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Equivocal Evidence for a Thermostat and Unusually Low Levels of Coral Bleaching in the Western Pacific Warm Pool

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Equivocal evidence for a thermostat and unusually low levels of coral bleaching in the Western Pacific Warm Pool

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[1] An ocean "thermostat" was recently proposed that limits Western Pacific Warm Pool (WPWP) sea surface temperature (SST) causing anomalously low coral bleaching rates. We analyze WPWP SST trends and bleaching using HadISST data and a coral bleaching database and find no strong evidence for a thermostat or for anomalously low bleaching. A region within the WPWP has a trend of maximum SST near zero, but this signal is not robust – by using different data or periods the signal disappears. We do find a negative correlation between the average warmest month for the years 1950–1969 (average SST max) and the linear trend of maximum monthly temperatures for the years 1950–2006 (linear trend SST max). However this correlation is not unique to the WPWP, it is also observed in a cooler region. Consequently it can not be explained by a thermostat. The observed sparsity of bleaching observations in the WPWP is not in agreement with estimated bleaching likelihood. The sparsity of observations is more likely due to the WPWP's remoteness. **Citation:** van Hooidonk, R., and M. Huber (2009), Equivocal evidence for a thermostat and unusually low levels of coral bleaching in the Western Pacific Warm Pool, *Geophys. Res. Lett.*, *36*, L06705, doi:10.1029/2008GL036288.

1. Introduction

[2] The current increase in ocean temperatures [*Barnett et al.*, 2005] can stress corals and cause massive coral bleaching. As a result of anthropogenic climate change, bleaching is predicted to occur annually on reefs in most tropical oceans within 30–50 years [*Hoegh-Guldberg*, 1999]. Bleaching is the condition where anomalous warm sea surface temperatures (SSTs) cause expulsion of symbiotic algae by corals, or cause a reduction in the algae's pigments, leaving the coral white [*Glynn*, 1993]. Because of the ecologic, economic and intrinsic importance of coral reefs, any mechanism that might prevent the decline of tropical coral reefs from bleaching should be thoroughly investigated. One such proposed mechanism is an ocean thermostat [*Kleypas et al.*, 2008] which limits the maximum SST to 29–31°C in the warmest region of the Pacific known as the Western Pacific Warm Pool (WPWP). Thermostat hypotheses have a long and varied history and they generally come in four categories of explanatory mechanisms. First there is the evaporative feedback mechanism [*Newell*, 1979], second the cirrus cloud albedo feedback [*Ramanathan and Collins*, 1991], third the production of dry air in "radiator fins" [*Pierrehumbert*, 1995], and the fourth is the ocean dynamics and heat transport mechanism [*Seager and Murtugudde*, 1997; *Clement et al.*, 2005].

[3] The *Kleypas et al.* [2008] study is pioneering because it is probably the first detailed discussion on the impacts of a thermostat on coral bleaching so it is a starting point for further investigation. A thermostat could have broad implications for coral reef survival in the region, but there are theoretical and observational problems with thermostat hypotheses, therefore some skepticism is warranted. The thermostat bleaching hypothesis of *Kleypas et al.* [2008] claims strong evidence of an impact of this thermostat on coral reef bleaching. To address the validity of both the thermostat and the anomalously low bleaching part of the hypothesis we have reframed their analyses.

[4] For the thermostat-bleaching hypothesis to be valid and useful, the following five conditions should be satisfied. (1) In the warmest regions where average maximum temperatures are above 29°C, the observed trend in maximum SST should be near zero or negative. (2) The negative feedback on SST should be unique to the warmest regions of the oceans. If the correlation between increasing average SST and decreasing SST trend can be found in cooler areas, a mechanism different from the proposed thermostat might explain the same phenomena in the WPWP. (3) Anomalously low bleaching must be observed where the thermostat is active, in the WPWP region where average maximum SST is greater then 29°C. (4) A physical basis for the thermostat has to be identified. A mechanism explaining why a hard upper limit on SST exists has to be offered and supported by observations and models. (5) Evidence for the thermostat should be in the geological archive. If the conditions for the mechanism were present in the past, paleotemperature proxies' records must be equal or below the proposed limit of 29°C. Geological evidence for widespread and healthy coral reefs should also be available from past periods of global warmth.

[5] While *Kleypas et al.* [2008] described results pertaining to most of these points, here we investigate in more depth the underlying assumptions and methodology. We show that there is some evidence for condition 1 but that the acceptance of conditions 2 and 3 may be premature. We follow that with a brief synopsis of the state of the art of thermostats in dynamics and in the paleoclimate record and show that conditions 4 and 5 are not supported.

2. Methods and Materials

2.1. SST Analysis

[6] For a clear comparison to *Kleypas et al.* [2008] we used the HadISST data set (1 × 1° of SST) [*Rayner et al.*, 2003]. To evaluate robustness, we applied the same analysis

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to the Extended Reconstructed Sea Surface Temperatures, version 3 (ERSST.v3) data set [*Smith et al.*, 2008]. The WPWP is defined by *Kleypas et al.* [2008] and is the region east of 110°E in the western Pacific where yearly averaged minimum SST for the period 1950–2006 is greater than 28°C (Figure 1). The 22–24°C region is defined as the area north of 10°S in the Pacific Ocean where the average 1950–2006 minimum temperature is between 22 and 24°C (Figure S1).[1] We do not use warming as defined by *Kleypas et al.* [2008], we use an alternative, and arguably more robust approach. A least squares linear trend in °C/century was computed from 1950–2006 yearly maximum SST. Average SST max (maximum) was calculated as the average of the warmest month for the years 1950–1969.

2.2. Coral Bleaching and Locations

[7] We reduced a high resolution file with reef locations [*Andréfouët et al.*, 2008] to a 1 × 1° resolution to match our bleaching data. A cell was noted as having a reef if there was at least one reef within that cell. We used the same reef observation data set that *Kleypas et al.* [2008] employed which record bleaching or the absence of bleaching [*ReefBase Project*, 2007]. This database collects observations of reefs and records the level of bleaching present. The maximum bleaching intensity in each grid cell recorded was used as the value of that grid cell. In each cell, the years when bleaching occurred were counted for the period 1980–2007 to calculate the observed yearly bleaching likelihood. The coldest maximum monthly SST of the years when bleaching occurred was used as a threshold for estimated bleaching. This threshold was extrapolated to locations where no observations of bleaching were present. We compared these observed and extrapolated thresholds with maximum monthly SST data from HadISST to estimate the likelihood of bleaching in the 1980–2007 period.

3. Results

3.1. Condition 1: In the Warmest Regions Where Average Maximum Temperatures are Above 29°C, the Observed Trend in SST Max Should be Near Zero or Negative

[8] We find significant spatial variability in regional linear trends of yearly maximum SST, and there is a region in the most eastern part of the WPWP where the SST is hardly increasing at all or even cooling (Figure 1). This is also the region that was the warmest in the beginning of the analysis period (1950–1969), with a SST max for the 1950–1969 period of 29.5 to 30.1°C. To test if the large positive trends in the WPWP's other parts are caused by the fact that they had not reached possible threshold temperature of 29.5°C we analyzed the linear trend of SST max for the period 1995–2006. In the WPWP region where average SST max for that period was greater than 30°C areas with a trend exceeding 3°C/century (Figure S2) are observed. For the period 1970–2006, the linear trend of SST max exceeds 1°C/century in most of the area where average SST for the period 1970–1989 is greater then 29.75°C (Figure S3). Furthermore, when using ERSST.v3 data, the spatial pattern of change in this region is noticeably different and the region of focused cooling is displaced largely outside of the WPWP as defined from HadISST data (Figure S4). So while the data analysis can produce results indicating an apparent thermostat above ~29.75°C, SST trends in this region are not robust and are sensitive to underlying uncertainties in the data as discussed by *Vecchi et al.* [2008]. Nevertheless it appears that condition 1 might be satisfied over a limited region on the eastern margin of the WPWP.

3.2. Condition 2: The Negative Feedback on SST Should be Unique to the Warmest Regions of the Open Oceans

[9] If a thermostat limits ocean temperatures, a negative correlation between average SST max and trend in SST max should be found as described in condition 1, but this behavior should be unique to the warmest regions. In agreement with the results of *Kleypas et al.* [2008] we find in the WPWP a strong negative correlation between SST max's linear trend and the average of SST max for 1950–1969. The trend is close to zero where average SST max for 1950–1969 is highest (Figure 2a). But, in a region where average minimum temperatures are 22–24°C we see similar results (Figure 2b). This implies that whatever causes this correlation is not unique to the regions with the highest SST and therefore is not caused by the hypothetical thermostat. In other words, while the warmest regions share trends consistent with a thermostat, so do cooler regions – this strongly suggests alternative mechanisms may be at play.

3.3. Condition 3: Anomalously Low Bleaching Must be Observed in the Region of the WPWP Where Average SST Max is Greater Than 30°C

[10] If we assume that a thermostat limits temperatures in the WPWP it only appears to be operating in a very small, sparsely sampled region of the WPWP where the linear trend of SST max for the period 1950–2006 is smaller then 0.4°C/century. Most reef localities have no observations in this region, only one reef location is observed (Figure 1), making it impossible to analyze the thermostat's effects on coral bleaching there with any rigor. In the WPWP as a whole, we find 198 1° × 1° cells with reefs. Of those, only 20 cells are recorded in a database of reef observations, 18 of those record bleaching (8% of all the cells with reefs in the WPWP). In the whole world, 24% of all reef locations are reported to have bleached. So indeed there are fewer observations of coral bleaching in the WPWP compared to the rest of the world, but it is important to note that there are also fewer observations in toto of reefs (bleached or not) in the WPWP. In the WPWP 9% of cells with reefs have observations of bleaching or no-bleaching. In the whole world 27% is reported in the observational database.

[11] With so few observations, what is the likelihood that WPWP bleaching events were simply under-reported? To answer this question a time series of pseudo bleaching events was generated for every grid cell with reefs. These pseudo observations are based on observed monthly thermal thresholds for reefs nearby with observations of bleaching. This technique is simple and large assumptions are made. Maximum monthly SSTs in every year were used as a predictor for bleaching. These temperatures might not have

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL036288.

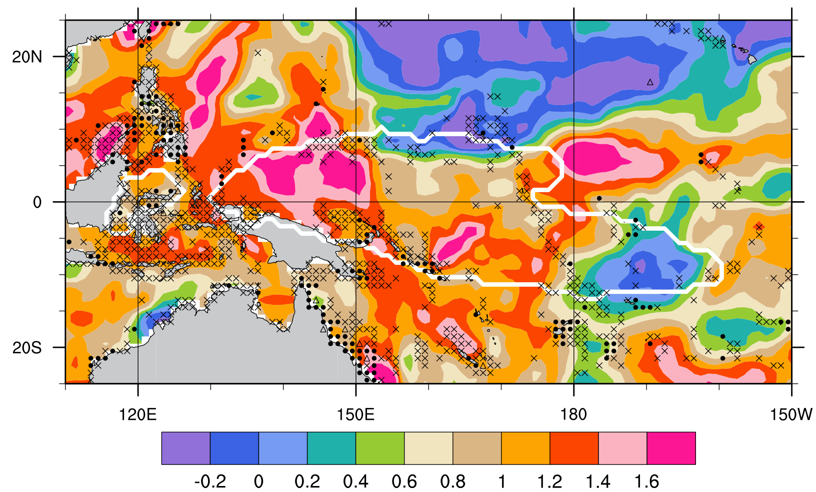

Figure 1. Locations of bleached (black dots) reefs reported in the data set that never experienced bleaching (triangles) and unobserved reefs (marked with an x) on a map of yearly maximum SST trends (in °C/century). The WPWP is outlined in white.

been contemporaneous with the bleaching event, but this choice was necessary because the observational database does not record the duration of the bleaching events. The assumptions made are similar to those made in the Degree Heating Week technique [*Liu et al.*, 2003] or in studies which predict anthropogenic global warming induced bleaching [*Hoegh-Guldberg*, 1999]. This approach predicts that reefs in the WPWP bleached many times in the 1980–2007 period (Figure 3b), including the reefs in the region of the WPWP where the trend of SST is less then 0.2°C/century (Figure 1). This contrasts sharply with the paucity of bleaching observations in the WPWP (Figure 3a) and is consistent with significant under-reporting of bleaching in this region.

3.4. Condition 4: A Physical Basis for the Thermostat has to be Identified

[12] As discussed by *Pierrehumbert* [1995, 1996], neither the evaporative or cloud radiative feedbacks can provide a true thermostat on large spatial scales or time scales greater than weeks. Therefore, these hypotheses have little support. The radiator fin hypothesis of *Pierrehumbert* [1995], while interesting and not disproved, remains speculative and little work has gone into evaluating its validity. Variations on this hypothesis, such as *Lindzen et al.*'s [2001] 'Iris hypothesis' have not generally been supported by modern studies [*Sud et al.*, 2008] and are generally in disagreement with the paleoclimate record [*Huber*, 2008]. Recent work using a coupled atmosphere-ocean model indicates that the observed limit of tropical SST will rise in a warming world [*Sud et al.*, 2008]. The ocean thermostat mechanism, discussed by *Kleypas et al.* [2008] and *Clement et al.* [2005], which requires an increase in the upwelling of cool equatorial water, has had some success as a mechanism to explain the slowing of tropical warming as greenhouse gasses are increased. There is nothing however, in the theory that provides a true thermostat, i.e. a hard limit on tropical temperatures. Instead, provided sufficient time – about 30 years, i.e. on the order of a subtropical cell turnover time [*Gu and Philander*, 1997] – warmer water will be subducted at the subtropical margins of the thermocline and eventually be upwelled in the eastern equatorial Pacific, warming the tropics as a whole. Thus this mechanism slows warming but provides no actual limit on warming. In fact, one popular hypothesis holds that this feedback operates in the opposite direction –warming leads to a shutdown in tropical upwelling and a warming of the tropics as a whole [*Philander and Fedorov*, 2003]. Modern observations are equivocal on the actual trend [*Vecchi et al.*, 2008].

3.5. Condition 5: Evidence of the Thermostat Should be in the Geological Archive

[13] Paleoclimate records do not support a thermostat [*Pearson et al.*, 2007; *Zachos et al.*, 2006; *Huber*, 2008, 2009]. In earlier work, oxygen isotope content analysis of foraminifera shells suggested that tropical SSTs during

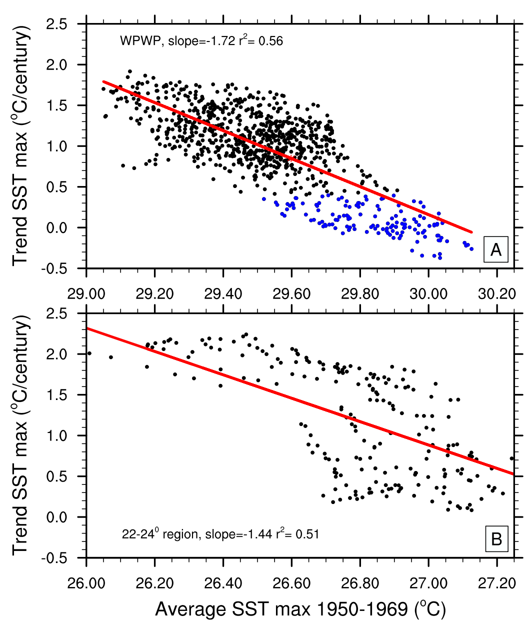

Figure 2. Linear trend of SST max in (a) the WPWP and (b) the 22–24 °C region for the period 1950–2006 plotted against the average of SST max for the period 1950–1969. In Figure 2a the blue dots represent cells in the WPWP where the linear trend of SST max <0.4 °C/century.

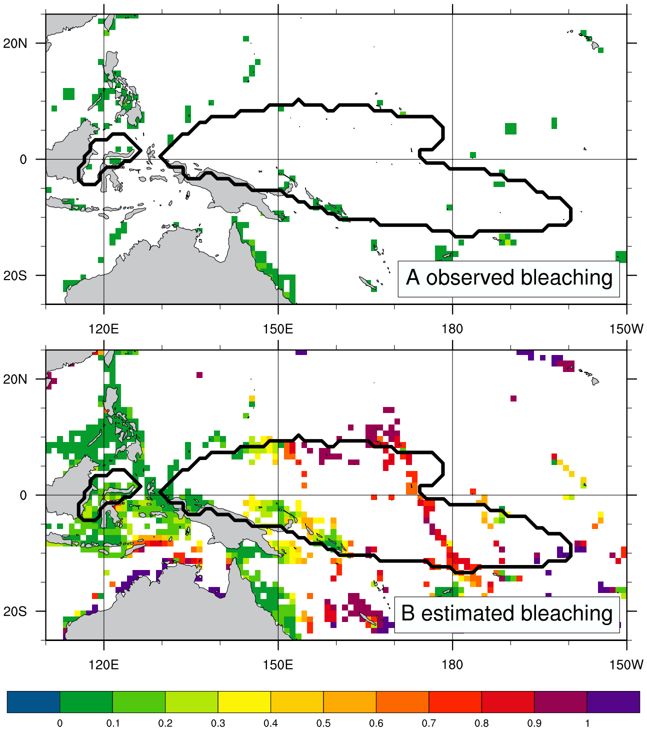

Figure 3. (a) Likelihood of bleaching in any given year based on observations of bleaching between 1980 and 2007 and (b) estimated likelihood of bleaching using pseudo observations generated from exceedances of thermal thresholds.

warm episodes such as the early Eocene were only slightly warmer than modern. Recently *Pearson et al.* [2007] came to a different conclusion offering diagenetic alteration as an explanation for the previously found stable tropical temperatures. Analysis of unaltered planktonic foraminifer shells showed that tropical SST did increase to 30–35°C in the early Eocene [*Pearson et al.*, 2007]. Applying a range of assumptions to existing tropical paleoclimate records for the greenhouse interval of the Eocene leads to a range of tropical SSTs from >30 to 42°C [*Huber*, 2008, 2009]. It is also worthwhile to consider that paleontological evidence supports evidence for massive die-offs of corals during periods of past warmth such as the Eocene and Miocene [*Kiessling and Baron-Szabo*, 2004; *Scheibner and Speijer*, 2008]. Thus, the existing paleoclimate and paleontological records give strong indications of tropical temperatures much warmer than modern (by ∼10°C) and massive reductions of the areal extent of coral reefs in the tropics.

4. Discussion and Summary

[14] In regions where average SST max is above 30°C there is a large positive trend in average SST max. Furthermore, the negative correlation found between SST max and the linear trend of SST max is not unique to the warmest regions. These results indicate the absence of a thermostat in the WPWP. Since no well established theory, model result, or paleo-records support the existence of a strict thermostat, the concept should be discarded. This leaves us with an interesting question. Why is coral bleaching not reported as frequently in the WPWP as in the surrounding regions?

[15] To accurately estimate bleaching frequency in the WPWP we need to know how likely it is that bleached reefs in the WPWP were missed in the observational database. Starting in the 1970s, coral reef research has been active and massive bleaching events were unlikely to be missed [*Glynn*, 1993] most places. This might not be the case in the WPWP since the remoteness of the locations makes not reporting a local bleaching event more likely. Remote reefs are also less likely to be disturbed, and have a greater capacity to survive or recover from bleaching events [*Sandin et al.*, 2008], decreasing the probability that a bleaching event would be recorded by chance observation even further. Extrapolating form observed thermal thresholds from nearby reefs and comparing these thresholds to historical SST data we estimate that coral bleaching was frequent in some areas of the WPWP in the 1980–2007 period (Figure 3b). Clearly more observations are necessary before we can be sure that bleaching in the WPWP occurs less frequently compared to the rest of the tropics. If rates really are anomalously low we must look for a better explanation than a thermostat. We suggest more field observations should be done in the WPWP to establish current and past bleaching patterns.

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