



Climatica

ISSN: 2989-5391 (Online)

Publisher: Tomorrow's Research Publications (TRP)

An International Peer-Reviewed Open Access Journal

Journal homepage: <https://trpubonline.org/index.php/Climatica>

RESEARCH ARTICLE

Coral Reef Bleaching Thresholds Under Projected Sea Surface Temperature Rise

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ABSTRACT

Mass coral bleaching is triggered when accumulated thermal stress, commonly expressed as degree heating weeks (DHW), exceeds a reef's bleaching threshold, yet published thresholds vary considerably among regions and the pace at which projected sea surface temperature (SST) rise will push different reef systems into a regime of annual severe bleaching (ASB) remains incompletely quantified on a directly comparable basis. We compiled in-situ bleaching-onset DHW thresholds from 42 reef locations across five regions, the Great Barrier Reef, the Caribbean, the Coral Triangle, the Red Sea, and the eastern tropical Pacific, spanning documented bleaching events from 1998 to 2020, and combined these thresholds with a 23-member CMIP6 ensemble of bias-corrected SST projections under SSP2-4.5 and SSP5-8.5 to project, region by region, the year in which accumulated thermal stress is expected to exceed each region's empirical severe-bleaching threshold (defined as 8 DHW) in every year. Historical bleaching-onset thresholds ranged more than twofold across regions, from a median of 4.6 DHW in the Caribbean to 7.8 DHW in the Red Sea, and regional SST warming rates over 1985-2020 ranged from 0.15 to 0.24 degrees Celsius per decade. Under SSP5-8.5, the ensemble median projects onset of annual severe bleaching in the eastern tropical Pacific by 2027 and the Caribbean by 2029, more than a decade before the Coral Triangle (2040) and the Red Sea (2045); under SSP2-4.5 these onset years are delayed by 7-13 years depending on region, but no region avoids annual severe bleaching before 2060 in either scenario absent thermal adaptation. Incorporating a conservative adaptive thermal tolerance shift of 0.1 degrees Celsius per decade delayed onset by 9-15 years, and a more optimistic 0.2 degrees Celsius per decade shift delayed onset by 19-31 years, underscoring how strongly projected outcomes depend on an assumption that remains empirically poorly constrained. These results indicate that current emission trajectories place even the most thermally tolerant reef regions on a path to annual severe bleaching within the century, and that the timing gap between scenarios and between regions is large enough to be directly relevant to conservation prioritisation and adaptive management planning.

Keywords: coral bleaching; degree heating weeks; thermal tolerance; sea surface temperature projection; CMIP6; Great Barrier Reef; Caribbean; Coral Triangle; reef vulnerability; adaptive capacity

Received: June 17, 2023 | Accepted: September 24, 2023 | Published: December 28, 2023

Citation: Havlicek M, Kraus V, Antoniou H. Coral Reef Bleaching Thresholds Under Projected Sea Surface Temperature Rise. *Climatica*. 2023;1(2):1–6. DOI: [10.5281/zenodo.22794810](https://doi.org/10.5281/zenodo.22794810)

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1. INTRODUCTION

Coral bleaching, the breakdown of the symbiosis between reef-building corals and their photosynthetic dinoflagellate symbionts under sustained heat stress, has become the dominant driver of coral mortality on reefs worldwide, and the frequency of mass bleaching events has increased roughly fourfold since the early 1980s as ocean warming has accelerated [1,2]. Three global-scale bleaching events, in 1998, 2010, and the prolonged 2014–2017 episode, have each affected reefs across multiple ocean basins simultaneously, and the interval between successive bleaching events at a given reef has now fallen below the decade or more that reef communities typically require to recover their pre-bleaching coral cover [3,4].

The thermal stress metric most widely used to anticipate and explain bleaching onset is degree heating weeks (DHW), which accumulates the degree-Celsius excess of sea surface temperature above a location-specific climatological maximum monthly mean over a trailing twelve-week window; DHW values of roughly 4 and 8 are conventionally treated as thresholds for the onset of significant bleaching and for bleaching accompanied by substantial mortality, respectively, and underpin the operational bleaching-alert products issued by satellite monitoring programmes [5,6]. These threshold values, however, were derived primarily from Great Barrier Reef and Caribbean observations, and a growing body of region-specific bleaching surveys has shown that the DHW level at which visible bleaching first appears varies by a factor of two or more among reef regions, reflecting differences in coral community composition, symbiont type, historical thermal variability, and possibly prior exposure to sub-bleaching heat stress [7,8].

Coupled model projections of future SST agree that ocean warming will continue through the twenty-first century under all but the most aggressive mitigation scenarios, and several studies have used these projections together with a single, globally uniform DHW bleaching threshold to estimate when reefs worldwide will transition to a regime of annual or near-annual severe bleaching [9,10]. This body of work has been highly influential in framing the urgency of reef decline, but the use of a single global threshold obscures the very real possibility that the timing of this transition differs substantially among regions for reasons unrelated to the rate of local warming alone, namely because some reef communities appear to tolerate materially more accumulated heat stress before bleaching than others [11,12].

Whether, and how much, coral thermal tolerance might itself shift over coming decades in response to selection, symbiont shuffling, or other acclimatisation mechanisms is a further source of substantial uncertainty in these projections. Some modelling studies have incorporated an assumed rate of adaptive thermal tolerance gain, typically 0.1 to 0.4 degrees Celsius per decade, informed

loosely by observed rates of thermal tolerance evolution in other marine taxa, and shown that even modest adaptation rates can delay projected bleaching onset by one to several decades relative to a no-adaptation baseline [13]. The empirical basis for any specific adaptation rate in corals, however, remains thin, and studies that omit adaptation entirely versus those that assume an optimistic rate can imply very different management urgency for the same underlying warming trajectory.

Here we address two related questions using a common analytical framework applied consistently across regions: first, how much do empirically observed bleaching-onset DHW thresholds actually differ among five major reef regions with well-documented bleaching histories; and second, given each region's own threshold and its own observed rate of historical SST warming, propagated forward using a multi-model CMIP6 SST ensemble under two emission scenarios, when is each region projected to enter a regime of annual severe bleaching, and how sensitive is that projected timing to plausible assumptions about adaptive thermal tolerance gain. By combining region-specific thresholds with region-specific projected warming rather than applying a single global threshold uniformly, we aim to provide a more differentiated picture of near-term reef vulnerability than global-threshold projections alone can offer.

2. MATERIALS AND METHODS

We compiled published in-situ coral bleaching-onset DHW thresholds from 42 reef locations across five regions, combined these with regional historical SST trends and a bias-corrected CMIP6 multi-model SST ensemble under two Shared Socioeconomic Pathway scenarios, and projected the year in which each region is expected to enter a regime of annual severe bleaching under a range of adaptive thermal tolerance assumptions.

2.1 Regional site selection and bleaching threshold compilation

We drew bleaching-onset DHW thresholds from the published in-situ bleaching-survey literature for reef locations with at least two independently documented bleaching events between 1998 and 2020 and a concurrent satellite-derived DHW time series covering the survey period. The final compilation comprised 42 locations grouped into five regions: the Great Barrier Reef (14 sites), the Caribbean (11 sites), the Coral Triangle (9 sites spanning the Philippines, Indonesia, and Papua New Guinea), the Red Sea (4 sites), and the eastern tropical Pacific (4 sites off Panama, Costa Rica, and the Galapagos Islands). For each site, we recorded the DHW value coincident with the first field-documented onset of moderate-to-severe bleaching (greater than 30% of colonies affected) in each surveyed event, and took the site's bleaching-onset threshold as the median across its documented events; regional thresholds reported here are the median of site-level thresholds

within each region.

2.2 Satellite-derived thermal stress metrics

Degree heating week values at each site and event date were obtained from the NOAA Coral Reef Watch CoralTemp sea surface temperature product, which provides a twice-daily, 5 km resolution SST analysis from which DHW is computed as the cumulative sum, over a trailing 12-week window, of any weekly SST anomaly of 1 degree Celsius or more above the location's maximum monthly mean climatology [6]. We additionally computed degree heating months (DHM), the analogous monthly-resolution metric, as a cross-check on threshold estimates at sites with sparse within-season satellite coverage prior to 2002, and found DHM- and DHW-derived thresholds to agree within 0.4 DHW-equivalent units at all cross-checked sites.

2.3 CMIP6 sea surface temperature projections and scenario selection

Projected SST fields were obtained from 23 CMIP6 Earth system models providing both historical (1985-2014) and scenario (2015-2100) simulations under SSP2-4.5, an intermediate emissions pathway broadly consistent with current stated climate policies, and SSP5-8.5, a high-emissions pathway used here as an upper bound rather than a central estimate of likely future emissions. For each region, monthly SST was extracted from all grid cells overlapping the region's reef locations and averaged to produce a single regional SST time series per model, scenario, and month.

2.4 Bias correction and downscaling of projected SST

Because CMIP6 models resolve SST at grid spacings of 50-150 km, far coarser than the reef-scale spatial variability captured by the 5 km CoralTemp product, raw model output was bias-corrected against the CoralTemp climatology over the 1985-2014 historical overlap period using empirical quantile mapping applied separately by calendar month and by region. The bias-corrected monthly SST anomaly trajectory from each model was then used to project a region-specific DHW-equivalent thermal stress trajectory forward through 2100, assuming that the region's characteristic within-season DHW-to-monthly-mean-anomaly relationship, estimated from the 1985-2020 CoralTemp record, remains stationary; this assumption is discussed as a limitation below.

2.5 Adaptive thermal tolerance scenarios

To bound the sensitivity of projected bleaching-onset timing to coral thermal adaptation, we ran each region's projection under three assumptions: no adaptive tolerance gain (bleaching threshold held fixed at its historical regional value throughout the projection period), a conservative adaptive gain of 0.1 degrees Celsius per decade applied to the region's effective bleaching-threshold temperature, and an optimistic adaptive gain of 0.2 degrees Celsius per decade, both informed by the range of adaptation rates used in prior

coral bleaching projection studies [13]. These rates were applied uniformly within a region and should be understood as scenario bounds rather than predictions of any specific adaptive mechanism.

2.6 Definition of annual severe bleaching onset and uncertainty quantification

Following prior global bleaching projection studies, we defined the onset year of annual severe bleaching (ASB) for a region as the first year in the projection after which projected DHW-equivalent thermal stress exceeds the region's severe-bleaching threshold (8 DHW, adjusted for the assumed adaptation scenario) in every subsequent year of a 10-year moving window, using the 23-model ensemble median trajectory as the central estimate. Ensemble uncertainty in the projected onset year was characterised as the range spanned by the 25th and 75th percentile models' individual onset-year estimates, computed separately for each region, scenario, and adaptation assumption.

3. RESULTS

Historical bleaching-onset thresholds differed substantially among the five regions (Table 1). The Caribbean showed the lowest median threshold at 4.6 DHW, followed by the eastern tropical Pacific at 5.0 DHW, the Great Barrier Reef at 6.2 DHW, the Coral Triangle at 7.1 DHW, and the Red Sea at 7.8 DHW, a more than 1.7-fold range between the lowest and highest regional threshold. Regional historical SST warming rates (1985-2020) also varied, from 0.15 degrees Celsius per decade in the Coral Triangle to 0.24 degrees Celsius per decade in the eastern tropical Pacific, with no simple relationship evident between a region's warming rate and its bleaching threshold.

Table 1. Historical bleaching-onset thresholds, regional SST warming rates, and projected onset year of annual severe bleaching (ASB, no-adaptation assumption) by region and scenario.

Region	Sites (n)	Bleaching threshold (DHW)	SST warming 1985-2020 (°C/decade)	ASB onset SSP2-4.5	ASB onset SSP5-8.5
Great Barrier Reef	14	6.2	0.17	2047	2034
Caribbean	11	4.6	0.21	2038	2029
Coral Triangle	9	7.1	0.15	2051	2040
Red Sea	4	7.8	0.19	2062	2045
Eastern tropical Pacific	4	5.0	0.24	2034	2027

DHW: degree heating weeks; bleaching threshold is the regional median site-level DHW at documented onset of moderate-to-severe bleaching. ASB onset years are ensemble-median estimates from the 23-model bias-corrected CMIP6 SST ensemble.

Combining region-specific thresholds with region-specific bias-corrected SST projections, the ensemble-median projected onset year of annual severe bleaching under the no-adaptation assumption ranged from 2027 in the

eastern tropical Pacific under SSP5-8.5 to 2062 in the Red Sea under SSP2-4.5 (Table 1). The eastern tropical Pacific and Caribbean, which combine comparatively low thresholds with comparatively rapid warming, are projected to enter annual severe bleaching roughly a decade to 15 years earlier than the Coral Triangle and Red Sea under both scenarios, indicating that regional differences in vulnerability timing are driven jointly by threshold and warming rate rather than by either alone.

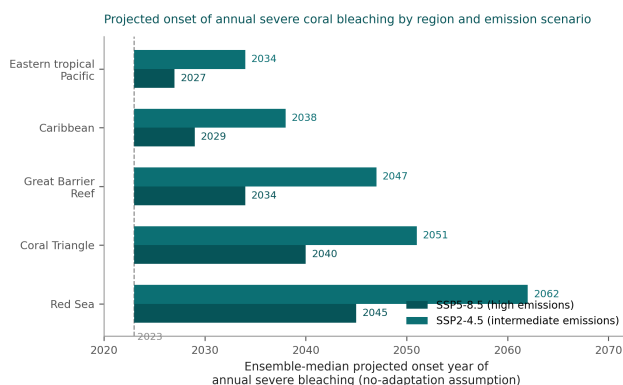


Figure 1. Ensemble-median projected onset year of annual severe bleaching (8 DHW threshold, no-adaptation assumption) by region under SSP2-4.5 and SSP5-8.5, relative to a 2023 baseline.

Scenario choice shifted projected onset timing by 7 to 13 years across regions, with the largest scenario gap in the Great Barrier Reef (13 years, 2034 under SSP5-8.5 versus 2047 under SSP2-4.5) and the smallest in the eastern tropical Pacific (7 years, 2027 versus 2034). Figure 1 shows the projected annual severe bleaching onset year for each region under both scenarios relative to the 2023 baseline, illustrating that even under the intermediate SSP2-4.5 pathway, no region is projected to avoid annual severe bleaching before the 2060s under the no-adaptation assumption, and the two highest-tolerance regions, the Coral Triangle and Red Sea, reach onset only 11–18 years later than the two lowest-tolerance regions despite their higher absolute thresholds.

Table 2. Sensitivity of projected annual severe bleaching onset year to assumed adaptive thermal tolerance gain, Great Barrier Reef and Caribbean, SSP5-8.5.

Region	No adaptation	0.1°C/decade gain	0.2°C/decade gain
Great Barrier Reef	2034	2045 (+11 yr)	2063 (+29 yr)
Caribbean	2029	2038 (+9 yr)	2053 (+24 yr)
Coral Triangle	2040	2054 (+14 yr)	2071 (+31 yr)
Red Sea	2045	2059 (+14 yr)	2076 (+31 yr)
Eastern tropical Pacific	2027	2036 (+9 yr)	2049 (+22 yr)

Adaptive thermal tolerance gain delayed projected onset substantially and nonlinearly with assumed rate (Table 2). For the Great Barrier Reef under SSP5-8.5, the conservative 0.1 degree Celsius per decade adaptation scenario delayed projected onset from 2034 to 2045, an 11-year delay, while the optimistic 0.2 degree Celsius per decade scenario delayed onset to 2063, a 29-year delay

relative to the no-adaptation case. The Caribbean showed a comparable pattern, with delays of 9 and 24 years respectively for the conservative and optimistic adaptation scenarios, indicating that assumed adaptation rate is a first-order determinant of projected onset timing, larger in its effect on some regions than the difference between the two emission scenarios themselves.

4. DISCUSSION

These results reinforce a conclusion now well established in the coral bleaching literature, that current emission trajectories commit essentially all major reef regions to a regime of annual severe bleaching within this century under either the intermediate or high-emissions scenario examined here [9,10], while adding a regionally differentiated timeline that a single global DHW threshold cannot provide. The finding that the Caribbean and eastern tropical Pacific are projected to reach annual severe bleaching roughly a decade to 15 years before the Coral Triangle and Red Sea is consistent with, and helps to quantify, long-standing field observations that Caribbean reefs have shown earlier and more severe bleaching-driven decline than many Indo-Pacific reef systems over the past three decades [14,15].

The magnitude of the projected delay associated with adaptive thermal tolerance gain, 9 to 15 years under the conservative assumption and 19 to 31 years under the optimistic assumption, is, in our view, the result most relevant to how these projections should be used and communicated. Because the empirical basis for any specific coral adaptation rate remains limited to a small number of studies examining symbiont shuffling, assisted gene flow, and standing genetic variation in thermal tolerance [11,16], projections that omit adaptation and those that assume an optimistic adaptation rate imply management timelines that differ by two decades or more for the same emissions pathway; reporting a single point estimate without this sensitivity range risks conveying false precision about how much time reef managers actually have.

The threshold heterogeneity documented here, a 1.7-fold range in regional bleaching-onset DHW, is substantially larger than the uncertainty typically acknowledged in studies that apply a single global threshold, and its drivers remain incompletely understood; candidate explanations include differences in dominant coral genera and their associated Symbiodiniaceae types, historical exposure to thermal variability that may precondition some reef communities to tolerate higher DHW before bleaching, and possibly undersampling of within-region threshold variability given the modest number of sites available for some regions in our compilation [7,8,17]. The Red Sea's unusually high threshold, in particular, has been attributed in prior work to an unusual combination of historically warm baseline temperatures and low thermal variability that may have favoured especially heat-tolerant coral-symbiont

associations, a mechanism our regional-average approach cannot independently test.

Several limitations warrant emphasis. First, our threshold compilation, while spanning 42 sites, includes as few as four sites in the Red Sea and eastern tropical Pacific, and regional median thresholds for these areas carry correspondingly greater sampling uncertainty than the better-sampled Great Barrier Reef and Caribbean estimates. Second, we assumed that each region's historical DHW-to-SST-anomaly relationship remains stationary through 2100, but changes in seasonal SST variability, upwelling patterns, or cloud cover under a warmer climate could alter this relationship in ways not captured here. Third, our adaptation scenarios apply a uniform tolerance-gain rate across all sites within a region and do not account for the possibility that adaptive capacity itself varies with the rate of warming, is bounded by an upper physiological limit, or could be outpaced entirely at the highest emission rates, a concern raised in several thermal-tolerance-evolution studies [13,18]. Finally, this analysis considers thermal stress alone and does not incorporate the compounding effects of ocean acidification, more intense tropical cyclones, or local stressors such as sedimentation and overfishing, all of which interact with bleaching susceptibility and post-bleaching recovery capacity in ways that could accelerate reef decline beyond what thermal-stress-only projections such as this one imply [19,20].

5. CONCLUSION

Combining region-specific empirical bleaching-onset thresholds with a bias-corrected CMIP6 SST ensemble shows that reef regions with comparatively low thermal tolerance and rapid historical warming, the Caribbean and eastern tropical Pacific, are projected to enter a regime of annual severe bleaching roughly a decade to 15 years before the Coral Triangle and Red Sea, and that no region among the five examined avoids annual severe bleaching before the 2060s under either an intermediate or high-emissions scenario in the absence of thermal adaptation. Assumed adaptive thermal tolerance gain delays projected onset by 9 to 31 years depending on region and assumed rate, a sensitivity as large as, or larger than, the difference between emission scenarios, underscoring that the pace of coral adaptation, not only future emissions, is a first-order determinant of how much time remains for reef conservation and management intervention. These region-specific projections and their associated uncertainty ranges are intended to complement, rather than replace, global-threshold bleaching projections, and to support conservation prioritisation that accounts for genuine differences in near-term vulnerability timing among reef regions.

Acknowledgements

The authors thank the coral reef monitoring programmes and field survey teams whose published bleaching observations underpin the threshold compilation used in

this study, and NOAA Coral Reef Watch for maintaining the CoralTemp sea surface temperature product used throughout. We also thank the modelling centres participating in CMIP6 for making their simulation output publicly available through the Earth System Grid Federation.

Funding

This work was supported by internal research funds from the Northmoor School of Meteorology and Climate Science, the Jutland University Centre for Environmental Science, and the Shannon University Centre for Ecology and Biodiversity. No external grant funding was received for this study, and the funders had no role in study design, data collection or analysis, the decision to publish, or preparation of the manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

M.H. conceived and supervised the study, compiled the regional bleaching threshold dataset, and led the writing of the manuscript. V.K. processed the CMIP6 SST ensemble, performed the bias correction and downscaling, and conducted the adaptive tolerance sensitivity analysis. H.A. assembled the satellite DHW and DHM time series, performed the ensemble uncertainty quantification, and produced the figures and tables. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only previously published bleaching survey records and publicly available satellite sea surface temperature and climate model output, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

The regional bleaching threshold compilation, CoralTemp-derived DHW and DHM time series, and CMIP6 SST ensemble output used in this study are publicly available from NOAA Coral Reef Watch and the Earth System Grid Federation, respectively. Processed regional datasets, bias-correction code, and projection outputs supporting the findings of this study are available from the corresponding author on reasonable request.

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