The 2014-17 Global Coral Bleaching Event: The Most Severe and Widespread Coral Reef Destruction

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Abstract

Ocean warming is increasing the incidence, scale, and severity of global-scale coral bleaching and mortality, culminating in the third global coral bleaching event that occurred during record marine heatwaves of 2014-2017. While local effects of these events have been widely reported, the global implications remain unknown. Analysis of 15,066 reef surveys during 2014-2017 revealed that 80% of surveyed reefs experienced significant coral bleaching and 35% experienced significant coral mortality. The global extent of significant coral bleaching and mortality was assessed by extrapolating results from reef surveys using comprehensive remote-sensing data of regional heat stress. This model predicted that 51% of the world's coral reefs suffered significant bleaching and 15% significant mortality, surpassing damage from any prior global bleaching event. These observations demonstrate that global warming's widespread damage to coral reefs is accelerating and underscores the threat anthropogenic climate change poses for the irreversible transformation of these essential ecosystems.

Full Text

The dramatic increase in marine heatwaves has exposed coral reef ecosystems to more frequent, more intense, and longer-lasting heat stress [1-4]. These are predicted to accelerate in the future [5-7], making anthropogenic climate change the foremost threat to coral reefs globally [1, 2, 5, 8-10]. Strong marine heatwaves cause mass-bleaching of corals, which occurs when the relationship between corals and their photosynthetic symbionts breaks down[11]. Bleached corals are physiologically damaged, nutritionally compromised, and can die if the bleaching is severe or prolonged. During what were then the four warmest years on record, [12-14], reefs around the world experienced the third global-scale coral bleaching event (GCBE3) [15, 16] that lasted from June 2014 to May 2017 (hereafter referred to as 2014-17). This was the most severe global heat stress event recorded on coral reef ecosystems [1, 3, 15], even stronger than the two prior global bleaching events recorded in 1998 [17] and 2010 [2, 18]. Moreover, this was the first time that a global bleaching event lasted longer than a single year [1, 3, 15] – this one spanning three years with bleaching at some locations continuing after the global event concluded [19-21]. Numerous studies have revealed how GCBE3 has impacted coral reefs locally at sites around the globe, including several showing the most severe impacts on record in many locations (see [22] and references therein). This paper provides the first global-scale analysis of the heat stress affecting coral reefs during 2014-17 and the resultant bleaching and mortality observed. We derive statistical relationships between global-scale, remotely-sensed heat stress and onsite surveys of coral bleaching and mortality and use these to estimate the impact of GCBE3, accounting for regional and inter-annual differences in bleaching and mortality responses.

Three Years of Heat Stress on Reefs

Satellite remote sensing was used to identify cumulative heat stress on coral reefs, using the Degree Heating Week (DHW) product from the National Oceanic and Atmospheric Administration's Coral Reef Watch (CRW). During 2014-17, 65.9% of ~5x5 km satellite remote-sensing pixels containing coral reefs

experienced heat stress classified as sufficient to cause significant coral bleaching (Alert Level 1, DHW ≥ 4 °C-weeks) (Fig. 1, Extended Data Fig. 1a, Extended Data Table 1 [23, 24]). A further 23.7% of reef-containing pixels were subjected to heat stress classified as sufficient to cause severe bleaching and significant mortality (Alert Level 2, DHW ≥ 8 °C-weeks). 47.3% of reef-containing pixels that reached DHW ≥ 4 °C-weeks and 20.9% of reef-containing pixels that reached DHW ≥ 8 °C-weeks did so at least twice during 2014-17 (Extended Data Table 1). Almost 1% of reef-containing pixels reached record levels of heat stress at 16-30 °C-weeks – designated here as a new heat stress threshold, where coral bleaching is likely to cause severe, widespread mortality (Alert Level 3, DHW ≥ 16 °C-weeks; Extended Data Table 1). Repeated heat stress exposure was widespread during GCBE3. 15.2% of those reaching Alert Level 3 did so in at least two years.

Bleaching and Mortality

In response to the widespread and severe heat stress, we assembled coral bleaching and mortality data from 15,066 in-water and aerial surveys from teams around the globe – totaling more observations than those found in the entire existing global bleaching database from the 1960s through 2010 [25, 26] (Extended Data Table 2, Extended Data Fig. 1b). During GCBE3, 80% of surveys reported a significant level of bleaching (affecting >10% of corals) while 31% reported severe (>50%) bleaching. Additionally, 35% reported significant (>10%) recent coral mortality, 6% of which was severe (>50%). Only 15% of surveys reported no significant bleaching or mortality.

Our global analyses showed a strong positive relationship of both bleaching and mortality with satellite-derived heat stress (DHW), with the rate of biological response to heat stress varying among ocean basins and bleaching years (June to May periods). Comparing observations of significant reef-level bleaching (Fig. 2, Extended Data Fig. 5) across all basins, bleaching sensitivity to heat stress was generally highest in 2015-16 and lowest in 2016-17 (Fig. 2a), reflecting either acclimatization or adaptation of surviving corals, or loss of heat-sensitive phenotypes [27]. Across years, bleaching sensitivity was highest in the Caribbean-Atlantic basin and lowest in the Asia-Pacific (Fig. 2b). Analysis of the full best-fitting model of significant bleaching to heat stress (Extended Data Fig. 5) showed interactions between years and regions, with the Caribbean mainly showing greater sensitivity than the Asia-Pacific in 2014-15 and 2015-16 than in 2016-17. However, the highest sensitivity was seen in the Indian Ocean/Middle East in 2016-17 (Extended Data Fig. 5). Corals in all years and basins generally bleached strongly in response to heat stress at levels above the 4 °C-week threshold normally used to classify significant bleaching [24]. Patterns of severe bleaching (Extended Data Fig. 6) were similar to those seen in significant bleaching, including greater sensitivity in 2015-2016 than 2016-2017 in the Asia-Pacific (Extended Data Fig. 6a), and reduced sensitivity in 2016-2017 in the Caribbean-Atlantic. Notably, 2014-2015 showed more severe bleaching at similar levels of heat stress than 2015-2016 in the Caribbean-Atlantic (Extended Data Fig. 6b). However, curves modeled for severe bleaching (Extended Data Fig. 6) had greater uncertainty than those for significant bleaching (Extended Data Fig. 5), likely due to the much smaller number of observations and uneven spatial distribution of severe bleaching. Fortunately, reports of severe were sporadic and scattered across the basins.

Higher heat stress levels were required to cause coral mortality than bleaching (at both significant and severe levels). Records of significant (>10%) coral mortality again varied among regions and years, with risk of significant mortality risk clearly increasing with heat stress level in the two Indo-Pacific regions (Fig. 3, Extended Data Fig. 7). Because there were less than half the number of mortality reports as bleaching reports, mortality response curves (Fig. 3, Extended Data Fig. 7) were less well constrained than those for bleaching (Fig. 2, Extended Data Fig. 5). Nevertheless, the strong temperature-dependence of mortality in the two Indo-Pacific regions supports the use of 8°C-weeks as a predictor of significant mortality. In contrast, the lack of a statistically discernable positive relationship between mortality and heat stress in the Caribbean in any year suggests that heat stress was probably not a primary driver of mortality in the Caribbean during 2014-17 (discussed below).

In 2016, over 15% of global reef area, including large areas of the tropical Pacific, the Indo-Pacific, and some of the Northwestern Hawaiian Islands, reached or exceeded heat stress of 16 °C-weeks, prompting the addition of a new Alert Level to the Coral Reef Watch products (Fig. 1). Surveys conducted in these areas showed most reefs suffered rapid and severe mortality of many coral species [28-32]. This level of heat stress corresponded with very high probabilities of significant bleaching (Fig. 2, Extended Data Fig. 5), and greater than 50% probabilities of severe bleaching (Extended Data Fig. 6), and significant mortality (Fig. 3, Extended Data Fig. 7). Establishment of a new Alert Level 3 at DHW≥16 °C-weeks will help capture the increasingly long marine heatwaves [3, 4] that became especially apparent during GCBE3 and are predicted to become more frequent in the future [7]. In contrast to the recent past, marine heatwaves in the tropics now span multiple seasons and in 2014-17 persisted more than a year on some equatorial reefs (e.g., record heat stress in 2014/17 at Jarvis Island in the central Pacific Ocean resulted from over 12 months of heat stress accumulation, with DHW ≥ 4°C-weeks lasting from March 2015 to May 2016 [29]).

Assessing the Global Footprint of the 2014-17 Bleaching

Using statistically modeled bleaching and mortality thresholds for each basin and year from the maximum satellite-measured heat stress at each reef-containing pixel, we estimate that 51% of global coral reef locations suffered significant bleaching with 15% suffering significant (>10%) mortality. This mortality likely represents much of the loss of the world's corals during 2009-2018 that was reported in the most recent global coral status report [33]. While GCBE3 progressed globally for three full years (June 2014-May 2017), bleaching and mortality varied in both time and space in relation to heat stress across the 21 GCBE3 regions in each year (Fig. 4).

In general, higher heat stress resulted in higher bleaching and mortality throughout the event and most GCBE3 regions followed this pattern (Figs. 2-3). However, more complex patterns in the ratio between bleaching and mortality emerge in some areas. Factors known to modulate bleaching sensitivity to DHW include cloud cover [34], nutrients [35], species assemblages, and selective mortality of more sensitive species or genotypes. Selective mortality has been seen in the Great Barrier Reef [36, 37] and elsewhere[38, 39], including during heat stress-associated disease outbreaks [40, 41].

Heat stress-driven mortality in most regions was modeled to occur in 30-50% of pixels where bleaching occurred. However, corals in much of the Caribbean-Atlantic bleached at similar heat-stress levels as other basins (Fig. 2, Extended Data Fig. 5) but showed remarkably low new mortality, with fewer than 15% of modeled 'bleaching' pixels experiencing significant mortality. This may have resulted from a long history and higher frequency of heat stress events in the Caribbean-Atlantic [1, 3]. Caribbean coral losses have been quite high in recent decades [33, 42], including bleaching-related mortality during both prior global bleaching events [18, 43], the 1982-83 bleaching event [44], the 2005 Caribbean bleaching event [8], and now disease-related mortality due to Stony-Coral Tissue Loss Disease [45]. These have combined to reduce coral density and diversity. Depauperate in species diversity for millennia, the decline in sensitive coral species since the 1980s has left many Caribbean reefs with especially stress tolerant species and genotypes that survive bleaching [46] but provide diminished ecosystem function [47, 48]. The exception within that basin were the unique coral assemblages found off the coast of Brazil [49]. These the turbid-zone corals experienced both low bleaching and low mortality during GCBE3. Unfortunately, these corals have suffered major losses due to heat stress subsequent to 2017 [50].

Coral bleaching and mortality during the GCBE3 were much greater than those reported in either the 1998 or 2010 global bleaching events [9, 25, 26, 33]. Using DHW calculated from a dataset covering 1982 to present, heat stress during the 2014-17 event (or even in 2016 alone) was more intense and widespread than prior mass bleaching events (Fig. 5).

Of course, bleaching has continued since GCBE. Some reefs damaged during May 2016 – June 2017 continued to see bleaching later in 2017 [19, 20], while others saw severe bleaching in subsequent years [21, 50, 52].

The 2014-17 GCBE3 was more widespread and damaging than any prior bleaching event on record, highlighting the increasing threat of climate change to coral reefs and further indicating that global warming is outpacing the capacity of corals to physiologically resist heat stress on most reefs [9, 52, 53] and may result in collapse or severe bottlenecks in coral populations. The occurrence and intensity of marine heatwaves on coral reefs [1, 25] and elsewhere [4], is accelerating because of anthropogenic release of heat-trapping gases and the resultant greenhouse effect, and is predicted to further intensify [6, 54]. As coral reefs are ecosystem builders that protect shorelines from wave-driven flooding and erosion, and provide food, medicines, cultural identity, and livelihoods for over a billion people [55], these essential ecosystems urgently need protection. Our study found severe coral reef losses due to global warming throughout this protracted three-year bleaching event; an acceleration of the threat that has already placed them as one of the world's most climate-threatened ecosystems [56]. Immediate global action to reduce, and ultimately reverse, escalating emissions of greenhouse gases is essential to halt the accelerating coral loss and associated reef degradation around the world.

Declarations

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Figures

Figure 1

Global pattern of maximum heat stress from 2014-17. Heat stress categories [1] of Alert Levels 1 and 2 correspond to heat stress likely to cause significant coral bleaching (DHW ≥ 4 °C-weeks) and severe bleaching with significant mortality (DHW ≥ 8 °C-weeks) respectively, and new Alert Level 3 corresponds to heat stress likely to cause severe, widespread mortality (DHW ≥ 16 °C-weeks). See Extended Data Fig. 1a for map showing global reef locations.

1.   Skirving, W., et al., *CoralTemp and the Coral Reef Watch Coral Bleaching Heat Stress Product Suite Version 3.1.* Remote Sensing, 2020. **12**(23).
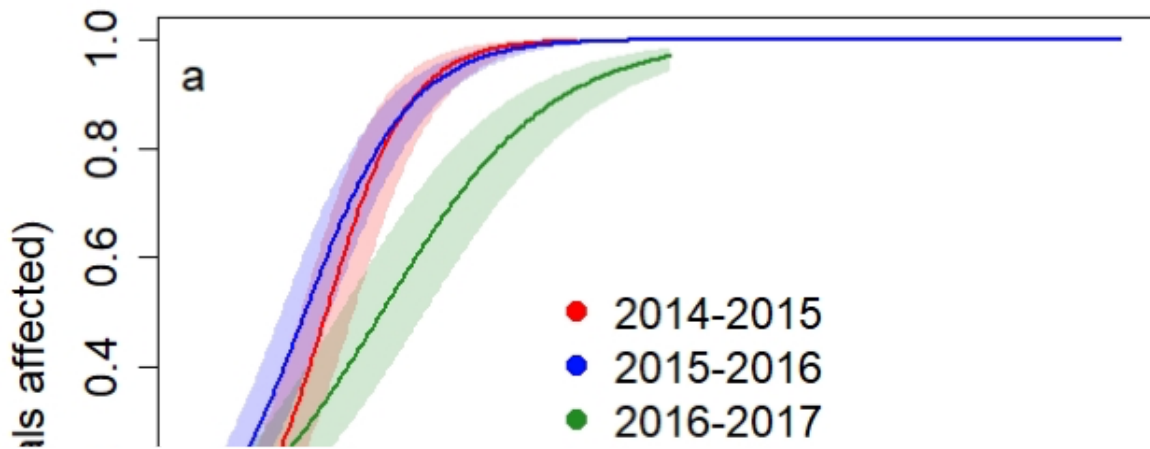
Figure 2

Fitted response curves for observed significant coral bleaching (affecting >10% of corals) as a function of heat stress varied among years and basins. Bleaching response curves, with 95% confidence limits (shading), in each of the: **a** three bleaching years 2014-15, 2015-16, 2016-17 and **b** three regions Asia-Pacific (AP), Caribbean-Atlantic (CA), and Indian Ocean-Middle East (IM)). The vertical axis is the probability of observed significant bleaching estimated from the bleaching database.
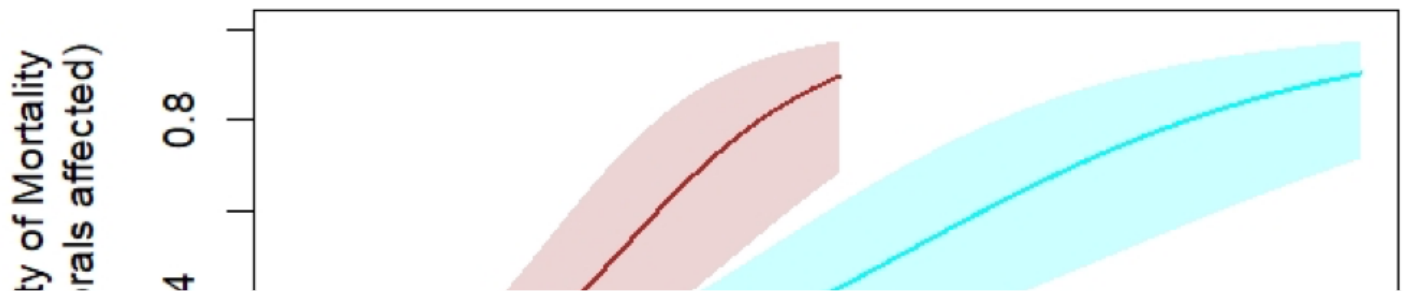
Figure 3

The response curves for observed significant coral mortality (affecting >10% of corals) as a function of heat stress varied among ocean basins across all years. The vertical axis is the probability of significant mortality calculated from the mortality data.
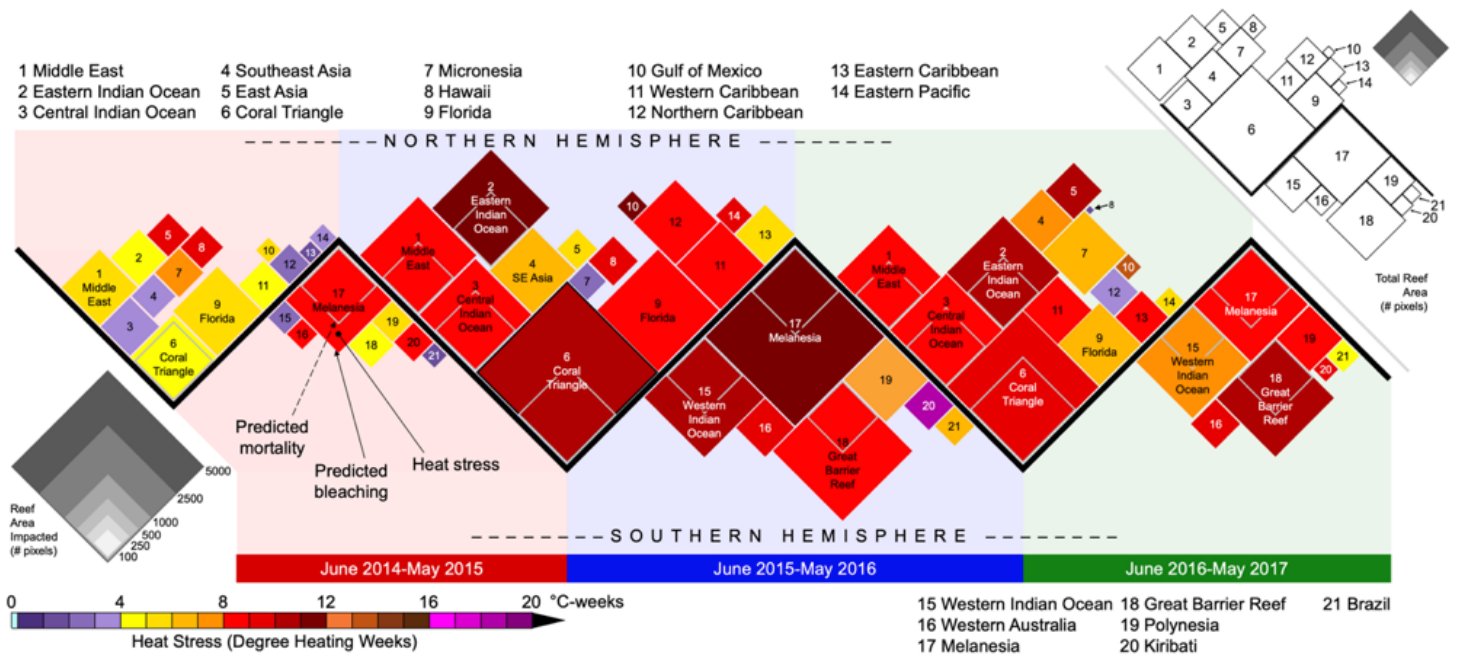

Figure 4

Projected coral bleaching and mortality impacts during GCBE3. Model-calculated area of reef impacted by significant (>10%) coral bleaching (solid diamonds) and mortality (sub-diamonds) for the 21 GCBE3 regions, in units of number of ~5×5 km^2 satellite pixels (scale at left). The Central solid black line denotes Equator through annual cycles. Colors represent the maximum heat stress (DHW data set in units of °C-weeks) in each region in that bleaching year (DHW scale at lower-left); to improve legibility white text used in diamonds for heat stress below 2 °C-weeks and above 9 °C-weeks; black text used for 2-9 °C-weeks. The inset (top-right) indicates the total reef area for each GCBE3 region (scale divisions in inset correspond with area scale in lower left of main image). Predicted mortality is shown only where the area exceeded 500 pixels (~0.1% of reef pixels). Eastern Atlantic region not shown due to small reef area (4 of 53,997 reef-containing pixels). Data in Extended Data Table 3.
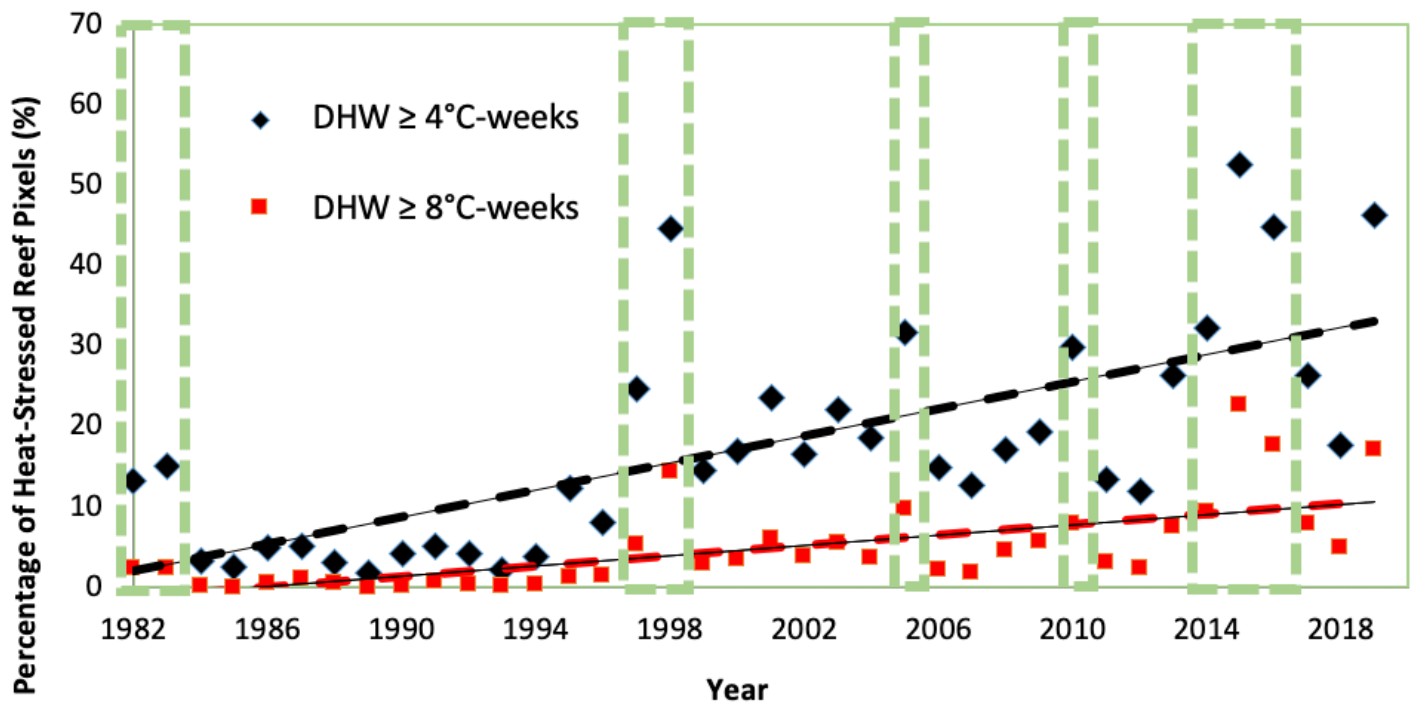

Figure 5

Percentage of global reef pixels reaching DHW ≥ 4 and 8 °C-weeks calculated from the NOAA Optimum Interpolation Sea Surface Temperature (OISST), Version 2.1 [2]. Years on the *x*-axis correspond to first year of each bleaching-year couplet (i.e., 2014 = June 2014 - May15). Green, dashed boxes correspond to major El Niño-Southern Oscillation events.

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Supplementary Files

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