The 4th Global Coral Bleaching Event: Unprecedented, unbounded, unrelenting

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Abstract

Increasingly frequent marine heatwaves have escalated the prevalence and extent of mass coral bleaching events. When marine heatwaves impact reef areas across all tropical ocean basins within a common period, global-scale coral bleaching can unfold. Here, we elaborate previous analyses to define set of objective criteria for defining a Global Coral Bleaching Event. Using this definition, we describe and compare the extent, intensity, and duration of accumulated heat stress contributing to each of the declared Global Coral Bleaching Events. In both global- and basin-scale analyses, the ongoing fourth Global Coral Bleaching Event is unprecedented in the extent and intensity of accumulated heat stress, which, based on our definition, has continued for a record duration of over six years. While the comprehensive ecosystem impacts resulting from the fourth Global Coral Bleaching Event are yet to be determined, verified field observations have confirmed coral bleaching from 83 countries spanning the northern and southern hemispheres of all ocean basins. However, an analysis of satellite-based heat stress accumulation patterns indicates that bleaching has likely impacted at least 97 of the 101 countries containing coral reefs. Following our objective analyses, there were only 175 days between the end of the third and the estimated start of the fourth Global Coral Bleaching Event; therefore the world has been experiencing global-scale coral bleaching-level heat stress for nearly the entirety of the last decade.

Introduction

Coral bleaching occurs when elevated surface ocean temperatures disrupt the endosymbiosis between the coral host and its endosymbiotic algae (Symbiodiniaceae), leading to an expulsion and/or mortality of the algal symbionts [1]. Anomalously high warm season ocean temperatures can result from local mechanisms, which persist for days to weeks [2], and may interact with synoptic-scale warming mechanisms (of 1,000 km or more), which persist for many weeks and months [3]. Local mechanisms can cause patchy bleaching at the scale of individual reefs to small regions and are usually sub-lethal. In contrast, synoptic-scale mechanisms are the only known cause of mass coral bleaching, characterised by reef-wide bleaching that typically encompasses entire reef systems or geographic realms [1], often resulting in significant levels of mortality. Mass coral bleaching is a relatively recent, though increasingly frequent, phenomenon that is related to global ocean warming and has only been documented since the 1980s [4,5].

Sublethal bleaching adversely affects coral growth, fecundity and population trajectories [6,7], and increases the risk of coral disease [8]. When heat stress is prolonged or particularly severe, widespread coral mortality will occur [9]. Whilst posited during the 1982-1983 period [10], the first record of multiple regional-scale mass coral bleaching events occurring simultaneously or subsequently throughout the Atlantic, Indian and Pacific Oceans during a single continuous period was in 1998, marking the first documented global-scale coral bleaching event (GCBE1) [11,12]. Additional GCBEs have been documented in 2010 (GCBE2) and 2014-2017 (GCBE3), each more widespread, enduring and consequential than the last [13]. In April 2024, the U.S. National Oceanic and Atmospheric Administration declared the fourth global event (GCBE4) [14], resulting from unprecedented synoptic-scale marine heatwaves in all three tropical ocean basins.

Here, we describe the geographic extent, duration and intensity of accumulated heat stress during GCBE4, measured using satellite-derived Degree Heating Weeks (DHWs, ˚C-weeks), the most commonly used bleaching predictor, incorporating the duration and severity of heat stress [15]. While the coral bleaching threshold to accumulated heat stress among reef locations can vary greatly, often due to differing thermal histories and/or species compositions [16–23] along with a coarse spatial resolution of satellite data relative to the size of individual reefs, a DHW threshold of 4˚C-weeks has been used as a reliable general indicator of significant bleaching at large spatial scales, globally [24–28]. A recent analysis has shown 4˚C-weeks to be a largely conservative threshold for predicting bleaching occurrences globally [29]. Regardless, it is important to note that we do not assume that a heat stress accumulation threshold of 4˚C-weeks is always indicative of bleaching during GCBE4 or any previous event. Rather, this heat stress accumulation threshold is used as a consistent and inter-comparative tool for describing and comparing a valid measure of known and documented thermal stress among GCBEs as well as during non-GCBE time periods.

Field observations of confirmed mass coral bleaching among the 101 identified countries containing coral reefs were collated throughout the GCBE4 period. A set of quality control procedures (see Methods) was used to verify observations within each region of ‘mass coral bleaching’ in a region, defined as bleaching events that **1)** are related in time and geographic area by a common cause or mechanism [30], **2)** involve a mechanism that occurs over synoptic scales (> 1,000 km) [31], and **3)** are ecologically significant (≥ 20% reef area bleached) [32]. Given that we relied primarily upon qualitative observations, we used the benchmark of 20% in the third criterion to ensure confidence in our inferences of mass bleaching. As the reef areas of some countries are relatively small, the categorisation of ‘mass bleaching’ must be taken within the context of the entire reef system (e.g., the reefs of Israel as part of the northern Gulf of Aqaba reef system), as well as the scale of the driving mechanism.

An analysis of unprecedented or extreme heat stress accumulations of ≥ 12˚C-weeks provides evidence of likely bleaching in countries in which surveys were not available. Given that this is a 3-fold higher amount of heat stress than what has been repeatedly shown in field and lab studies to elicit bleaching (reviewed in [29]), we utilise this threshold to conservatively infer countries lacking in-water surveys have also likely undergone significant and widespread (mass) coral bleaching during GCBE4. The results that follow show the heat stress accumulated on reefs during GCBE4 to be unprecedented by every investigated metric.

Methods

Satellite data

All sea surface temperature (SST) and heat stress metric data were derived from the daily global 5 km NOAA CRW Heat Stress Monitoring Product Suite version 3.1 dataset, covering 1st Jan 1985 to present day. A reef pixel dataset (i.e., reef mask) was overlayed onto the SST or heat stress metric datasets to identify pixels that contain coral reefs. The reef mask obtained from Skirving et al. [24] did not have reef pixels populated for Cabo Verde and Easter Island; these pixels were manually added for this analysis following Heron et al. [33]. The reef mask was divided into the three ocean basins, the boundaries of which were obtained from Skirving et al. [24]. Individual masks of the 101 reef-containing geopolitical regions were developed on a 5 km global grid and used in tandem with the reef mask for analysis of heat stress within countries.

Identification and monitoring

A global-scale coral bleaching event (GCBE) must first be clearly defined to identify and monitor global coral bleaching risk. The first objective definition of a GCBE, proposed by Skirving et al. [24], references the worldwide bleaching event of 1998 as a baseline; this is widely recognised as the first GCBE [11,12]. The following definition applies logical extensions, including a minimum length of time with persistent global heat stress [34] and the calculation of the metric over a 365-day period, both of which are in keeping with the intentions of the original GCBE definition. The primary metric utilised for our determination of a GCBE is the percentage of 5 km (0.05˚ × 0.05˚) reef-containing satellite pixels that had experienced ≥ 4˚C-weeks in a 365-day period, calculated daily and encompassing data up to and including the given date. We termed this the 'annual bleaching stress extent', which can be calculated for the global oceans, individual ocean basins, or distinct marine regions. By encompassing a full year period, the annual bleaching stress extent is accounting for recent heat stress affecting both Northern and Southern hemisphere, or global, reefs.

As in Skirving et al. [24], the characteristics of the first global event in 1998 (GCBE1) were used as a definitive baseline to identify the presence of subsequent GCBEs [24]. During GCBE1, our analysis shows that the annual bleaching stress extent in the Atlantic, Indian and Pacific Ocean basins reached a maximum coverage of 34.5%, 35.4% and 12.5% of reef pixels, respectively. The annual bleaching stress extent was 12% or more in all three ocean basins for a period of 219 days. Lastly, the maximum annual bleaching stress extent globally (across all three ocean basins) during this period was 20.2%. Therefore, by rounding these values achieved during GCBE1 down to the nearest percent and nearest week, the required criteria for a GCBE are set forth as:

- **(A)** each of the three tropical ocean basins (Atlantic, Indian and Pacific) must simultaneously have an annual bleaching stress extent of 12% or more.
- **(B)** the conditions of the first criterion must remain consistently present for a period of at least 217 consecutive days (31 weeks).
- **(C)** the extent of the annual bleaching stress extent across all reef pixels globally must reach 20% or more within the period of the second criterion.

Under these criteria, the heat stress contributing to every subsequent GCBE is at least as large and lasting as GCBE1. Once a GCBE has been identified, the duration of the event can be determined (termed the 'total event period'). Since each daily metric is totalled over 365 days (i.e., the number of days used to calculate the annual bleaching stress extent), the start date is

364 days prior to the date of meeting criterion **(A)**. The total event period is therefore the number of days during which criteria **(A)** are satisfied plus 364 days, totalling a minimum of 581 days (217 days + 364 days). The assigned start date of each total event period is a general approximation of the event's initiation, as this is when accumulated heat stress begins being factored into the GCBE metric. The cumulative bleaching stress extent of a GCBE is determined and calculated as the total global percentage of reef pixels that accumulated ≥ 4˚C-weeks during total event period.

Collation of bleaching observations

In addition to satellite data of heat stress over coral reefs, we have compiled initial observations of in situ coral bleaching during the total event period of the fourth Global Coral Bleaching Event (GCBE4). Here, we attempt to identify which political states or countries (among those which contain coral reefs within their political boundaries) were likely affected by GCBE4. In classifying these, reef areas of some countries were split into multiple regions if they occupied different ocean basins (e.g., Pacific and Atlantic reefs of Panama). As some countries govern or oversee multiple separate territories, these were included under the single overarching federal government only in the cases of non-self-governing territories (as defined under the Charter of the United Nations), overseas departments and special municipalities. Alternatively, those classified as an independent state, overseas collectivity, constituent country, or internally self-governing state were listed and analysed as individual entities. We identify 101 distinct countries that contain coral reefs within their established boundaries.

Instances of observed mass coral bleaching within the total event period of GCBE4 (August 2018 to June 2025; see Results) were acquired for each country by requesting submission of in situ bleaching surveys from researchers and managers, direct communication with local contacts with experience observing bleaching events, searching through published literature and media reports, and by the voluntary submission of observations to the National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch (CRW) program from several international stakeholders (**S1 Table**). Quality control measures were implemented to validate these observations. The reliability of the observation was assessed by categorising the expertise of the data submitter. Coral reef researchers and managers, who conduct regular scientific monitoring/assessments of coral reefs, were considered 'reliable' observers. Observations from untrained surveyors (e.g., recreational divers, tourists, journalists) were considered 'less reliable' observers. However, three or more independent observations on the same reef area from 'less reliable' observers were considered sufficient to classify the declaration of mass bleaching in that location as reliable.

Additionally, it was necessary to develop and apply methods to establish that observations of bleaching included in the analysis were those from an ecologically significant and widespread bleaching event (i.e., 'mass bleaching'; as defined in the main text), as opposed to minor or localised bleaching, such as driven by local factors (e.g., freshwater runoff) or coral disease mistakenly identified as bleaching. Photo and/or video evidence was used as a crucial tool to establish a confirmation of coral bleaching in the instances where the estimated percent cover bleached was not provided. When photos were assessed, we considered them with reference to the above criteria before inferring if a reported event truly corresponded to mass bleaching.

Geopolitical analysis of heat stress

Some countries had no available surveys of coral reefs during or after the periods of heat stress throughout GCBE4, often due to socio-economic limitations and/or impediments to open communication (e.g., Yemen). However, over the total event period of GCBE4, the annual (within one calendar year) maximum Degree Heating Week (DHW) was calculated for each reef pixel and the greatest 80th percentile yearly value among those within the political bounds of each country was identified. By using records of extreme satellite heat stress within the corresponding region, we could confidently infer that bleaching likely occurred in many areas that lacked in situ observations. Mass bleaching in a country lacking in situ surveys was inferred with high confidence when the corresponding 80^{th} percentile maximum DHW value had achieved 12˚C-weeks or greater, 3-fold above the typical DHW threshold of 4˚C-weeks. If the 80^{th} percentile maximum DHW value was 8˚C-weeks or greater (but less than 12˚C-weeks), mass bleaching was inferred if this was an all-time high within the satellite record.

Results

Global coral heat stress

Using the updated satellite-based SST criteria to define a Global Coral Bleaching Event (GCBE) [24], we found that GCBE4 was unprecedented by every investigated metric. GCBE4 had an estimated start in August 2018 and continues to the present, lasting more than six years. All results that follow are those as of 1^{st} June 2025. During GCBE4, bleaching-level heat stress (DHW ≥ 4˚C-weeks) [24] had impacted > 85% of the world's reef locations (defined as 0.05˚ × 0.05˚, or ~5 km, satellite pixels containing coral reefs) at least once. All three ocean basins have had DHW ≥ 4˚C-weeks accumulated in over 80% of their reef locations since August 2018 (**Table 1**). The total event period of each GCBE has become progressively longer, with GCBE1 lasting for 1.6 years, compared to 6.8 years so far for GCBE4. The gap between GCBE3 and GCBE4 was merely 175 days, roughly 6 months. The global maximum annual bleaching stress extent (i.e., the greatest global extent of DHW ≥ 4 within a 365-day period) during GCBE4 has affected 78.5% of reef locations (20^{th} February 2024 – 18^{th} February 2025), nearly four times that achieved during GCBE1 (**Fig. 1**); the annual bleaching stress extent in each of the individual ocean basins during GCBE4 has also been record-setting (**Table 1**). Previous annual bleaching stress extent records were set during GCBE3, apart from the Atlantic Ocean basin where the previous record was set during GCBE2 (54%). At least 99.9% of Atlantic Ocean reef locations during GCBE4 have experienced bleaching-level heat stress within 365 days (6th September 2023 – 4th September 2024). During GCBE4, the maximum annual bleaching stress extent during GCBE4 in the Indian and Pacific Oceans were 83.5% and 74.1%, respectively.

Table 1. Global Coral Bleaching Event statistics.

Event	Event Dates (estimated)	Event Duration	Global Extent	Atlantic Extent	Indian Extent	Pacific Extent
GCBE1	22nd Sep 1997 – 27th Apr 1999	583 days (1.6 years)	**20.6%** (20.2%)	**34.8%** (34.5%)	**35.7%** (35.4%)	**12.8%** (12.5%)
GCBE2	23rd Jun 2009 – 5th Nov 2011	866 days (2.4 years)	**37.2%** (35.2%)	**55.7%** (54.0%)	**37.1%** (36.7%)	**33.8%** (31.8%)
GCBE3	28th Aug 2014 – 19th Feb 2018	1,272 days (3.5 years)	**68.2%** (56.1%)	**56.8%** (44.0%)	**74.7%** (71.4%)	**68.1%** (58.9%)
GCBE4	13th Aug 2018 – 1st June 2025*	2,485 days (6.8 years)	**86.8%** (78.5%)	**99.9%** (99.9%)	**89.1%** (83.5%)	**83.5%** (74.1%)

The estimated start and end dates of each event define the duration (number of days) of each global coral bleaching event (time in years in parentheses). The extent (i.e., cumulative percentage of reef locations exposed to DHW ≥ 4˚C-weeks, at least once) for the total event period of each Global Coral Bleaching Event (GCBE), with these metrics being presented globally as well as for individual ocean basins (*bold values*). Additionally, values listed in *parentheses* signify the maximum annual bleaching stress extent (the maximum percentage of reef locations accumulating DHW ≥ 4˚C-weeks within a 365-day period) achieved during each GCBE, globally and for each individual ocean basin. *GCBE4 is ongoing at the time of writing; values are not final.

Fig. 1. Global annual bleaching stress extent. Daily values (25th March 1986 – 1st June 2025) of the annual bleaching-level heat stress extent, showing the percentage of reef locations globally that had accumulated ≥ 4˚C-weeks in the previous 365 days (solid black line). Sections under this line shaded in *red* depict the total event periods during which accumulated heat stress contributed towards a GCBE (see Methods). Sections shaded in *blue* depict periods during which accumulated heat stress did not contribute to a GCBE. Black dashed line shows the percentage of reef locations globally that had accumulated ≥ 8˚C-weeks in the previous 365 days.

The severity of heat stress during GCBE4 has also been unprecedented. Among all reef locations during each global event, the median of peak DHW values increased with each subsequent event, from 1.4˚C-weeks during GCBE1 to 8.5˚C-weeks during GCBE4 (**Fig. 2**). Further, by examining the annual extent of heat stress accumulation with a higher threshold of 8˚C-weeks, a DHW level often associated with coral mortality [23,35], the extent during GCBE4 is also unprecedented in both global- and basin-level comparisons. The maximum global extent of reef locations experiencing DHW ≥ 8˚C-weeks within a 365-day period, 45.9%, is more than double the previous maximum extent (20.6%) during GCBE3. During GCBE4, the record-high maximum annual extents at the 8˚C-weeks threshold within the individual ocean basins are 96.0%, 45.1% and 40.4% for the Atlantic, Indian and Pacific, respectively (see **S2 Table**). The global extent of coral mortality during GCBE4 is currently undetermined, and these results do not aim to estimate them.

Fig. 2. Distribution of heat stress accumulation among GCBEs. The percentage of global reef locations at each DHW value (rounded to the nearest 0.1˚C-weeks), for each GCBE. Distribution curves on each graph are smoothed using a running average of 31 points along the horizontal axis. The vertical dashed line on each graph shows the median DHW value among all reef locations within the total event period.

The international extent of GCBE4

To begin to understand the extent of socio-economic impacts of GCBE4, we investigated confirmations and likelihoods of mass bleaching from all coral reef-containing countries (or political states). Reliable observations of mass bleaching (see Methods) were sourced from 83 of the 101 reef-containing countries (**Fig. 3**). Further analysis shows that 71 countries accumulated ≥ 12˚C-weeks on at least 20% of their reef locations, a heat stress level corresponding to a high probability of severe bleaching and multi-species mortality [36]. Among the 18 countries that did not have reliable in situ observations of mass bleaching, 12 experienced ≥ 12˚C-weeks on 20% or more of their reef area, and an additional two countries (Myanmar and Somalia) had at least 20% of their reef locations experiencing ≥ 8˚C-weeks, with these being an all-time high within the 40-year satellite record, giving us high confidence that a mass bleaching event had affected these regions as well [27]. Three of the remaining four countries (Tonga, Chile [Easter Island], and Timor-Leste) accumulated between 5.5 and 11.5˚C-weeks on at least 20% of their reef locations. As previous heat stress accumulations in these locations had exceeded this, we considered this insufficient to infer the presence of mass bleaching with high confidence. Niue remains the only country with an 80th percentile DHW below the bleaching-level threshold (2.04˚C-weeks), indicating that mass bleaching here during GCBE4 is unlikely. Based on conservative logical deduction, using these thresholds of extreme and/or unprecedented heat stress accumulations, we conclude that no fewer than 96% of all reef-containing countries have been substantially affected by the ongoing GCBE4 (**Table 2**). As the scale of reef areas of different countries are highly varied (e.g., Papua New Guinea as compared to Nauru), it is important to note that the goal of this analysis was not to compare the ecological impacts of GCBE4 among these locations, but to identify the extent of likely impacts to human societies and governments globally.

Fig. 3. Map of confirmed in situ observations of coral bleaching. Global map (40˚N – 40˚S) of maximum DHW accumulation throughout the total event period of GCBE4 (13th August 2018 – 1st June 2025). White stars signify reliable observations of confirmed mass bleaching in the general region during GCBE4. Location of stars do not correspond to exact coordinates of observations and not all observations during GCBE4 are represented within this map.

Table 2. Heat stress and assessment of mass coral bleaching in reef-containing countries.

Ocean Basin	Country/State	Reef area (5 km reef pixels)	GCBE4 80th Percentile DHW	Date of peak GCBE4 heat stress	All-time maximum DHW event	Assessment of significant bleaching
Atlantic	**Antigua and Barbuda	32	22.60	7/11/24	GCBE4	Observed
	Aruba	27	23.01	3/12/24	GCBE4	Observed

	**Bahamas	1815	19.13	22/10/23	GCBE4	Observed
	**Barbados	17	23.22	12/11/24	GCBE4	Observed
	**Belize	270	18.70	18/10/24	GCBE4	Observed
	Brazil	288	20.44	10/5/24	GCBE4	Observed
	**Cabo Verde	120	20.09	5/11/23	GCBE4	High confidence
	Caribbean Netherlands	57	21.59	8/11/24	GCBE4	Observed
	Colombia (Atlantic)	114	17.71	13/10/24	GCBE4	Observed
	Costa Rica (Atlantic)	13	17.73	17/11/23	GCBE4	Observed
	**Cuba	1090	18.53	22/9/23	GCBE4	Observed
	Curaçao	30	22.70	2/12/24	GCBE4	Observed
	**Dominica	21	21.20	17/11/24	GCBE4	High confidence
	**Dominican Republic	211	18.65	27/10/23	GCBE4	Observed
	France (Atlantic)	96	21.74	13/11/24	GCBE4	Observed
	**Grenada	28	22.53	7/11/24	GCBE4	Observed
	**Haiti	255	20.83	29/10/23	GCBE4	High confidence
	Honduras	97	15.38	24/10/24	GCBE4	Observed
	**Jamaica	161	21.23	13/11/23	GCBE4	Observed
	Mexico (Atlantic)	292	19.26	17/10/23	GCBE4	Observed
	Nicaragua	400	23.58	11/11/23	GCBE4	High confidence
	Panama (Atlantic)	227	20.01	17/11/23	GCBE4	Observed
	Puerto Rico	155	20.70	31/10/24	GCBE4	Observed
	St. Barthelemy	7	21.45	7/11/24	GCBE4	Observed
	**St. Kitts and Nevis	24	21.35	9/11/24	GCBE4	High confidence
	**St. Lucia	19	22.25	13/11/24	GCBE4	High confidence
	**St. Vincent and the Grenadines	28	22.45	9/11/24	GCBE4	Observed
	St. Martin	8	17.78	24/10/23	GCBE4	Observed
	**São Tome and Principe	1	12.27	1/5/24	GCBE4	High confidence
	Sint Maarten	8	21.60	7/11/24	GCBE4	Observed
	**Trinidad and Tobago	27	22.49	7/11/24	GCBE4	Observed
	United Kingdom (Atlantic)	441	17.80	26/10/23	GCBE4	Observed
	United States (Atlantic)	331	20.85	10/11/24	GCBE4	Observed
	Venezuela	144	24.50	26/11/24	GCBE4	High confidence
Pacific	Australia (Pacific)	5289	9.67	7/3/24	GCBE4	Observed
	Brunei	41	7.76	29/6/24	GCBE4	Observed
	Chile (Easter Island)	1	5.49	27/3/25	Regional (2000)	Low confidence
	China	204	15.99	8/9/20	GCBE4	Observed
	Colombia (Pacific)	10	20.83	24/7/23	GCBE4	Observed
	**Cook Islands	152	12.13	20/5/24	GCBE3	Observed
	Costa Rica (Pacific)	47	17.64	8/4/24	GCBE4	Observed
	Ecuador (Galapagos)	74	17.33	9/5/23	GCBE1	Observed
	El Salvador	6	13.63	27/9/23	GCBE4	Observed
	**Federated States of Micronesia	967	14.20	22/10/24	GCBE4	Observed
	**Fiji	1328	8.38	19/2/23	Regional (2014)	Observed
	France (Pacific)	1075	10.83	21/3/22	GCBE3	Observed
	French Polynesia	1261	7.27	9/4/24	GCBE4	Observed
	Indonesia	9369	6.96	1/1/24	GCBE3	Observed
	Japan	460	17.43	14/9/24	GCBE4	Observed
	**Kiribati	382	15.54	1/11/23	GCBE4	Observed
	Malaysia	823	7.39	11/6/24	GCBE4	Observed
	**Marshall Islands	793	7.64	5/11/24	GCBE4	Observed
	Mexico (Pacific)	26	17.99	20/10/23	GCBE4	Observed
	**Nauru	5	15.70	7/11/19	GCBE3	High confidence
	**Niue	16	2.04	6/4/24	Regional (1988)	Unlikely
	**Palau	142	9.16	22/10/24	GCBE4	Observed
	Panama (Pacific)	90	14.30	8/10/23	GCBE4	Observed
	**Papua New Guinea	3439	17.16	6/1/23	GCBE4	Observed
	Philippines	5051	8.36	13/7/20	GCBE4	Observed
	**Samoa	88	15.27	19/5/24	GCBE4	Observed
	**Singapore	374	5.04	16/6/24	GCBE2	Observed
	**Solomon Islands	1400	11.46	21/2/25	GCBE4	Observed
	Taiwan	153	18.67	16/9/24	GCBE4	Observed
	Thailand	430	12.70	7/6/24	GCBE4	Observed
	**Timor-Leste	183	6.19	3/1/20	GCBE4	Low confidence

	**Tonga	323	11.52	7/3/23	Regional (2000)	Low confidence
	**Tuvalu	58	13.38	3/6/24	GCBE4	Observed
	United States (Pacific)	650	10.02	1/11/19	GCBE3	Observed
	**Vanuatu	476	9.99	15/3/24	GCBE4	Observed
	Vietnam	210	12.32	4/6/24	GCBE4	Observed
	Wallis and Futuna	35	15.25	13/5/24	GCBE4	Observed
Indian	Australia (Indian)	1237	20.95	6/3/25	GCBE4	Observed
	Bahrain	189	10.16	7/9/21	Regional (1986)	Observed
	**Comoros	86	6.30	14/4/24	GCBE4	Observed
	Djibouti	98	12.35	12/10/23	GCBE4	Observed
	Egypt	674	26.64	28/9/24	GCBE4	Observed
	Eritrea	452	18.89	16/10/23	GCBE4	High confidence
	France (Indian)	17	16.98	6/4/2025	GCBE3	Observed
	India	395	12.02	21/5/20	GCBE4	Observed
	Iran	106	8.93	1/8/24	GCBE4	Observed
	Israel	5	23.66	17/9/24	GCBE4	Observed
	Jordan	5	23.66	17/9/24	GCBE4	Observed
	Kenya	127	12.89	16/4/24	GCBE4	Observed
	Kuwait	29	22.26	12/9/24	GCBE4	Observed
	Madagascar	865	14.17	5/5/24	GCBE4	Observed
	**Maldives	1024	5.93	15/5/24	GCBE3	Observed
	**Mauritius	129	13.22	13/4/25	GCBE3	Observed
	Mayotte	104	9.59	22/4/24	GCBE4	Observed
	Mozambique	430	9.83	14/4/24	GCBE4	Observed
	Myanmar	425	9.43	4/6/24	GCBE4	High confidence
	Oman	74	14.31	2/8/24	GCBE4	Observed
	Qatar	15	6.75	3/9/21	Regional (1986)	Observed
	Saudi Arabia	1095	23.68	17/9/24	GCBE4	Observed
	**Seychelles	273	15.25	26/4/24	GCBE4	Observed
	Somalia	79	8.50	17/4/24	GCBE4	High confidence
	Sri Lanka	123	8.70	17/5/24	GCBE3	Observed
	Sudan	227	13.77	13/10/23	GCBE4	High confidence
	Tanzania	529	13.48	5/4/24	GCBE4	Observed
	United Arab Emirates	277	5.66	7/9/23	Regional (1986)	Observed
	United Kingdom (Indian)	500	6.27	16/4/24	GCBE3	Observed
	Yemen	203	14.29	20/10/23	GCBE4	High confidence

Coral reef-containing countries, organised by ocean basin, with the number of reef-containing 5 km pixels within their jurisdiction, the greatest annual 80th percentile maximum DHW value among reef locations within the corresponding political boundaries during GCBE4, the date of peak GCBE4 heat stress accumulation (based on the 80th percentile annual maximum DHW), the global or regional event corresponding with all-time maximum heat stress accumulation, and the assessment of mass coral bleaching during GCBE4. Assessments of mass coral bleaching are categorised as ‘Observed’ when there are reliable in situ reports of widespread bleaching, ‘High confidence’ when observed bleaching was absent but there was either extreme heat stress accumulation (DHW ≥ 12˚C-weeks) within the region or an all-time high accumulation of heat stress ≥ 8˚C-weeks, and ‘Low confidence’ when accumulated heat stress during the GCBE4 period was ≥ 4˚C-weeks on at least 20% of the country's reef locations. 'Unlikely' signifies that there is no expectation that mass bleaching occurred in that country during GCBE4. Countries listed with a double asterisk are identified as sovereign Small Island and Developing States (SIDS).

Discussion

Reefs facing new and repeated extremes

Corals can exhibit increased thermal tolerance after repeated exposure to marine heatwaves [22,37]; however, the ability of reefs to genetically adapt at a rate and scale necessary to combat the current and projected rate of warming has not been demonstrated [38–40]. In addition to advantageous thermal and adaptive histories, some coral colonies, with the aid of heat-tolerant symbionts, food availability, and/or favourable oceanography, demonstrate a capacity to recover from heat stress capable of causing mortality under alternate circumstances [41,42]. There is, however, an expected heat stress accumulation threshold for near-complete, reef-wide coral mortality of ≥ 20˚C-weeks [43–45], albeit with one known exception in the northern Red Sea [46]. This level of heat stress accumulation was surpassed on more than 26% of reef locations within the Atlantic Ocean basin during GCBE4 (primarily in 2023), a region that has already experienced multiple devastating disturbance events over the past 40-50 years [47,48]. From 2023 to the time of writing, nearly 30% of reef locations globally experienced higher SST, and nearly 60% accumulated higher DHW, than at any prior time within the satellite record (1985-2022). The most extreme heat exposures occurred in the Caribbean, southern Atlantic, Red Sea, Persian Gulf, and the eastern and western Pacific. Reports of observed bleaching were relatively fewer from 2020–2022 than in the remainder of the GCBE4 period, likely influenced by reduced monitoring efforts during the COVID-19 pandemic. Government lockdowns and other COVID-19-related restrictions left many reefs around the world unmonitored upwards of 61 weeks at a time [49]. The satellite data shows a continuous period of global coral heat stress despite reduced monitoring over this period.

The increased frequency of repeated exposure to heat stress is threatening the long-term persistence of reef systems. Since the start of GCBE3 (mid-2014), there was only a roughly six-month gap during which GCBE conditions were not met; it is currently uncertain when GCBE4 might end. More than half of the world's reef locations experienced multiple bleaching-level heat stress events during GCBE4. By the end of GCBE3, the average time between severe bleaching events globally was only 6 years [5]. Within the 6.8-year duration of GCBE4 thus far, 63% of the world's reef locations accumulated ≥ 4˚C-weeks at least twice, whereas over 25% experienced this level of heat stress four times or more. Further, nearly one-third of the world's reef locations experienced ≥ 8˚C-weeks at least twice during this period. One of the most notable examples of repeated heat stress and mass bleaching occurred on the Great Barrier Reef, Australia, the world's largest continuous coral reef ecosystem, which experienced mass coral bleaching in at least five of the first seven austral summers during GCBE4 (2020, 2021, 2022, 2024 and 2025) [50–52], with a trend of an increasingly early onset of heat stress [53]. Among other reef systems, mass coral bleaching was observed during at least three of the GCBE4 boreal summers in both the Caribbean (2019, 2023 and 2024) and in the Red Sea (2020, 2023 and 2024) (see **S1 Table**). Repeated heat stress events can have long-lasting and species-specific effects, even in those colonies that appear healthy visually, raising concerns about the capacity for reef resilience under future marine heatwaves [54]. With an expectation of longer-lasting heat stress events and potentially annual marine heat extremes [5], corals will face increased pressure for genetically driven adaptation and, if unable to do so, their survival under accelerating warming is increasingly unlikely [55,56].

Most reef-containing nations likely experienced mass coral bleaching during GCBE4. Some countries observed mass bleaching for the first time on important reef systems that would have previously been considered 'thermal refugia' (e.g., reef locations within Solomon Islands, southern Great Barrier Reef) [57]. This illustrates that the predicted loss of local-scale refugia [56] is well underway, as the global number of recorded bleaching events continues to rapidly increase [5].

Mass coral bleaching and mortality effects are not restricted to just the immediate marine ecosystem but extend to the socio-economic systems that rely on them. The value of ecosystem services provided by coral reefs globally has been estimated to be roughly US$10 trillion [58], including US$109 billion in coastal protection [59]. The global costs of coral bleaching, with effects on fisheries, tourism, coastal protection, biodiversity and more, has been estimated to be tens of billions of US dollars [60]. Mass coral bleaching and mortality can be variably detrimental to the populations within [61] and socio-economic status of an individual political states, with some countries being more vulnerable than others [62,63]; most notable are those categorised by the United Nations as 'Small Island and Developing States' (SIDS), which face unique social, economic and/or environmental vulnerabilities. Coral reefs are key ecosystems for sustaining the socio-economic status of SIDS as a source of economic growth, food, and coastal protection [64], with 94% of their total population living within 100 km of a coral reef [65]. Of the 101 coral reef-containing countries identified, 36 are SIDS (**Table 2**).

The world has been in a chronic state of bleaching-level stress since August 2018, affecting nearly all reef locations globally. Whilst future work is essential to assess the resulting ecological impacts (coral bleaching, mortality and disease) during GCBE4 and to understand the follow-on effects of these upon social and economic systems, the record extent and severity of observed heat stress suggests that these are likely to be dire.

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Supporting information captions

S1 Table. Select sources of confirmed bleaching during GCBE4.

The select publications, reports, organisations, and/or individuals (personal communications or media statements) that were used to conclude a reliable confirmation of observed mass bleaching for each country (and the corresponding year) during GCBE4.

S2 Table. Annual extent of DHW ≥ 8˚C-weeks.

The maximum annual extent of mortality-level heat stress (the maximum percentage of reefs accumulating DHW ≥ 8˚C-weeks within a 365-day period) achieved during each GCBE, globally and for each individual ocean basin. *GCBE4 is ongoing at the time of writing; values are not final.

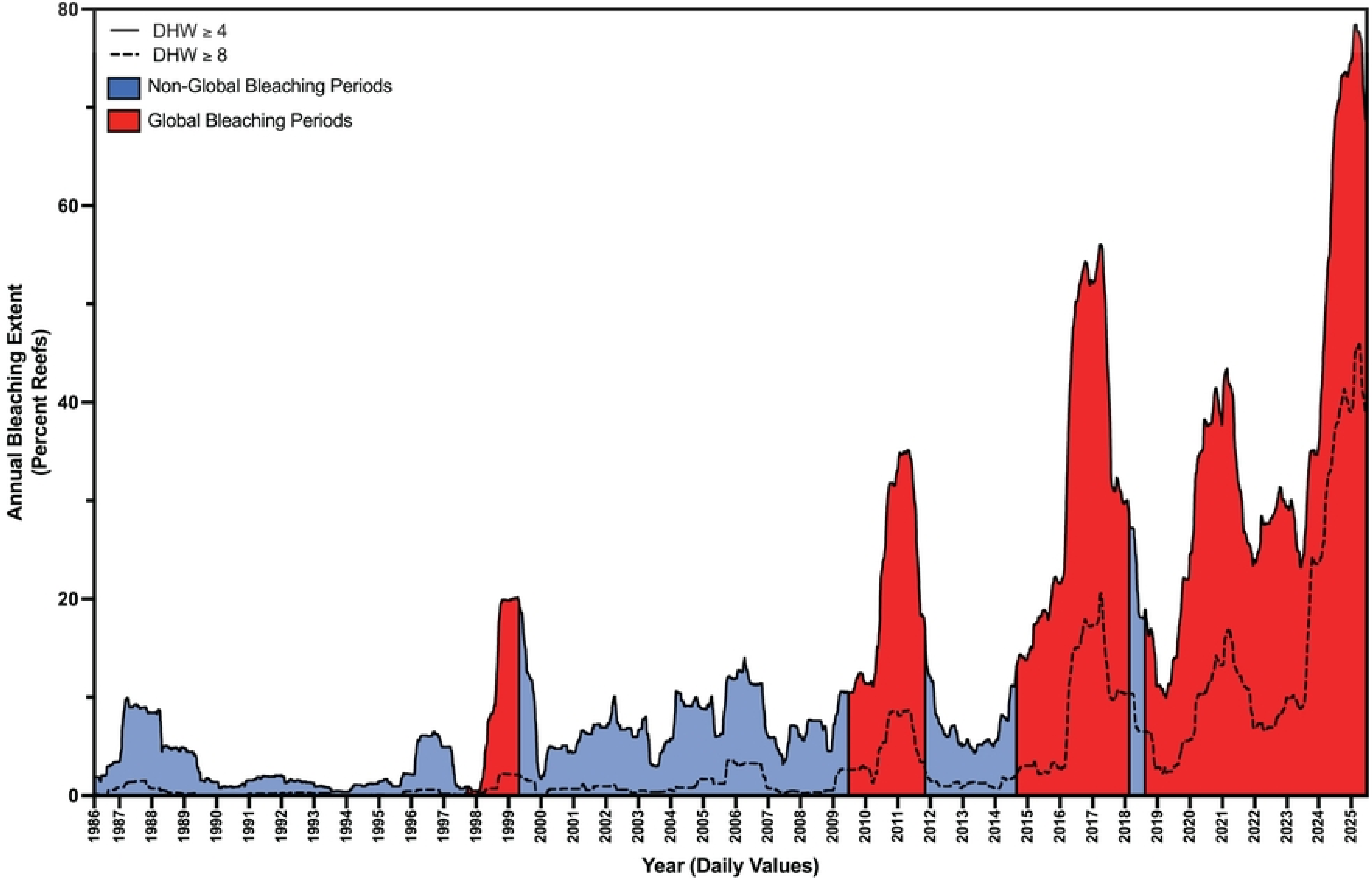


Fig. 1. Global annual bleaching stress extent

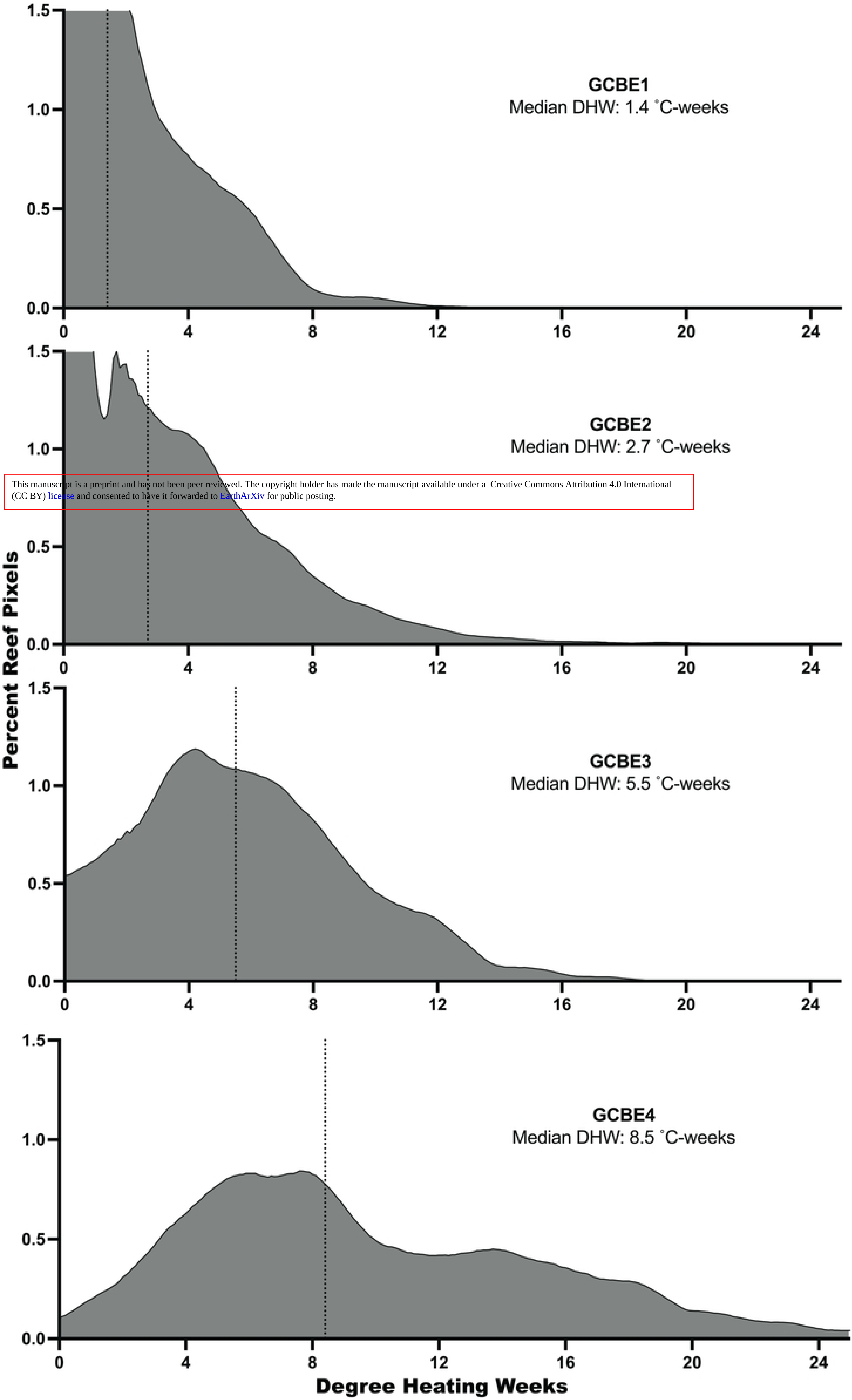
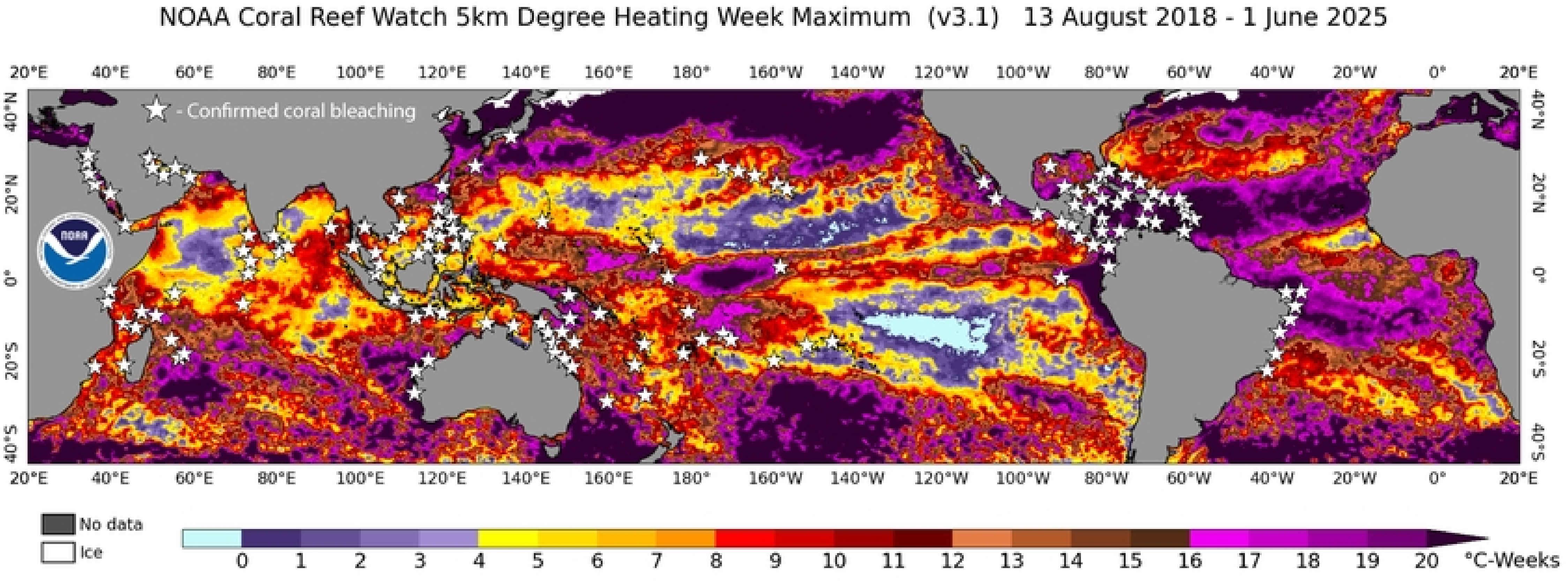


Fig. 2. Distribution of heat stress accumulation among


NOAA Coral Reef Watch 5km Degree Heating Week Maximum (v3.1) 13 August 2018 - 1 June 2025
- Confirmed coral bleaching
20°E 40°E 60°E 80°E 100°E 120°E 140°E 160°E 180° 160°W 140°W 120°W 100°W 80°W 60°W 40°W 20°W 0° 20°E
40°N 20°N 0° 20°S 40°S
No data
Ice
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 °C-Weeks

Figure