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Potential role of the ocean thermostat in determining regional differences in coral reef bleaching events

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[1] Several negative feedback mechanisms have been proposed by others to explain the stability of maximum sea surface temperature (SST) in the western Pacific warm pool (WPWP). If these "ocean thermostat" mechanisms effectively suppress warming in the future, then coral reefs in this region should be less exposed to conditions that favor coral reef bleaching. In this study we look for regional differences in reef exposure and sensitivity to increasing SSTs by comparing reported coral reef bleaching events with observed and modeled SSTs of the last fifty years. Coral reefs within or near the WPWP have had fewer reported bleaching events relative to reefs in other regions. Analysis of SST data indicate that the warmest parts of the WPWP have warmed less than elsewhere in the tropical oceans, which supports the existence of thermostat mechanisms that act to depress warming beyond certain temperature thresholds. **Citation:** Kleypas, J. A., G. Danabasoglu, and J. M. Lough (2008), Potential role of the ocean thermostat in determining regional differences in coral reef bleaching events, *Geophys. Res. Lett.*, *35*, L03613, doi:10.1029/2007GL032257.

1. Introduction

[2] Sea surface temperature (SST) records across the region suitable for coral reef growth (where temperatures remain >16°C year round) document a 0.3–0.4°C warming over the last two to three decades (Figure 1a). Such rapid warming is considered a major cause of large-scale coral bleaching events [*Berkelmans et al.*, 2004; *Lough*, 2000] that have become increasingly common in the last three decades [*Wilkinson*, 2004]. SSTs are expected to increase further with increasing atmospheric greenhouse gas concentrations, leaving coral reef ecosystems increasingly vulnerable to future coral bleaching events. Some predictions suggest that many coral reefs will experience bleaching annually by the middle of this century [*Hoegh-Guldberg*, 1999]; others suggest that adaptation could reduce this vulnerability [*Donner et al.*, 2005]. Regardless of the range of predictions, the question is no longer "will coral reef bleaching continue in the coming decades?" but "will coral reefs persist despite increased bleaching frequency?"

[3] A factor that may affect bleaching frequency in the future is the hypothesized "ocean thermostat." This proposes that maximum SSTs in the ocean should be around 30–31°C, based on both theory [*Newell*, 1979] and observations [*Clement et al.*, 2005]. The presence of ocean thermostat mechanisms is important to coral reefs because those that exist in the warmest regions of the open ocean may experience less warming in the future, and thus less coral bleaching. Three main processes that limit open ocean SSTs have been proposed: (1) latent heat flux or evaporation-wind-SST feedback [*Newell*, 1979; *Wallace*, 1992]; (2) cloud-SST feedback or cloud shortwave radiative forcing [*Ramanathan and Collins*, 1991]; and (3) ocean dynamics and heat transport [*Seager and Murtugudde*, 1997; *Sun and Liu*, 1996]. Latent heat flux acts at all spatial scales but, as evidenced by higher temperatures in enclosed seas, limits SSTs to 33–34°C at best. In the open oceans, maximum SSTs are typically around 30–31°C due to large-scale mechanisms such as convective processes that increase cloud cover and winds, or advective heat transport by ocean currents, that further lower the SST limit. Thus, a combination of processes operating at different scales act to restrain maximum SSTs [*Li et al.*, 2000], and a change in one or more–say, with increased greenhouse gas forcing–may ultimately change the upper SST limit.

[4] The thermostat hypothesis has mixed support from paleontological modeling and observations (see auxiliary material).[1] We look for evidence of an ocean thermostat by analyzing the patterns of recent SST warming in the tropics, using the past five decades of the HadISST monthly SSTs. We examine whether regional differences in warming coincide with regional differences in coral bleaching reports from the ReefBase Coral Bleaching database [*ReefBase Project*, 2007]. We also examine SST simulations from the National Center for Atmospheric Research (NCAR) Community Climate System Model version 3 (CCSM3) for its ability to capture the same regional differences and thus serve as a predictive tool. We pay particular attention to the WPWP because this is a region where maximum SSTs are thought to be limited by negative feedbacks [*Clement et al.*, 1996; *Newell*, 1979; *Ramanathan and Collins*, 1991; *Sun and Liu*, 1996]. The WPWP has been defined by both geographic and temperature limits; here, we apply the WPWP definition as the area where SST > 28°C year-round [*Yan et al.*, 1997].

2. Methods

2.1. Observed SSTs

[5] Several globally-gridded data sets of in-situ and satellite-observed SST were considered for analysis: (1) HadISST monthly SSTs [*Rayner et al.*, 2003], on a 1° × 1° grid, for the period 1887–2006; (2) ERSST monthly SSTs [*Smith and Reynolds*, 2003], on a 2° × 2°

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL032257.

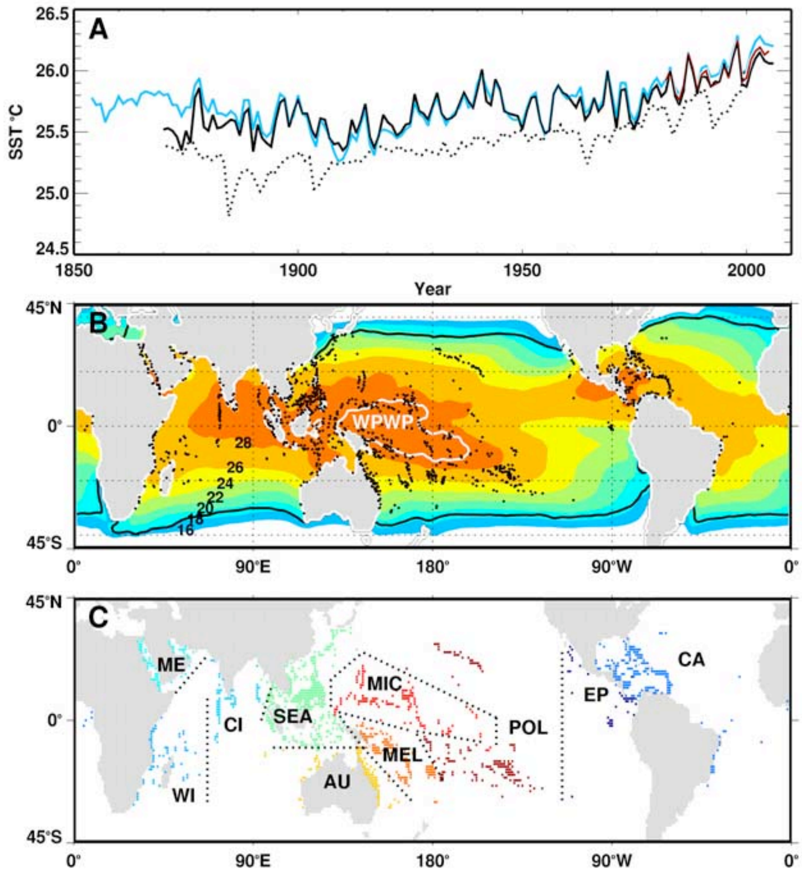

Figure 1. (a) Average annual SST for the region of analysis, from HadISST (black), ERSST (blue), Reynolds OISST weekly data (red), and CCSM3 four-member ensemble of 20th Century integrations (dotted). (b) Region of analysis, where monthly SST > 16°C year-round (black line). Also shown is average SST (°C) for years 1950–1969 (from HadISST); note SST contour labels in Indian Ocean. White line, WPWP boundary. Black dots, reef locations. (c) 1° × 1° reef cells within reef regions: EP, East Pacific; CA, Caribbean/Atlantic; WI, West Indian; CI, Central Indian; ME, Middle East; SEA, Southeast Asia; AU, Australia; MEL, Melanesia; MIC, Micronesia; POL, Polynesia.

grid, for the period 1850–2006; and (3) OISST weekly SSTs [*Reynolds et al.*, 2002], on a 1° × 1° grid, for the period 1982–2006. Given the similarity of these SST reconstructions (Figure 1a) we limit our analyses to the HadISST data, and to the years 1950–2006 because of the higher number and quality of SST observations for this time period. Beginning in 1950, 10-year and 20-year averages of annual mean, minimum and maximum SSTs are determined for every 1° × 1° grid cell where SSTs are not limiting to coral reefs (i.e., where minimum SSTs > 16°C; Figure 1b). Averages are calculated from the monthly SSTs by first determining the mean, minimum and maximum for each year of a particular period, and then averaging those values.

2.2. Model SST Data

[6] Modeled estimates of SSTs are obtained from a four-member ensemble of 20th Century (1870–2000) CCSM3 simulations [*Collins et al.*, 2006]. These integrations include anthropogenic forcings as well as natural forcings such as solar variability and volcanic aerosols [*Meehl et al.*, 2006]. Atmospheric CO_2 levels reach 370 ppmv by the end of year 2000. The ocean model resolution is uniform at 1.125° in the longitudinal direction; and varies considerably in the latitudinal direction, with a resolution of about 0.3° in equatorial and tropical regions [*Danabasoglu et al.*, 2006]. We analyze the CCSM3 monthly-mean SST fields following the same procedures used for the HadISST record.

2.3. Coral Bleaching Data

[7] Coral bleaching records are obtained from the ReefBase Coral Bleaching dataset [*ReefBase Project*, 2007]. This is a global, *ad hoc* compilation of formal and voluntary coral bleaching reports, mainly from the period 1980–2005 (a potential bias in this database is that remote reefs may be observed less often than other reefs). Most reports include an estimate of bleaching severity as mild, moderate, or severe. We summarize the number of bleaching reports, by bleaching severity, for 1° × 1° cells consistent with the HadISST grid. A "reef cell" is defined as a 1° × 1° cell that contains at least 1 reef (Figure 1c), and is identified as "bleached" if a bleaching event of any severity was ever noted in that particular cell during 1980–2005, and as

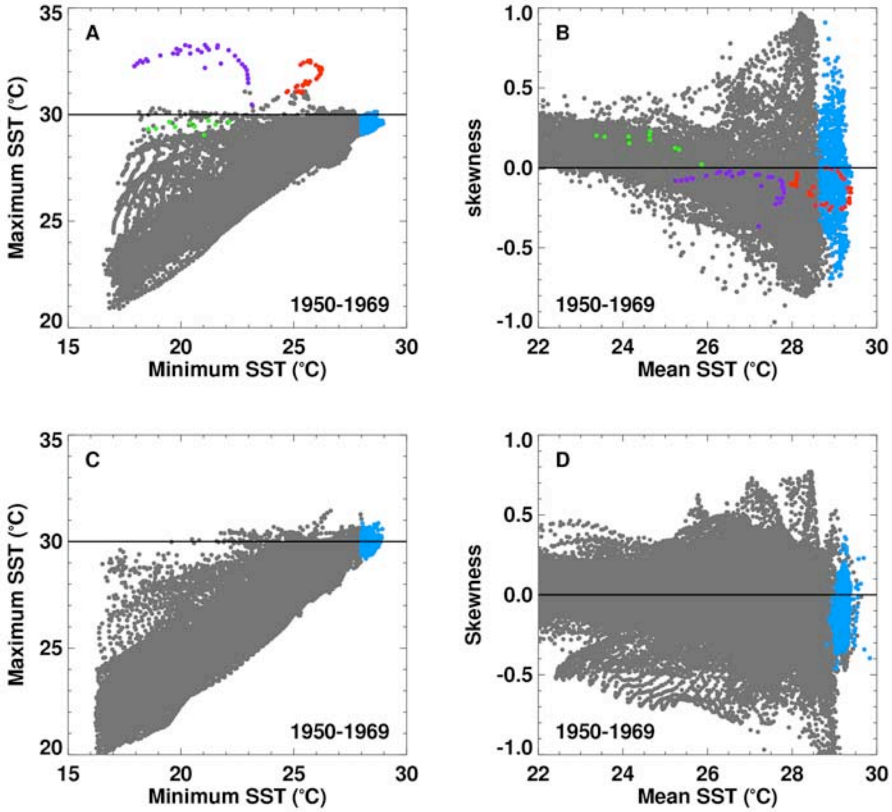

Figure 2. Characteristics of tropical SSTs, calculated for years 1950–1969. (a) Average annual SST_{max} versus average annual SST_{min}. (b) Skewness versus average SST. Blue, WPWP; red, Red Sea; purple, Persian Gulf; green, Gulf of California; gray, other locations. (c, d) As in Figures 2a and 2b, based on CCSM3 four-member ensemble of 20th century integrations. Note that enclosed seas are not resolved in the CCSM3.

"severely bleached" if a severe bleaching event was ever noted. Some reef cells along coastlines are not covered by the HadISST data set.

3. Results

3.1. SSTs

3.1.1. SST Patterns

[8] The distribution of average maximum SST (SST_{max}) versus average minimum SST (SST_{min}) for the period 1950–1969 (Figure 2a) illustrates a sharp limit to SST_{max} near 30°C. This limit is apparent regardless of the time interval analyzed. Locations where SST_{max} exceeds this limit are almost entirely within enclosed seas.

[9] Monthly SST distributions from sites where mean SST remained below 28°C (SST_{mean}< 28°C) are normal to slightly positively skewed (Figure 2b). Where SSTs are limited to some maximum value, warming should result in a shift in the SST distribution toward negative skewness [*Clement et al.*, 2005]. Based on the 1950–1969 HadISST data, the SST distribution patterns vary greatly, but become increasingly negatively skewed where SST_{mean} exceeds 28°C (where SST_{mean} < 28°C, 44% are negatively skewed; where SST_{mean} > 28°C, 65% are negatively skewed). The SST distributions have also become increasingly negatively skewed over time and, by 1987–2006, 78% of the SST_{mean} > 28°C locations are negatively skewed. Maximum SSTs from the modeled data are slightly warmer than the HadISST data (Figure 2c), but trends in skewness of the SST distributions versus SST_{mean} are similar to those in the HadISST data, i.e., a shift toward negative skewness with increasing SST. For 1950–1969, where SST_{max} < 28°C, 46% of locations are negatively skewed; where SST_{max} > 28°C, 70% are negatively skewed (Figure 2d).

3.1.2. Warming Versus Maximum SST

[10] If mechanisms act to limit open ocean SSTs to some maximum value, then within the recent warming trend in the tropics one would expect less warming in the warmest waters than elsewhere. The difference between SST_{max} for the periods 1950–1969 and 1987–2006 shows an average warming of about 0.2–0.4°C where SST_{max} < 29.5°C; above 29.5°C the degree of warming drops off rapidly (Figure 3a). Where SST_{max} > 29.0°C, the degree of warming is negatively correlated with SST_{max} (Pearson correlation coefficient = −0.99, n = 2162 grid cells). These results are very similar for comparisons between other time-slices, including: 1950–1959 versus 1990–1999 and 1960–69 versus 1999–2006. Warming of the tropical oceans has thus led to an expansion of the WPWP, but without a large increase in WPWP SST_{max} (see Figure S1 of the auxiliary material).

[11] Model simulations of SSTs for the 20th Century show variations similar to the HadISST record, although average model SSTs are cooler by 0.2–0.3°C (Figure 1a). CCSM3 results agree with HadISST in that warming of maximum SSTs was less for regions with higher maximum

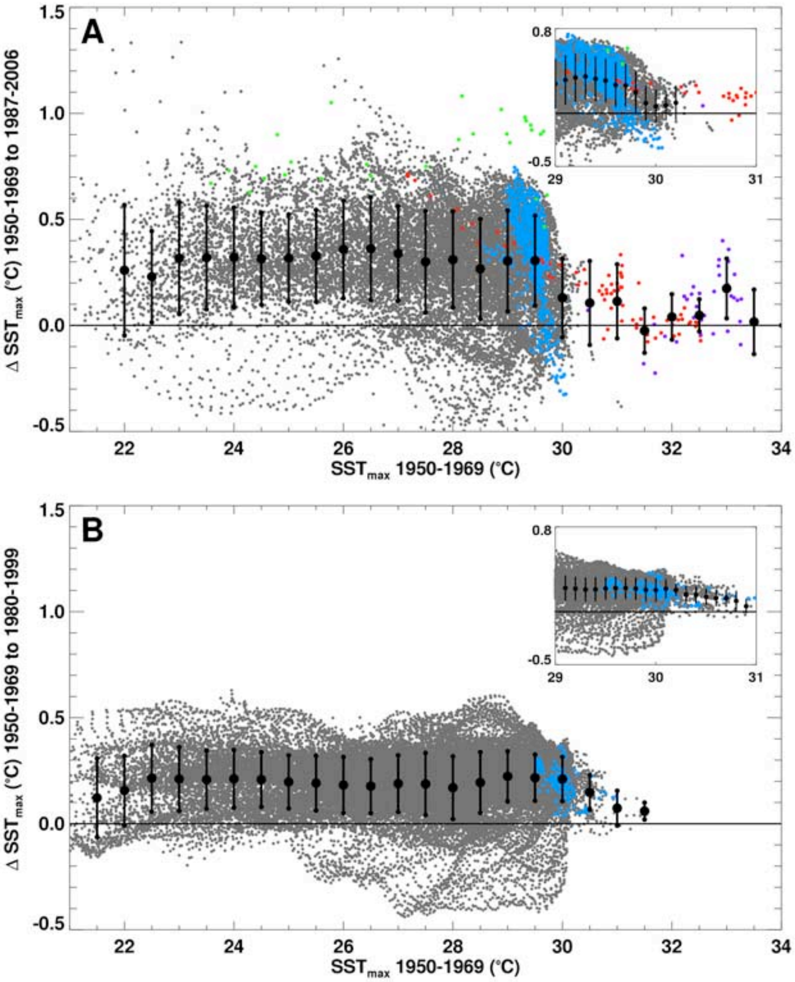

Figure 3. (a) Warming of average maximum SSTs between 1950–69 and 1987–2006; mean (large black dots) and standard deviations (vertical lines) are shown for 0.5°C intervals. Inset expands data for 29–31°C, with mean and standard deviation at 0.1°C intervals. Blue, WPWP; red, Red Sea; purple, Persian Gulf, green, Gulf of California; gray, other locations. (b) As in Figure 3a, but comparing 1950–69 and 1980–1999, based on one member of the 20th Century CCSM3 integrations. Note that enclosed seas are not resolved in the CCSM3.

SSTs (Figure 3b). However, the modeled temperature where warming dropped off was higher than in the HadISST compilation (modeled $SST_{max} > 30.2°C$, versus HadISST $SST_{max} > 29.5°C$) and the reduction in warming at higher modeled SST_{max} was weaker, with correlation coefficients ranging between −0.04 and −0.24 for the four ensemble members (n > 6000 grid cells).

3.2. Coral Bleaching

[12] On a global basis, 40% of 1205 1° × 1° reef cells have experienced at least one bleaching event between 1980 and 2005, and 22% have experienced at least one severe event (Table 1). By geographic region, the percentage of cells that has experienced bleaching varies between 15–74%; for severe bleaching, the percentage varies between 8–48%. Eastern Pacific reefs have experienced the most bleaching, while Micronesia, Melanesia and Polynesia reefs the least. Interestingly, warming in the Caribbean/Atlantic region between 1950–1969 and 1987–2006 was lower than for other regions. This was previously reported by *Lough* [2000], who noted that thermal stress in the Caribbean appeared earlier in the century than in other coral reef regions.

[13] For SST-defined reef regions (Table 2), the warmest (annual average SST > 29°C) has a lower percentage of bleached cells than any other geographic or SST-defined region. Of the six bleaching events in this region, two were attributed to factors other than SST. For the other four events, bleaching occurred when both HadISST monthly and Reynolds weekly SSTs were elevated by 0.2–0.3°C above the normal annual SST maximum, which is considerably less than the commonly observed bleaching threshold of 1–2°; and when the degree heating month index [*Liu et al.*, 2006] was 0.

4. Discussion and Summary

[14] Over the past 50–60 years, SSTs in the warmest parts of the oceans have warmed less than in surrounding areas. This supports previous suggestions of an upper limit to maximum SST. If SST_{max} in the WPWP is already near this limit, then the highly biodiverse marine communities in

Table 1. Summary of Bleaching Events From ReefBase, 1980–2005, for Geographically Defined Reef Areas[a]

Region	Average SST			$1° \times 1°$ Reef Cells		
	1950–1969, °C	1987–2006, °C	Δ SST, °C	Number	Bleached, %	Severely Bleached, %
E Pacific	26.00	26.32	0.32	43	74	42
Caribbean/Atlantic	27.30	27.35	0.05	194	57	25
W Indian	26.38	26.82	0.44	72	67	39
C Indian	28.21	28.64	0.44	50	60	48
Middle East	27.06	27.32	0.26	58	43	29
SE Asia	27.78	28.28	0.49	307	32	16
Australia	25.78	26.15	0.37	91	63	41
Melanesia	27.53	27.80	0.28	121	26	11
Micronesia	28.57	28.81	0.25	120	15	8
Polynesia	26.75	26.98	0.22	149	19	11
All	27.32	27.63	0.31	1205	40	22

[a]See Figure 1c. Average SST for $1° \times 1°$ reef cells in each region calculated from HadISST.

this region will be exposed to fewer severe events than other regions. There is, however, considerable debate regarding what the upper SST limit might be in this region (see Table S1), what processes control this limit, and how those processes will be affected by global warming.

[15] The CCSM3 was able to reproduce the observed warming trend during the late 20th Century and the shift towards negative skewness with increased SSTs, but showed weaker SST capping at higher temperatures. These simulations exhibit biases common to many state-of-the-art coupled climate models, such as a double Inter Tropical Convergence Zone structure in the tropical Pacific, a persistent bi-annual ENSO, and a rather weak Madden-Julian Oscillation (MJO) [*Collins et al.*, 2006; *Large and Danabasoglu*, 2006], which may influence the WPWP properties [*Waliser*, 1996]. A preliminary look at CCSM3 results subject to future greenhouse gas forcings (at a rate of 1% y^{-1} increase in atmospheric CO_2) did not illustrate an effective thermostat; i.e., SSTs in the WPWP warmed at a similar rate to surrounding regions. We identify three potential explanations for the lack of an effective thermostat in model simulations of future SST: (1) the model does not adequately capture the processes controlling SST in the tropics; (2) the thermostat temperature is higher than predicted or transiently 'adjusts' to a higher temperature under increased radiative forcing; and (3) a 1% y^{-1} increase in atmospheric CO_2 exceeds the rate at which thermostat feedbacks can act to suppress warming. The last is particularly important because it points to the importance of determining the rate of CO_2 increase that still allows effective thermostat feedbacks. A 1% y^{-1} increase in atmospheric CO_2 is considerably higher than the 0.2–0.5% y^{-1} increase over the period 1950–2000. We are investigating the apparent lack of a thermostat in future scenario integrations.

[16] Ocean thermostat mechanisms do not appear to work effectively everywhere in the tropical oceans. There is evidence that these feedbacks can be outweighed by remote forcing from larger-scale climate dynamics [*Fasullo and Webster*, 1999; *Waliser*, 1996] such as the MJO, or the southeast Asian monsoon in the Indian Ocean. The latter may explain, for example, the extreme SSTs and mass coral bleachings that have occurred in the Indian Ocean.

[17] Coral bleaching is affected by other climatic factors such as solar radiation, wind and water flow, but are not addressed here as they are usually related to the same factors that determine SST. Many non-climatic factors, however, determine the sensitivity of coral reefs to bleaching. Coral sensitivity to elevated SST varies across species and coral communities [*Marshall and Baird*, 2000]. It also varies with reef habitat [*McClanahan et al.*, 2005] and across oceans [*Wilkinson*, 2004], which is determined in part by the natural variability of the system; e.g., sensitivity to SST extremes is inversely related to the natural SST variability [*McClanahan and Maina*, 2003]. Thus, because WPWP reefs experience less exposure to elevated temperatures, they may be more sensitive to small temperature increases.

[18] Regardless of these factors, the percentage of reefs affected by bleaching appears to be lowest in and near the

Table 2. Summary of Bleaching Events From ReefBase, 1980–2005, for SST-Defined Reef Areas[a]

Average SST, °C	Average SST			$1° \times 1°$ Reef Cells		
	1950–1969, °C	1987–2006, °C	Δ SST, °C	Number	Bleached, %	Severely Bleached, %
21–22	21.39	21.65	0.25	7	0	0
22–23	22.41	22.88	0.47	8	25	13
23–24	23.48	23.88	0.40	26	65	31
24–25	24.51	24.88	0.37	61	36	25
25–26	25.52	25.83	0.31	100	40	21
26–27	26.64	26.93	0.29	154	42	27
27–28	27.57	27.84	0.27	266	42	22
28–29	28.41	28.74	0.33	483	33	17
>29	29.13	29.36	0.23	40	10	5

[a]See Figure 1b. Average SST for $1° \times 1°$ reef cells in each region calculated from HadISST. Middle East reefs are excluded from the calculations.

WPWP where SSTs have warmed the least since the 1950s. The lower bleaching rate may possibly be an artifact of less reliable reporting from these remote areas, but these results are consistent with other observations that coral bleaching in Micronesia and nearby areas has been relatively low compared to other regions [*Wilkinson*, 2004].

[19] Our analysis highlights the potential role of the ocean thermostat in reducing the exposure of western tropical Pacific coral reefs to future changes in SST. While maximum SSTs in the tropics have increased by an average of 0.3–0.4°C, the warmest parts of the open ocean (where average SST > 29°C) have increased by only half that amount and have had the lowest observed coral bleaching rate. This supports the notion that various negative feedbacks may slow the rate of warming in some tropical regions. Although many climatic and biological factors determine the vulnerability of coral reefs to bleaching, the possibility that the center of coral reef biodiversity may experience less exposure to temperature extremes is important to the maintenance of these ecosystems in a changing climate. Therefore, we recommend improvements in our understanding and modeling of ocean thermostat processes, as well as improved monitoring of temperatures and bleaching on WPWP reefs.

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