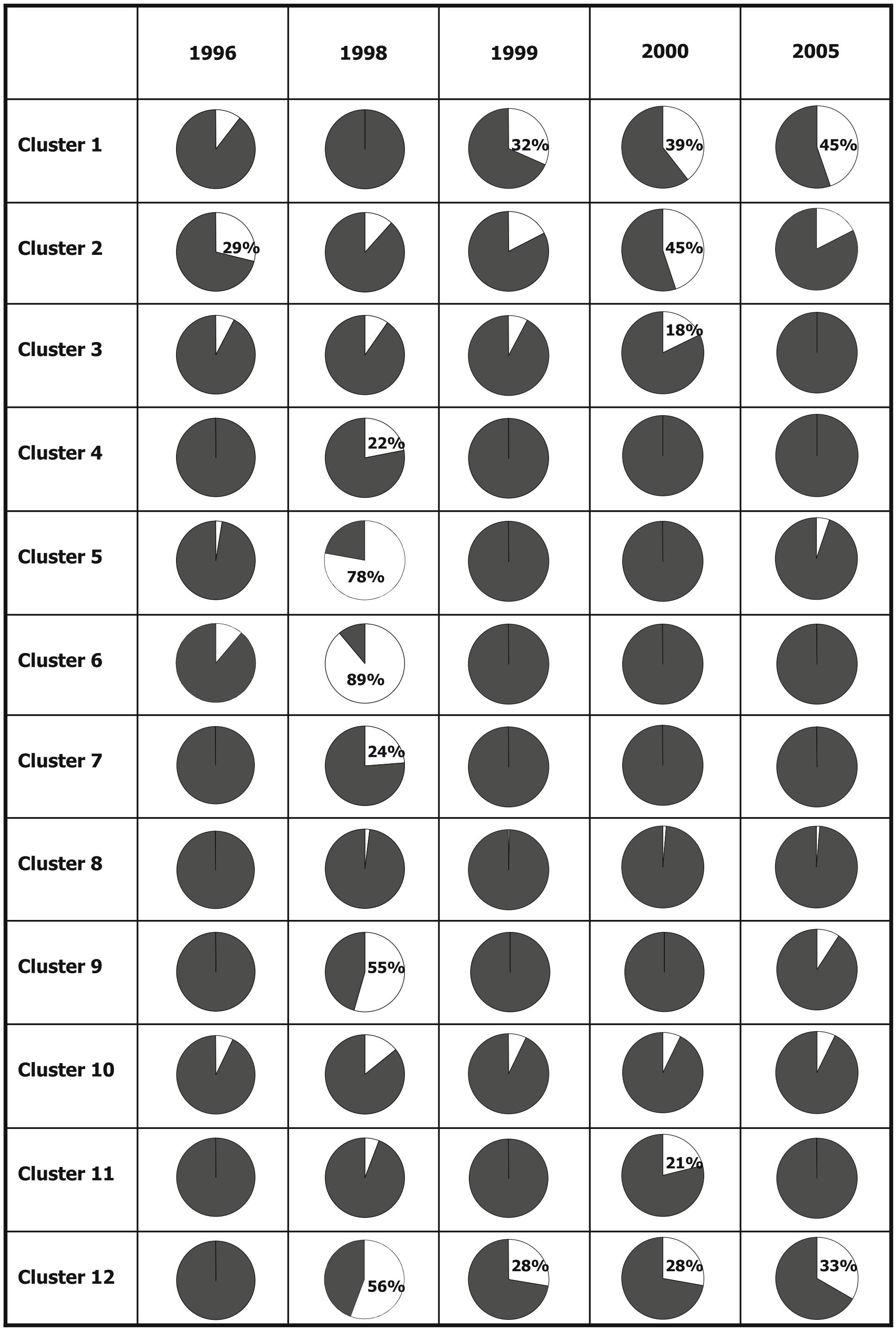
Fig. 6 Annual percentages of all known reef-containing pixels in the entire Coral Triangle reaching thermal stress thresholds of DHW > 0 (*left*) and DHW ≥ 4 (*right*)

The WPWP is of particular interest as this part of the Pacific has been shown to have warmed less over the past six decades in comparison to other tropical seas (Kleypas et al. 2008). This suggests a higher sensitivity of the corals in this region to small temperature fluctuations, yet these reefs seem to have a lower proportion of bleaching reports relative to other reefs in the world (Kleypas et al. 2008). Reefs in southeastern Papua New Guinea have not only experienced a relatively high frequency of thermal stress events (Fig. 5) but also showed a lower rate of increase in SST and experienced more extreme temperature fluctuations that oscillated about a relatively stable mean (Figs. 3, 4, respectively). In contrast, the inner seas of Indonesia had a few to no occurrences of significant thermal stress (DHW ≥ 4) even during the latter 11 years. The low frequency of thermal stress events in these areas may possibly have been due to the complex hydrodynamic processes in these areas (Gordon 2005; Qu et al. 2005). The complex geometry and connectivity through straits and passages coupled with other factors such as surface heat flux, tidal mixing, and monsoonal winds drive the complex distribution of SST in this region (Qu et al. 2005).

In order to investigate changes in thermal stress level for the CT, a temporal analysis of DHW data was performed for pixels known to contain coral reefs. The annual thermal stress levels are shown in Fig. 6, which shows that 1998 was the most anomalous year with 77% of the reef pixels having DHW > 0 and 25% with DHW ≥ 4. Higher levels of thermal stress were observed in 1996–2006 as compared to 1985–1995. The dramatic increase in the levels of thermal stress during the 1996–2006 period may have been linked to the Pacific Decadal Oscillation (PDO) reversal in the late 1990s (Strong et al. 2006). The PDO refers to the interdecadal (∼2–3 decades) oscillation of Pacific Ocean temperatures between warm and cold phases (Strong et al. 2006; Mantua and Hare 2002).

Further analysis was performed on the data from the five years with the highest percentages of reef pixels with DHW ≥ 4: 1996, 1998, 1999, 2000, and 2005 (Fig. 7). These years are concurrent with the La Niña events with the exception of 2005, which is an ENSO-neutral year. 2005 is currently the warmest year on record based on global temperature averages (Shein 2006). In this analysis, only pixels with DHW ≥ 4 were included since this level of thermal stress has been observed to indicate significant bleaching in corals (Skirving et al. 2006b; Strong et al. 2006). The year 1998, when a very strong La Niña occurred, again stands out with the highest number of clusters showing bleaching-level stress. This further supports the occurrence of widespread bleaching in many parts of the CT in 1998. Noticeably, clusters 5 and 6 in the northernmost Philippines are the most impacted during the very strong La Niña. Cluster 1, at the southeastern extent of the CT, is the only cluster that had no reef pixels with bleaching-level thermal stress in 1998. The observed SST in that year (Fig. 4) was not high enough or sustained for long enough to cause bleaching-level thermal stress. Clusters 2 and 3 also have lower proportions of reef pixels with this level of thermal stress in 1998 but all the three clusters (1, 2, and 3) showed higher percentages of stress in the other four years. Figure 7 also shows that reef pixels in clusters 1, 2, 3, 10, and 12 have more frequent occurrences

Fig. 7 Percentages of reef pixels (*white portion* in each pie chart) for each cluster with DHW $\geq$ 4 during selected years



of bleaching-level thermal stress (DHW $\geq$ 4) in the selected five years, while the middle latitude clusters, 4 and 7, are among the least frequent. Cluster 8 seemed to be the least affected overall with very low proportions of this level of stress.

Overall, this study shows that more warming and more thermal stress events were observed from 1996 onward as compared to the earlier half of the record. This is likely to be a consequence of climate change, i.e., PDO phase shift superimposed on the warming trend. However, further investigation is needed to check that this increase is not an artifact of the relatively short satellite SST record. Results also show the variability of SST in both time and space for various parts of the Coral Triangle. There are areas that are warming up faster but are experiencing less frequent annual SST fluctuations. These areas are also affected by significant levels of thermal stress as in the case of the northern Coral Triangle (particularly clusters 5 and 6). Corals in these areas are likely to be susceptible to future bleaching occurrences if they cannot cope with the rapid increase in SST.

There are also areas that afford natural protection from warming events as in the case of the inner seas of Indonesia. Some areas in the southern portion of the region (clusters 1, 10, and 12) have highly fluctuating SSTs accompanied with frequent thermal stress events, and yet exhibit no significant increase in long-term SST. In these areas, corals may be more adapted to warm SST anomalies and more likely to see slower warming in coming decades. Also, more thermal stress occurrences were observed in the easternmost parts of the region (clusters 2 and 3), which may have provided opportunity for the development of corals that are more resistant to thermal stress events. The effect of the faster warming rates on corals located in these areas needs further investigation.

The analyses of SSTs and thermal stress in the Coral Triangle portray a significantly varied story. The northern areas are experiencing greater increases in SST through time compared to the southern areas. The eastern parts of the region, on the other hand, show significant increases in thermal stress events compared to the western parts. Lastly, significant bleaching events are more likely to occur in the Coral Triangle during a La Niña, and not during El Niño, with the northern areas more likely affected during a very strong event.

Acknowledgments This study was supported by the World Bank/GEF Coral Reef Targeted Research program—Remote Sensing Working Group with chair Dr. Peter Mumby. The authors are also grateful to Dr. Bruce Maxwell of Colby College, Waterville for his assistance in the clustering analysis, and Dr. C. Mark Eakin of NOAA-NESDIS CRW for his invaluable comments on the manuscript. The manuscript contents are solely the opinions of the authors and do not constitute a statement of policy, decision, or position on behalf of NOAA or the U.S. Government.

References

Allen GR, Werner TB (2002) Coral reef fish assessment in the 'coral triangle' of southeastern Asia. Environ Biol Fish 65:209–214

Arthur D, Vassilvitskii S (2007) K-means ++: The advantages of careful seeding. Proceedings of the 18th annual ACM-SIAM Symposium on Discrete Algorithms, pp 1027–1035

Barber RT, Chavez FP (1986) Ocean variability in relation to living resources during the 1982–83 El Niño. Nature 319:279–285

Berkelmans R, Willis BL (1999) Seasonal and local spatial patterns in the upper thermal limits of corals on the inshore Central Great Barrier Reef. Coral Reefs 18:219–228

Berkelmans R, De'ath G, Kininmonth S, Skirving WJ (2004) A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns, and predictions. Coral Reefs 23:74–83

Briggs JC (2005) Coral reefs: Conserving the evolutionary sources. Biol Conserv 126:297–305

Briggs JC (2007) Marine longitudinal biodiversity: causes and conservation. Divers Distrib 13:544–555

Bruno JF, Selig ER (2007) Regional decline of coral cover in the Indo-Pacific: Timing, extent, and subregional comparisons. PLoS ONE 2:e711. doi:10.1371/journal.pone.0000711

Bruno JF, Selig ER, Casey KS, Page CA, Willis BL, Harvell CD, Sweatman H, Melendy AM (2007) Thermal stress and coral cover as drivers of coral disease outbreaks. PLoS Biol 5:e124. doi:10.1371/journal.pbio.0050124

Buddemeier RW, Smith SV, Swaney DP, Crossland CJ, Maxwell BA (2008) Coastal typology: An integrative "neutral" technique for coastal zone characterization and analysis. Estuar Coast Shelf Sci 77:197–205

Burke L, Selig E, Spalding M (2002) Reefs at risk in Southeast Asia. World Resources Institute, Washington D. C.

Carpenter KE, Springer VG (2005) The center of the center of marine shore fish biodiversity: the Philippine Islands. Environ Biol Fish 72:467–480

Carpenter KE, Abrar M, Aeby G, Aronson RB, Banks S, Bruckner A, Chiriboga A, Cortés J, Delbeek JC, DeVantier L, Edgar GJ, Edwards AJ, Fenner D, Guzmán HM, Hoeksema BW, Hodgson G, Johan O, Licuanan WY, Livingstone SR, Lovell ER, Moore JA, Obura DO, Ochavillo D, Polidoro BA, Precht WF, Quibilan MC, Reboton C, Richards ZT, Rogers AD, Sanciangco J, Sheppard A, Sheppard C, Smith J, Stuart S, Turak E, Veron JEN, Wallace C, Weil E, Wood E (2008) One-third of reef-building corals face elevated extinction risk from climate change and local impacts. Science 321:560–563

Eakin CM, Lough JM, Heron SF (2009) Climate variability and change: Monitoring data and evidence for increased coral bleaching stress. In: van Oppen M, Lough JM (eds) Coral bleaching: Patterns, processes, causes and consequences. Springer, Heidelberg, pp 41–67

Edinger EN, Jompa J, Limmon GV, Widjatmoko W, Risk MJ (1998) Reef degradation and coral biodiversity in Indonesia: Effects of land-based pollution, destructive fishing practices and changes over time. Mar Pollut Bull 36:617–630

Enfield DB (2001) Evolution and historical perspective of the 1997–1998 El Nino-Southern Oscillation event. Bull Mar Sci 69:7–25

Fox HE, Pet JS, Dahuri R, Caldwell RL (2003) Recovery in rubble fields: long-term impacts of blast fishing. Mar Pollut Bull 46: 1024–1031

Gordon AL (2005) Oceanography of the Indonesian seas and their throughflow. Oceanography 18:14–27

Green A, Mous PJ (2004) Delineating the Coral Triangle, its ecoregions and functional seascapes. Report on an expert workshop held in Southeast Asia Center for Marine Protected Areas, Bali, Indonesia, April 30-May 2, 2003, The Nature Conservancy

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

Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, Harvell DR, Sale PF, Edwards AJ, Caldeira K, Knowlton N, Eakin CM, Iglesias-Prieto R, Muthiga N, Bradbury RH, Dubi A, Hatziolos ME (2007) The carbon crisis: coral reefs under rapid climate change and ocean acidification. Science 318:1737–1742

IPCC (2007) Summary for Policymakers. In: Climate change 2007: Synthesis report. Contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change. IPCC, Switzerland http://www.ipcc.ch/ipccreports/ar4-syr.htm

Jokiel PL, Brown EK (2004) Global warming, regional trends and inshore environmental conditions influence coral bleaching in

Hawaii. Global Change Biol 10:1627–1641. doi:10.1111/j.1365-2486.2004.00836.x

Kawahata H, Gupta LP (2004) Settling particles flux in response to El Niño/Southern Oscillation (ENSO) in the equatorial Pacific. In: Shiyomi M, Kawahata H, Koizumi H, Tsuda A, Awaya Y (eds) Global environmental change in the ocean and on land. Terrapub, Tokyo, pp 95–108

Kleypas JA, Danabasoglu G, Lough JM (2008) Potential role of the ocean thermostat in determining regional differences in coral bleaching events. Geophys Res Lett 35:L03613. doi:10.1029/2007GL032257

Liu G, Strong AE, Skirving W (2003) Remote sensing of sea surface temperatures during 2002 Barrier Reef coral bleaching. EOS Trans Am Geophys Union 84:137–144

Lough J, Berkelmans R, van Oppen M, Wooldridge S, Steinberg C (2006) The Great Barrier Reef and climate change. Bull Aust Meteor Oceanogr Soc 19:53–58

Mantua NJ, Hare SR (2002) The Pacific Decadal Oscillation. J Oceanogr 58:35–44

McClanahan TR, Ateweberhan M, Graham NAJ, Wilson SK, Sebastian CR, Guillaume MMM, Bruggemann JH (2007) Western Indian Ocean coral communities: bleaching responses and susceptibility to extinction. Mar Ecol Prog Ser 337:1–13

McGowan JA, Cayan DR, Dorman LM (1998) Climate-ocean variability and ecosystem response in the Northeast Pacific. Science 281:210–217

McPhaden MJ (1999) Genesis and evolution of the 1997–98 El Niño. Science 283:950–954

McPhaden MJ, Zebiak SE, Glantz MH (2006) ENSO as an integrating concept in Earth science. Science 314:1740–1745

Mora C, Chittaro PM, Sale PF, Kritzer JP, Ludsin SA (2003) Patterns and processes in reef fish diversity. Nature 421:933–936

Oliver JK, Berkelmans R, Eakin CM (2009) Coral bleaching in space and time. In: van Oppen M, Lough JM (eds) Coral bleaching: Patterns, processes, causes and consequences. Springer, Heidelberg, pp 21–39

Pratchett MS, Wilson SK, Baird AH (2006) Declines in the abundance of Chaetodon butterflyfishes following extensive coral depletion. J Fish Biol 69:1269–1280. doi:10.1111/j.1095-8649.2006.01161

Qu T, Du Y, Strachan J, Meyers G, Slingo J (2005) Sea surface temperature and its variability in the Indonesian region. Oceanography 18:50–61

Shein KA (ed) (2006) State of the climate in 2005. Bull Am Meteorol Soc 87:S1-S102

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

Skirving W, Strong AE, Liu G, Arzayus F, Liu C, Sapper J (2006b) Extreme events and perturbations of coastal ecosystems: Sea surface temperature change and coral bleaching. In: Richardson LL, LeDrew EF (eds) Remote sensing of aquatic coastal ecosystem processes: Science and management applications. Springer, Netherlands, pp 11–25

Strong AE, Arzayus F, Skirving W, Heron SF (2006) Identifying coral bleaching remotely via Coral Reef Watch–Improved integration and implications for changing climate. In: Phinney JT, Hoegh-Guldberg O, Kleypas J, Skirving W, Strong A (eds) Coral reefs and climate change: Science and management, coastal and estuarine studies 61. American Geophysical Union, Washington, D.C, pp 163–180

Wilkinson C (ed) (1998) Status of coral reefs of the world: 2000. Australian Institute of Marine Science, Townsville, Queensland, Australia

Wilkinson C (ed) (2004) Status of the coral reefs of the world: 2004. Australian Institute of Marine Science, Townsville, Queensland, Australia