Coral Reefs
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RESEARCH

The 4th global coral bleaching event: ushering in an era of near-annual bleaching

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Abstract Increasingly frequent marine heatwaves have escalated the prevalence and extent of mass coral bleaching events. Global-scale coral bleaching events (GCBEs) can unfold when marine heatwaves impact reefs across all tropical ocean basins within a common period. Here, we define an objective, quantifiable index to compare periods of satellite-derived coral heat stress accumulation globally from 1985 to 2025 and examine their relationship to confirmed GCBEs. We uncover an uninterrupted and ongoing period of global coral heat stress from 2018 to 2025, affecting an unprecedented 87% of reef areas globally. The average intensity has also been record-setting, with the median global heat stress accumulation on reef areas nearly 50% greater than the previous GCBE record. This has largely been driven by general ocean warming, as recent baseline global surface ocean temperatures (2019–2023) are comparable to extreme anomalous conditions observed ~ 25 years ago. The development of a strong El Niño event in 2023, superimposed upon the already anomalously warm ocean, culminated in the 4th GCBE, the most extensive and intensive on record. Qualitative observations of coral bleaching have been reported from 84 countries spanning all coral-containing ocean basins. An analysis of the extent and magnitude of heat stress suggests that bleaching may have impacted 98 of the 102 countries with coral reefs. GCBE4 (2023–present) marks a period of heat stress that is unprecedented by every investigated metric. However, global-scale coral bleaching-level heat stress has persisted for almost the entirety of the last decade, bringing many reef areas into an era of near-annual bleaching.

Keywords Coral bleaching · Coral reef · Degree heating week · Global-scale bleaching · Remote sensing · Sea surface temperature

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Introduction

Coral bleaching occurs when elevated surface ocean temperatures disrupt the endosymbiosis between the coral host and its endosymbiotic dinoflagellate algae (Symbiodiniaceae), leading to an expulsion and/or mortality of the algal symbionts (Glynn 1993; Brown 1997). Sublethal bleaching can adversely affect coral growth, fecundity and population trajectories (Edmunds 2005; Hughes et al. 2019a; Johnston et al. 2020; Brown et al. 2023), and increase the risk of coral disease (Bruno et al. 2007). When heat stress is prolonged or particularly severe, widespread coral mortality will occur (Eakin et al. 2010; Hughes et al. 2018b). Anomalously high warm-season ocean temperatures can result from local mechanisms, which persist for days to weeks (Vogt et al. 2022), and may interact with synoptic-scale warming mechanisms (of 1,000 km or more), which persist for many weeks or months (McGregor 2024). Local mechanisms can cause patchy bleaching at the scale of individual reefs to small regions (Heron et al. 2012; Green et al. 2019). 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 (Brown 1997; Skirving et al. 2018), often resulting in significant levels of mortality.

Mass coral bleaching is a relatively recent, though increasingly frequent, phenomenon related to global ocean warming, which has only been documented since the 1980s (Fankboner and Reid 1981; Glynn 1984; Lasker et al. 1984; Hoegh-Guldberg et al. 2014; Hughes et al. 2018a; Oliver et al. 2018b). Although widespread bleaching was reported in several regions during 1982–1983 (Coffroth et al. 1990), the first documented occurrence of regional-scale mass bleaching events, occurring simultaneously or subsequently across the Atlantic, Indian and Pacific Oceans within a single continuous period, was in 1998 (Wilkinson 1999; Goreau et al. 2000), marking the inaugural global-scale coral bleaching event (GCBE1). Additional GCBEs were documented in 2010 (GCBE2) and 2014–2017 (GCBE3), each more widespread, enduring and consequential than the last (Eakin et al. 2019, 2026). In April 2024, the U.S. National Oceanic and Atmospheric Administration declared the fourth global event (GCBE4), following synoptic-scale marine heatwaves starting in February 2023 and subsequently spreading across all three tropical ocean basins (National Oceanic and Atmospheric Administration 2024; Reimer et al. 2024).

Here, we identify periods of global-scale coral heat stress and describe the geographic extent, duration and intensity of accumulated heat stress during each period. We compare past periods and associated GCBEs with the current ongoing period, leading up to and including GCBE4. Heat stress was quantified with satellite-derived sea surface temperature (SST) and Degree Heating Week (DHW, °C-week), the most commonly used bleaching predictor, representing the duration and magnitude of heat stress (Skirving et al. 2020). The DHW threshold for coral bleaching can vary among reef locations, often due to differing thermal histories and/or coral community compositions (Berkelmans 2002; van Hooidonk and Huber 2009; Carilli et al. 2012; Hughes et al. 2018b, 2021; Mollica et al. 2019; McClanahan et al. 2020; Liu et al. 2024) along with a coarse spatial resolution of satellite data relative to the size of individual reefs and smaller scale (i.e. spatial scales smaller than that which satellite data provides) in situ thermal variability. A DHW threshold of 4 °C-weeks has been widely used as a reliable general indicator of the onset of reef-wide bleaching at large spatial scales globally (Liu et al. 2006; Eakin et al. 2010; Hughes et al. 2017; Kayanne 2017; Skirving et al. 2019). Although local bleaching responses may occur at higher or lower heat stress accumulations depending on reef-specific conditions, recent analyses suggest that this threshold is generally conservative for predicting bleaching occurrence at the global scale (Whitaker and DeCarlo 2024). In this study, 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. Ultimately, we aim to understand GCBE4 in the context of both past GCBE heat stress patterns and long-term trends in global surface ocean temperatures. We demonstrate not only the unprecedented geographic extent of GCBE4, but also the extent of potential socio-political impacts by providing a report of countries with observed or likely mass coral bleaching throughout the post-GCBE3 period (2018–present).

Methods

Satellite data

All SST and heat stress metric data were derived from the National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch (CRW) Daily Global 5 km ($0.05° \times 0.05°$) Satellite Coral Bleaching Heat Stress Monitoring Product Suite version 3.1 dataset, covering 1 Jan 1985 to 17 Dec 2025. A reef pixel dataset (i.e. reef mask) obtained from Skirving et al. (2019) was overlaid onto the SST heat stress metric datasets to identify pixels that contain coral reefs. The reef mask did not have reef pixels populated for Cabo Verde and Easter Island; these pixels were manually added for this analysis following Heron et al. (2016). The reef mask was divided into the three tropical ocean basins (Atlantic, Indian and Pacific), the boundaries of which were also obtained from Skirving et al. (2019). Individual masks of the 102 reef-containing geopolitical regions were developed on the same 5-km global grid system and used to isolate regions of the reef mask for analysis of heat stress within countries. Mean daily SST was calculated for all ocean pixels from 45°N to 45°S throughout the satellite record to examine trends in general surface ocean warming and their relationships to the El Niño-Southern Oscillation (ENSO) and global bleaching. This latitudinal band was chosen to capture the tropical and subtropical regions where ENSO forcing and related oceanic atmospheric teleconnections are strongest (Rasmusson and Carpenter 1982; McPhaden et al. 2006), while excluding those high-latitude regions where variability is dominated by local seasonal cycles, sea-ice processes, and certain circulation regimes (Deser et al. 2010; Armour et al. 2016). ENSO-associated atmospheric and oceanic anomalies extend well into the subtropics globally, typically confined within 30°–45° N/S (Horel and Wallace 1981; Alexander et al. 2002; Johnson et al. 2022).

Global coral heat stress index

To monitor, measure and compare bleaching risk during a global-scale coral bleaching event (GCBE), Skirving et al. (2019) developed a satellite-based Global Bleaching Index, comparing periods of likely global coral bleaching with the 1998 worldwide bleaching event (GCBE1), which serves as a baseline. The index calculated a single global or individual ocean basin value for each 'Heat Stress Year', which used different 12-month time periods for the Northern and Southern Hemispheres (offset from each other to account for their distinct heat stress periods), to determine the global and individual ocean basin extents of reef areas (5-km reef-containing satellite pixels) that had experienced ≥ 4 °C-weeks. For any Heat Stress Year in which the Atlantic, Indian and Pacific Ocean basins each exceeded an extent of 12% (a basin-wide baseline threshold derived from GCBE1; Skirving et al. 2019), the global extent was expressed relative to that of the baseline event of 1998. Heat Stress Years resulting in a global index value > 1 (i.e. a global extent larger than during GCBE1) indicated a global coral bleaching event.

Here, we modify the Global Bleaching Index developed by Skirving et al. (2019) to allow it to run continuously with near real-time data inputs. To distinguish this enhancement from the original index, we have termed this the 'Global Coral Heat Stress Index'. This metric is aimed at identifying periods of global heat stress on coral reefs by providing more temporal information, including outside of declared global bleaching events, and introducing more criteria to classify these periods, such as a minimum length of time with persistent global heat stress (Little et al. 2022). The primary metric utilised for the Global Coral Heat Stress Index is the 'annual bleaching stress extent', which is the percentage of reef areas experiencing ≥ 4 °C-weeks in a 365-day period, calculated daily and encompassing data up to and including the given date. The annual bleaching stress extent can be calculated for the global ocean, individual ocean basins, or distinct marine regions. By encompassing a full annual cycle, the annual bleaching stress extent accounts for recent seasonal heat stress affecting both Northern and Southern hemispheres, or global reefs. To ensure that only information from within the 365-day period is included, all calculations of annual bleaching stress extent used the NOAA CRW Bleaching Alert Area threshold of Alert Level 1, which signifies a DHW ≥ 4 °C-weeks but also requires a HotSpot ≥ 1 °C (i.e. occurrent stress). A HotSpot is a measure of instantaneous heat stress on coral reefs, which accumulates into the DHW calculation when values are ≥ 1 °C. Using the Bleaching Alert Area only incorporates active heat stress, avoiding the 12-week DHW accumulation window influencing the results with heat stress prior to the start of the 365-day window.

As in Skirving et al. (2019), the characteristics of GCBE1 were used as a definitive baseline to identify subsequent periods of heat stress comparable to that associated with GCBE1. Our analysis identifies the period that coincides with GCBE1 where the annual bleaching stress extent in the Atlantic, Indian and Pacific basins reached a maximum coverage of 34.2%, 34.8% and 12.4% of reef pixels, respectively. The annual bleaching stress extent was 12% or more in all three ocean basins for a period of 156 days. Lastly, the maximum annual bleaching stress extent globally (across all three ocean basins) during this period was 20.0%. Therefore, by rounding these values achieved during GCBE1 (the baseline conditions) down to the nearest per cent and nearest week (i.e. the 7-day window nearest in time to the beginning of each rolling 365-day period), the required criteria for identifying active global bleaching stress are set forth in the Global Coral Heat Stress Index as:

A. Each of the three tropical ocean basins (Atlantic, Indian and Pacific) must concurrently have an annual bleaching stress extent of 12% or more within the same rolling 365-day period.
B. The conditions of the first criterion must remain consistently present for a period of at least 154 consecutive days (22 weeks).
C. 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, global heat stress accumulations that are at least as large and lasting as GCBE1 can be identified as periods of global coral heat stress. Once global coral heat stress has been identified, the duration of the continued stress can be determined (termed the 'global stress 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 global stress period is therefore the number of days during which criterion **(A)** is satisfied, plus 364 days, totalling a minimum of 518 days (154 days + 364 days). The assigned start date of each global stress period is a general approximation of the event's initiation, as this is when accumulated heat stress begins being factored into the Global Coral Heat Stress Index. A cumulative bleaching stress extent is determined and calculated as the total global percentage of reef pixels that accumulated ≥ 4 °C -weeks during the global stress period.

Collation of bleaching observations

In addition to satellite data of heat stress over coral reefs, we compiled qualitative coral bleaching observations during the recent and ongoing global stress period leading up to and including GCBE4 (August 2018 to December 2025; see Results). A set of quality control procedures were used as conservative benchmarks to increase confidence that the reports were 'mass coral bleaching', defined as bleaching events that: (1) are related in time and geographic area by a common cause or mechanism (Williams and Bunkley-Williams 1990), (2) involve a mechanism that occurs over synoptic scales (> 1000 km; Glynn 1996), and (3) are ecologically significant (≥ 20% reef area bleached; Lachs et al. 2021). As the reef areas of some countries are relatively small, the categorisation of 'mass coral 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.

These criteria were applied to determine which political states or countries (among those that contain coral reefs) were likely affected by mass bleaching from 2018 to the present day. In classifying these, reef areas of some countries were divided into multiple regions if they spanned different ocean basins (e.g. the 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, an overseas collectivity (i.e. semi-autonomous administrative divisions of France), a constituent country, or an internally self-governing state were listed and analysed as individual entities. We identify 102 distinct geopolitical regions that contain coral reefs within their established boundaries. For simplicity, we refer to these as countries. While not quantitative, this categorisation was an effective way to communicate the scale and spread of GCBE4 impacts to the international media and public (e.g. Einhorn 2024; Readfearn 2024; Dickie and Withers 2025).

Instances of observed mass coral bleaching and associated mortality within the most recent global stress period were acquired for countries by requesting submission of bleaching surveys from researchers and resource managers, direct communication with local contacts with strong experience observing bleaching events, searching through published literature and media reports, and by the voluntary submission of observations to NOAA CRW from several international stakeholders (Table S1). Coral reef researchers and managers, who conduct regular scientific monitoring/assessments of coral reefs, were categorised as 'reliable' observers, although their observations were still reviewed. Observations from untrained surveyors (e.g. recreational divers, tourists, journalists) were considered 'less reliable' and not included in the analysis, unless there were three or more independent bleaching observations on the same reef location, at which time the observations were considered reliable and sufficient to confirm mass bleaching in that location.

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 coral bleaching'), 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 confirm coral bleaching in the instances where the estimated percent cover bleached was not provided. When photographs were assessed, we considered them with reference to the above criteria before inferring if a report corresponded to mass bleaching.

Geopolitical analysis of heat stress

Some countries did not have any known and/or available surveys of coral reefs during or after the heat stress accumulation period, which occurred throughout the recent global coral heat stress period (August 2018–present), often due to socio-economic limitations and/or impediments to open communication (e.g. Yemen). However, over this period, the annual (within one calendar year) maximum DHW was calculated for each reef pixel and the 80th percentile value among those within the political bounds of each country was identified. The 80th percentile threshold represents an upper extreme of heat stress exposure while still encompassing a substantial proportion of a region's reef area. By examining the DHWs within the corresponding region, we inferred bleaching at heat stress exposures that have been repeatedly demonstrated to elicit bleaching in other reef areas, as documented extensively in the literature. This includes locations that do not conform to the standard threshold typically considered to cause bleaching (i.e. ≥ 4 °C-weeks). These outliers have been hypothesised to be a result of local-scale physical factors, community shifts to assemblages of more heat-tolerant coral species and/or genotypes, as well as shifts in tolerance due to ecological memory of acclimatisation (McClanahan et al. 2007, 2020; DeCarlo et al. 2019; Hughes et al. 2019b; Mollica et al. 2019; Lachs et al. 2023). Mass bleaching in a country lacking in situ surveys was inferred with high confidence when the corresponding 80th percentile maximum DHW value had exceeded 12 °C-weeks. Given that this is a threefold higher amount of heat stress than what has been repeatedly shown in field and lab studies to elicit bleaching (reviewed in Whitaker and DeCarlo (2024)), we utilise this threshold to conservatively infer that countries lacking surveys have also likely experienced coral bleaching during this period. If the 80th percentile maximum DHW value was 8 °C-weeks or greater (but less than 12 °C-weeks; see Heron et al. 2016; Hughes et al. 2017; Kayanne 2017), mass bleaching was inferred with high confidence only if this was an all-time high within the satellite record.

Results and discussion

Global coral heat stress

There is a perceptible correlation between GCBEs and El Niño phases of ENSO (Eakin et al. 2019), though not necessarily a causal link. Since GCBE1, every El Niño event with a peak Oceanic Niño Index (ONI) value ≥ 1.5 °C (considered a 'strong' El Niño; Marjani et al. 2019) has been associated with a GCBE (Fig. 1). The 1997–1998 El Niño (peak ONI: 2.4 °C) was the strongest event since instrumental records began in 1950, up until that point in time (McPhaden 1999), helping to drive unprecedented heat stress accumulations and widespread global bleaching (Wilkinson 1999; Goreau et al. 2000). The global (45°N–45°S) average of daily mean surface ocean temperatures during this period peaked at 23.2 °C in March 1998, 0.5 °C above the long-term average within the satellite record at that time (1985–1997). An El Niño of comparable strength in 1982–1983 (Wolter and Timlin 1998) also resulted in widespread bleaching, though this has not been categorised as a global-scale event, possibly due to a lack of documentation. The 2009–2010 strong El Niño (peak ONI: 1.6 °C), while not as severe as recent strong events, together with warmer average SSTs contributed to another unprecedented global heat stress event and

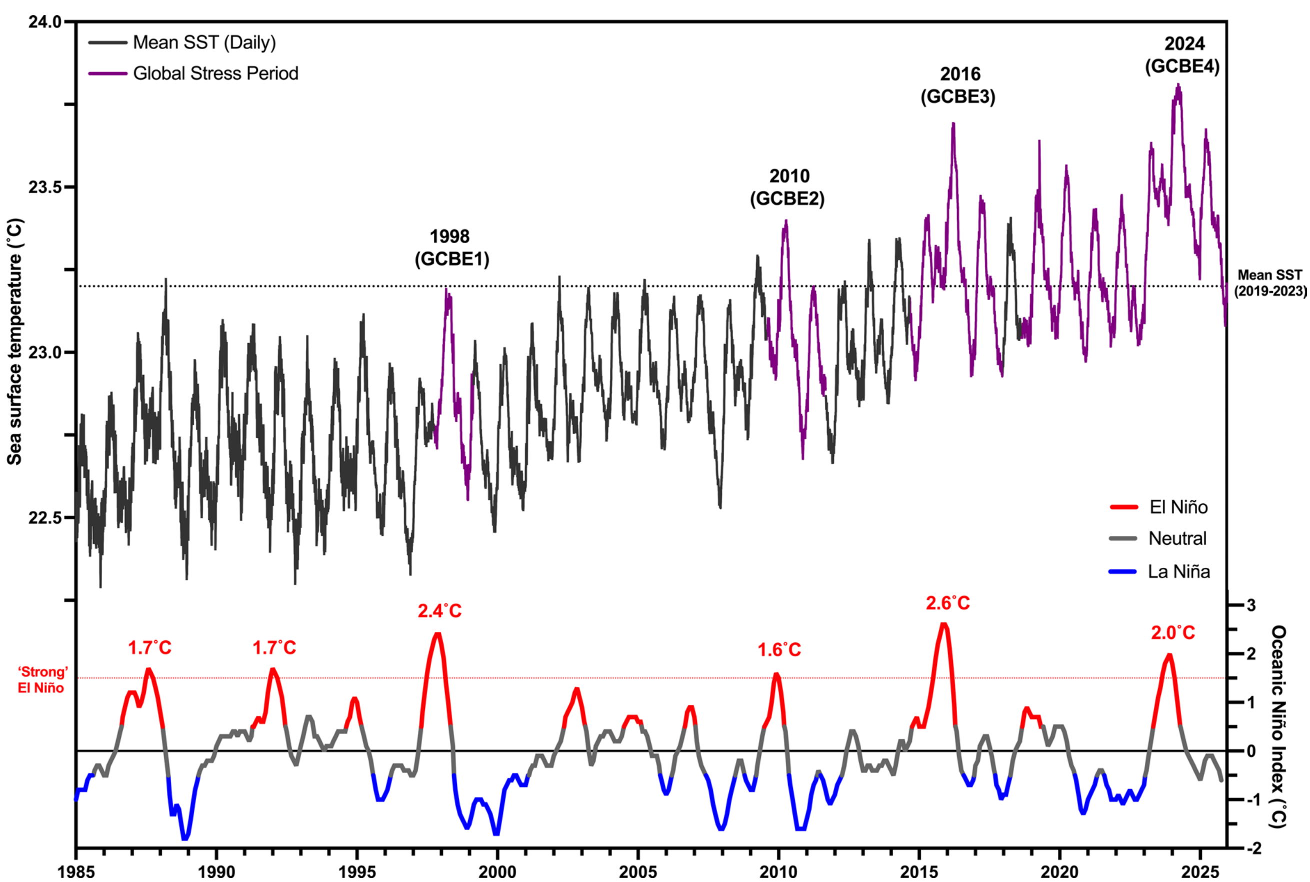

Fig. 1 Trends in global sea surface temperature (SST) and El Niño-Southern Oscillation (ENSO) strength from 1985 to 2025. Daily mean global (all ocean pixels from 45°N to 45°S) SST is shown in the upper time-series (left y-axis). Intervals in which the SST time-series is purple indicate global stress periods. Lower time-series (right y-axis) shows the ENSO strength based on the Oceanic Niño Index (ONI) within the Niño 3.4 region (3-month running mean; NOAA ERSST.v5). ENSO time-series is coloured blue during La Niña periods, grey during ENSO neutral periods, and red during El Niño periods. Peak SSTs corresponding to both a confirmed global-scale coral bleaching event (GCBE) and a strong El Niño (ONI ≥ 1.5 °C; dotted red line; peak ONI values labelled in red) are labelled with the year and corresponding GCBE number. The dotted black line indicates the recent baseline surface ocean temperature, calculated as the mean global SST from June 2019 to March 2023 (a period consisting of ENSO neutral or La Niña phases)

record-high daily average surface ocean temperature of 23.4 °C in March 2010. The 2014–2016 El Niño remains the strongest ever recorded (peak ONI: 2.6 °C) as well as the longest continuous El Niño phase (19 months), which, coupled with further increased baseline SSTs, resulted in yet another record-high daily average surface ocean temperature (23.7 °C; March 2016) and an unprecedented GCBE.

A mild and short-lived El Niño (2018–2019) developed after GCBE3, followed by ENSO neutral and La Niña phases from June 2019 to March 2023. The mean of daily average global surface temperatures during this nearly 4-year period was 23.2 °C, demonstrating the most recent baseline global SST without influence from El Niño. This recent multi-year baseline in average SST is the same value as the peak daily average temperature during the very strong 1997–1998 El Niño (Fig. 1). Recent mean global surface ocean temperatures during ENSO neutral and La Niña phases are now on par with the anomalous peak temperature during the 1997–1998 El Niño event, ~ 25 years earlier. With continuously elevated baseline temperatures, strong El Niño events are no longer a prerequisite for global-scale heat stress accumulation events on reefs.

Using the satellite-based SST criteria to define periods of global coral heat stress, we identified four distinct intervals within the satellite record (Fig. 2). The first three intervals correspond well with the first three confirmed GCBEs. However, following GCBE3, SSTs on the world's reefs have continuously exceeded comparative collective conditions that had contributed to GCBE1, despite La Niña conditions dominating mid-2019 to mid-2023. When these anomalously warm global conditions were met with the strong El Niño of 2023–2024 (peak ONI: 2.0 °C), the most extensive and severe global heat stress on record accumulated, leading to the announced GCBE4. The heat stress accompanying GCBE4 was unprecedented by every investigated metric in both intensity and spatial extent on both annual and long-term scales.

The fourth period of global coral heat stress, based on the Global Coral Heat Stress Index, began in August 2018 and persists as of the writing of this manuscript (17

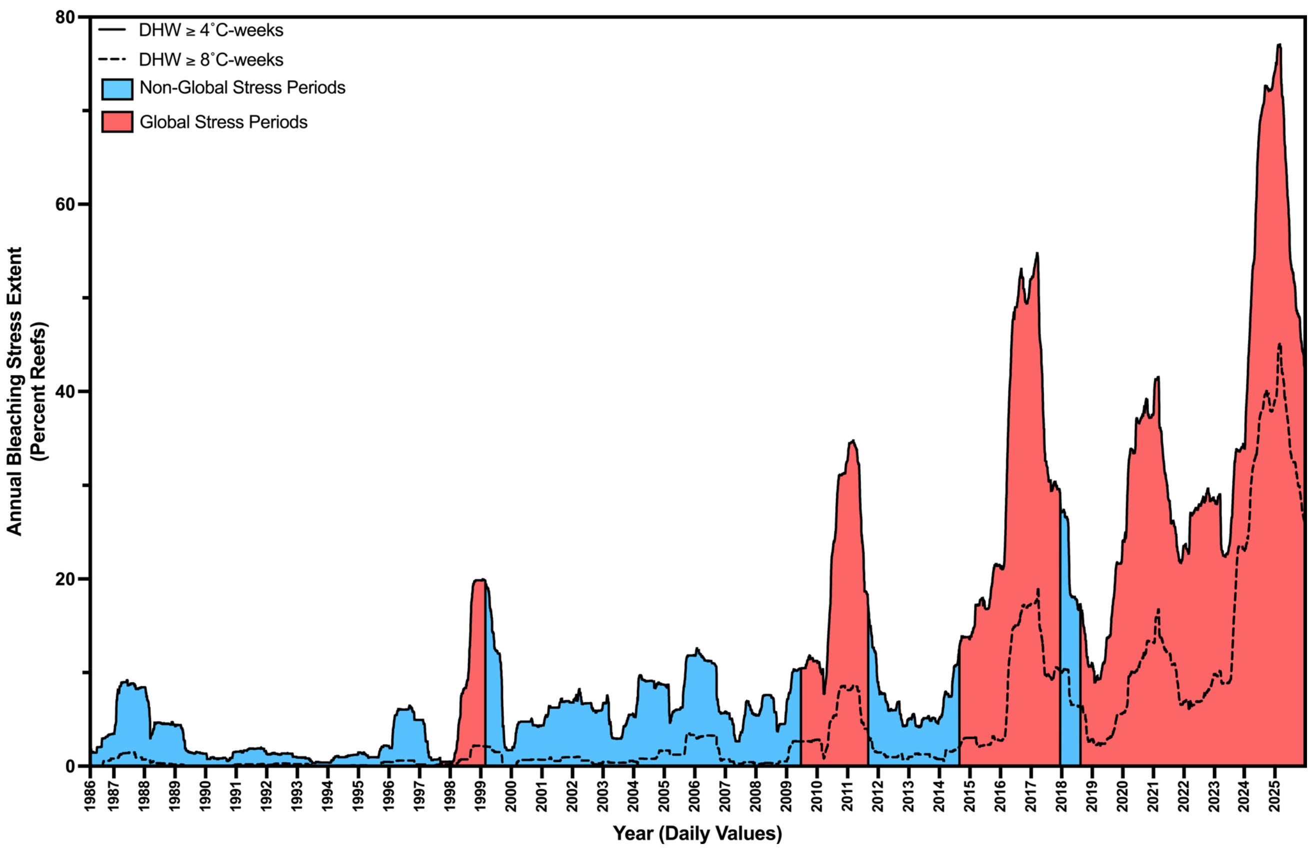

Fig. 2 Daily values (25 March 1986–17 December 2025) of the annual bleaching-level heat stress extent, as calculated by the Global Coral Heat Stress Index, showing the percentage of reef locations globally that had accumulated Degree Heating Weeks (DHW) ≥ 4 °C-weeks in the previous 365 days (solid black line). Sections under this line shaded in *red* depict periods of global stress on coral reefs as defined by the Global Coral Heat Stress Index (see Methods). Sections shaded in *blue* depict periods during which accumulated heat stress did not meet the criteria of a global stress period. The black dashed line shows the percentage of reef locations globally that had accumulated DHW ≥ 8 °C-weeks in the previous 365 days

December 2025), lasting more than seven years. During the continuous global stress period, bleaching-level heat stress (DHW ≥ 4 °C-weeks; Skirving et al. 2019) impacted 86.8% of the world's reef locations (defined as 0.05° × 0.05°, or ~ 5-km, satellite pixels containing coral reefs) at least once. Each of the three ocean basins has had DHW ≥ 4 °C-weeks accumulated in at least 83.6% of their reef locations at least once during this period (Table 1). Each consecutive global stress period has become progressively longer, from 1.4 years to 7.3 years thus far. The gap between the third and fourth periods was merely 240 days (roughly 8 months), suggesting that global heat stress conditions comparable to those during GCBE1 have been nearly omnipresent for the past decade.

Despite identifying a prolonged period (August 2018–present) of global heat stress on coral reefs, defining a start or end date of GCBEs based on SSTs and DHW is no longer straightforward because of the now-omnipresent levels of heat stress that previously correlated with GCBE1. As has been necessary for the designation of the first three GCBEs, comprehensive in situ confirmations throughout the period should be the primary indicator of a global event's presence. While significant heat stress has persisted for over seven years, the heat stress that accumulated during the confirmed period of GCBE4 (February 2023–present; National Oceanic and Atmospheric Administration 2024) driven by the recent strong El Niño, underlies the record-setting extent and intensity. The largest global maximum annual bleaching stress extent on record (i.e. the greatest global extent of DHW ≥ 4 °C-weeks within a 365-day period) occurred during GCBE4, affecting 77.2% of reef locations (20th February 2024–18th February 2025), nearly four times that achieved during GCBE1 (Fig. 2). Furthermore, the annual bleaching stress extent in each of the individual ocean basins during GCBE4 has also been record-setting (Table 1). The previous annual bleaching stress extent records were set during GCBE3, apart from the Atlantic Ocean basin where the record was set during GCBE2 (~ 53%). Over 99.9% of Atlantic Ocean reef locations during GCBE4 have experienced bleaching-level heat stress within the 365-day period of 10 June 2023 to 8 June 2024. During GCBE4, the maximum annual bleaching stress extent during GCBE4 in the Indian and Pacific Oceans were 83.3% (4 March 2024–3 March 2025) and 72.3% (2nd February 2024–31st January 2025), respectively.

The magnitude of DHWs during GCBE4 has also been unprecedented. Among all reef locations during each global event, the median of peak DHW values increased sequentially, from 1.4 °C-weeks (GCBE1) to 8.2 °C-weeks (GCBE4) as of this writing (Fig. 3). 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 (Donner et al. 2005; Hughes et al. 2018b), the extent during GCBE4 is also unmatched in both global- and basin-level comparisons. The maximum global extent of reef locations experiencing DHW ≥ 8 °C-weeks within a 365-day period, 45.1%, is more than double the previous maximum extent (19.1%) 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 39.7% for the Atlantic, Indian and Pacific, respectively (see Table S2). The global extent of coral mortality during GCBE4 is currently undetermined, and these results do not aim to estimate them. Initial studies have shown catastrophic impacts in some locations, including mortality exceeding 90% and localised functional extinctions (López-Pérez et al. 2024; Doherty et al. 2025; Manzello et al. 2025; Tkachenko et al. 2025), but other locations have reported nuanced or lesser impacts than feared (Edmunds and Lasker 2025; Mies et al. 2025).

International reports of mass bleaching

To begin to understand the extent of socio-economic impacts of recent heat stress accumulations, we investigated confirmations and inferred likelihoods of mass bleaching from all

Table 1 A description of global stress periods as calculated by the Global Coral Heat Stress Index

Global stress period	Duration	Global extent (annual maximum)	Atlantic extent (annual maximum)	Indian extent (annual maximum)	Pacific extent (annual maximum)
24 Sep 1997–25 Feb 1999	520 days (1.4 years)	**20.1%** (20.0%)	**34.2%** (34.2%)	**34.8%** (34.8%)	**12.5%** (12.4%)
23 Jun 2009–4 Sep 2011	804 days (2.2 years)	**37.1%** (34.8%)	**55.1%** (52.8%)	**37.1%** (36.7%)	**33.8%** (31.1%)
28 Aug 2014–15 Dec 2017	1,206 days (3.3 years)	**67.7%** (54.9%)	**56.8%** (41.8%)	**74.0%** (71.1%)	**67.7%** (57.3%)
13 Aug 2018–17 Dec 2025*	2,684 days (7.3 years)	**86.8%** (77.2%)	**99.9%** (99.9%)	**89.1%** (83.3%)	**83.6%** (72.3%)

The approximate start and end dates as well as the duration (number of days) of each global stress period (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 global stress periods, with these metrics being presented globally as well as for individual ocean basins (*bold values*). Values listed in *parentheses* signify the maximum of annual bleaching stress extents (the maximum percentage of reef locations that had accumulated ≥ 4 °C-weeks among all individual 365-day windows) achieved during each period, globally and for each individual ocean basin. *This global stress period is ongoing at the time of writing; values are not final

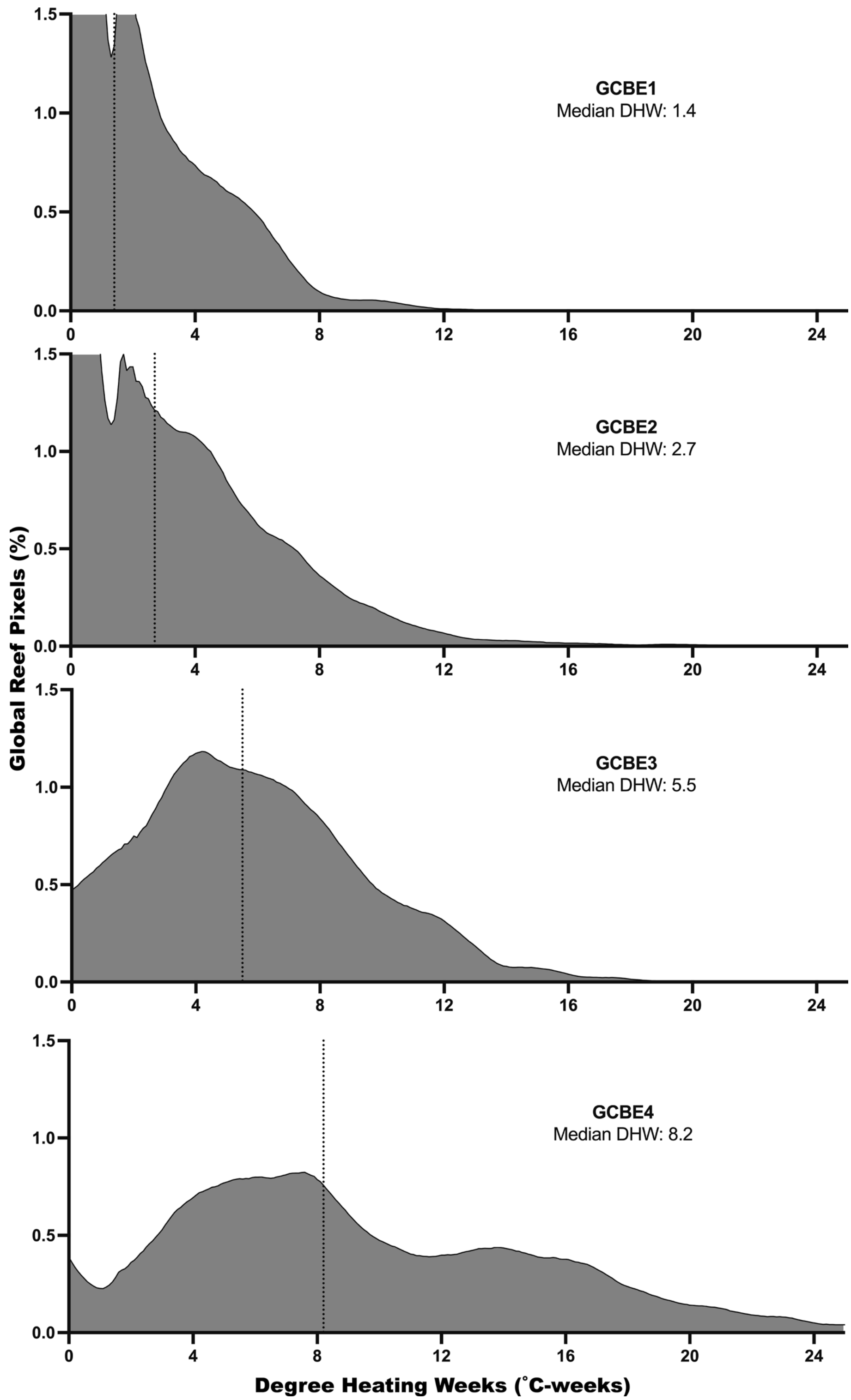

Fig. 3 The percentage of global reef locations at each DHW value (rounded to the nearest 0.1 °C-weeks), during each GCBE. Distribution curves on each graph are smoothed using a running average of 31 points along the horizontal axis. The vertical dashed line on each graph shows the median DHW value among all reef locations within the GCBE. Distributions for GCBE1 and GCBE2 exceed the upper limit of the y-axis; however, because this occurs only at relatively low DHW accumulations (<4 °C-weeks, the y-axis was fixed at 0–1.5% to enhance visibility and allow clearer comparison of distributions beyond the 4 °C-week threshold across events

coral reef-containing countries (or political states) during the ongoing global stress period (August 2018–present). Reliable observations of mass bleaching were sourced from 84 of the 102 reef-containing countries (Fig. 4). Seventy-two countries had an 80th percentile max DHW ≥ 12 °C-weeks, a heat stress level usually associated with severe bleaching and multi-species mortality (Hsu et al. 2025). Among the 18 countries that did not have bleaching surveys available, 12 experienced an 80th percentile max DHW ≥ 12 °C-weeks. Additionally, Myanmar and Somalia experienced an 80th percentile max DHW ≥ 8 °C-weeks, with these values being an all-time high within the 40-year satellite record. These

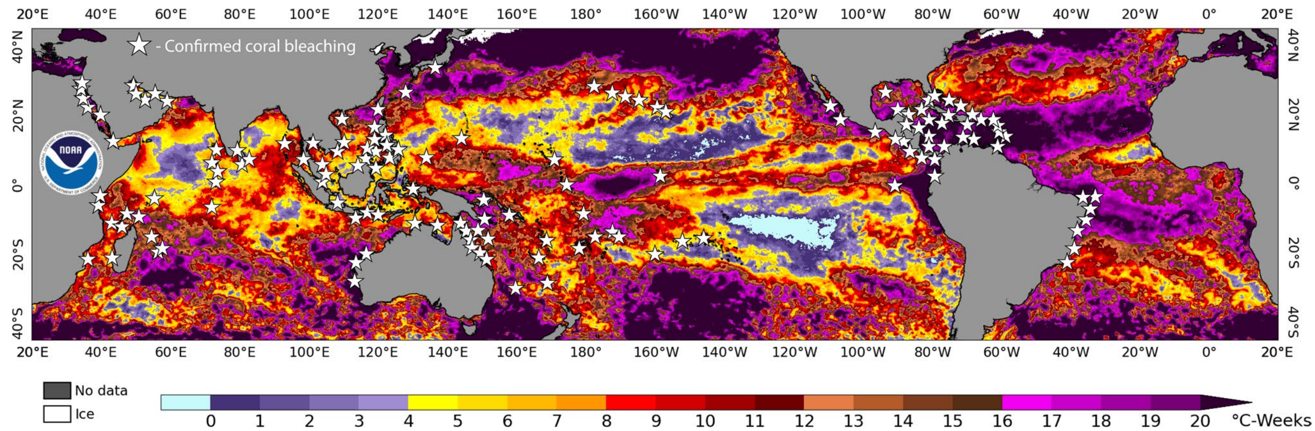

Fig. 4 Global map (45°N–45°S) of maximum Degree Heating Week accumulations throughout the ongoing global stress period (13 August 2018–17 December 2025) including GCBE4. White stars signify reliable observations of confirmed mass bleaching in the general region. For display purposes, the locations of stars may not correspond exactly to observed coordinates, and not all observations from this period are represented on the map

extreme and/or unprecedented DHW accumulations suggest that heat stress and bleaching most likely affected 14 of the 18 countries that lack bleaching surveys. The 80th percentile max DHWs of three of the remaining four countries (Tonga, Chile [Easter Island], and Timor-Leste) were 5.5 to 11.5 °C-weeks. As previous heat stress accumulations in these locations had exceeded these respective levels, we considered it inconclusive to infer if mass bleaching occurred in these countries. Niue remains the only country with an 80th percentile max DHW (2.04 °C-weeks) below the bleaching-level threshold, indicating that recent mass bleaching here is unlikely. Based on conservative logical deduction, we conclude that no fewer than 98 of the 102 reef-containing countries have likely been substantially affected during the ongoing global stress period (Table 2). As the scale of reef areas of different countries are highly varied (e.g. Papua New Guinea having 3,439 reef-containing satellite pixels as compared to 5 reef pixels in Nauru), it is important to note that the goal of this analysis was not to compare ecological impacts among these locations, but to identify the extent of likely impacts to individual local human societies and governments within a global context.

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 annually (Costanza et al. 2014), including US$109 billion in coastal protection (Burke and Spalding 2022). The global costs of coral bleaching and the resultant declines in structural complexity negatively affect fisheries, tourism, coastal protection, biodiversity and more (Ferrario et al. 2014; Rogers et al. 2014; Harris et al. 2018), with losses over a 50-year time horizon estimated in 2008 to reach upwards of $84 billion US dollars (Conservation International 2008). Mass coral bleaching and mortality can be variably detrimental to human populations and related to the socio-economic status of individual political states, with some countries being more vulnerable than others (Westmacott et al. 2000; Siegel et al. 2019; Ainsworth et al. 2021). 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 (Hafezi et al. 2020), with 94% of their total population living within 100 km of a coral reef (Sing Wong et al. 2022). Our analysis indicates that, of the 102 coral reef-containing countries identified, 36 are SIDS; three SIDS had a designation of 'low confidence' or 'unlikely' bleaching since 2018 (Table 2).

Reefs facing new and repeated extremes

With an apparent omnipresent state of global heat stress risk to coral reefs, classifying global-scale bleaching as discrete 'events' may no longer be an appropriate approach. The warming of the oceans has ushered in an era of increasingly unprecedented heat stress accumulations and near-annual bleaching. Regardless of designation, reefs globally are undoubtedly experiencing more frequent and severe marine heatwaves, as previously highlighted (Hughes et al. 2018a; Oliver et al. 2018a). Corals and reef communities can exhibit increased thermal tolerance after repeated exposure to marine heatwaves due to a range of potential mechanisms from acclimatisation to mortality-driven species composition shifts (Hughes et al. 2021; Lachs et al. 2023); however, the ability of corals to genetically adapt at a rate and scale necessary to combat the current and projected rate of

Table 2 Heat stress and bleaching in coral reef-containing countries during the ongoing global stress period

Ocean Basin	Country/State	Reef area (5 km reef pixels)	80th percentile annual max DHW 2019	2020	2021	2022	2023	2024	2025*	Date of record heat stress accumulation	Assessment of significant bleaching
Atlantic	**Antigua and Barbuda	32	9.83	5.07	5.47	1.98	19.79	22.60	12.18	7 Nov 2024	Observed
	Aruba	27	5.09	14.17	7.06	11.19	19.15	23.01	15.11	3 Dec 2024	Observed
	**Bahamas	1815	7.21	5.14	5.22	5.26	19.13	12.40	11.78	22 Oct 2023	Observed
	**Barbados	17	3.15	7.52	6.18	3.14	18.60	23.22	11.43	12 Nov 2024	Observed
	**Belize	270	12.96	12.79	9.21	2.94	18.57	18.70	11.71	18 Oct 2024	Observed
	Brazil	288	15.28	12.59	0.00	6.25	3.38	20.44	12.10	10 May 2024	Observed
	**Cabo Verde	120	0.18	5.24	2.92	4.65	20.09	7.58	2.79	5 Nov 2023	High confidence
	Caribbean Netherlands	57	7.02	10.23	4.16	6.82	19.55	21.59	13.02	8 Nov 2024	Observed
	Colombia (Atlantic)	114	4.49	9.49	3.28	1.96	17.11	17.71	7.41	13 Oct 2024	Observed
	Costa Rica (Atlantic)	13	5.89	8.98	1.90	5.01	17.73	15.41	3.35	17 Nov 2023	Observed
	**Cuba	1090	8.08	3.78	0.49	1.44	18.53	12.82	11.99	22 Sep 2023	Observed
	Curaçao	30	6.05	13.84	6.13	10.98	19.48	22.70	14.72	2 Dec 2024	Observed
	**Dominica	21	6.33	4.87	4.60	2.37	20.02	21.20	12.52	17 Nov 2024	High confidence
	**Dominican Republic	211	8.10	3.32	2.48	1.97	18.65	18.41	7.92	27 Oct 2023	Observed
	France (Atlantic)	96	7.33	4.71	4.29	2.38	20.30	21.74	12.27	13 Nov 2024	Observed
	**Grenada	28	1.73	6.45	5.57	3.58	17.40	22.53	9.61	7 Nov 2024	Observed
	Guatemala	8	13.22	14.71	12.51	3.34	17.65	20.23	14.09	11 Oct 2024	Observed
	**Haiti	255	7.85	4.09	1.21	4.61	20.83	20.71	10.83	29 Oct 2023	High confidence
	Honduras	97	7.41	6.41	3.57	2.18	15.36	15.38	8.31	24 Oct 2024	Observed
	**Jamaica	161	7.11	4.54	2.11	3.54	21.23	17.20	9.83	13 Nov 2023	Observed
	Mexico (Atlantic)	292	8.29	9.50	3.96	2.67	19.26	16.51	13.46	17 Oct 2023	Observed
	Nicaragua	400	12.42	15.61	7.48	10.94	23.58	19.97	10.24	11 Nov 2023	High confidence
	Panama (Atlantic)	227	5.65	13.17	5.54	9.29	20.01	17.65	5.26	17 Nov 2023	Observed
	Puerto Rico	155	6.54	3.04	3.44	1.88	17.57	20.70	7.96	31 Oct 2024	Observed
	St. Barthelemy	7	6.96	2.56	4.78	1.68	17.77	21.45	9.04	7 Nov 2024	Observed
	**St. Kitts and Nevis	24	7.12	2.31	3.40	1.37	18.27	21.35	10.52	9 Nov 2024	High confidence
	**St. Lucia	19	3.38	5.76	5.68	3.37	18.76	22.25	11.95	13 Nov 2024	High confidence
	**St. Vincent and the Grenadines	28	2.54	6.24	5.65	2.99	18.30	22.45	10.38	9 Nov 2024	Observed
	St. Martin	8	7.76	3.01	4.61	1.92	17.78	21.74	8.90	24 Oct 2023	Observed
	**São Tome and Principe	5	0.34	1.05	0.00	0.00	0.15	12.50	0.29	1 May 2024	High confidence
	Sint Maarten	8	7.89	2.86	4.78	1.77	17.64	21.60	8.87	7 Nov 2024	Observed
	**Trinidad and Tobago	27	3.62	11.19	6.56	7.70	16.64	22.49	9.42	7 Nov 2024	Observed
	United Kingdom (Atlantic)	441	8.09	3.80	4.14	2.35	17.80	17.22	12.16	26 Oct 2023	Observed
	United States (Atlantic)	331	6.89	4.29	3.85	5.72	17.76	20.85	8.62	10 Nov 2024	Observed
	Venezuela	144	8.73	17.66	8.36	13.81	20.48	24.50	15.54	26 Nov 2024	High confidence
Pacific	Australia (Pacific)	5289	1.68	9.46	5.93	6.64	2.45	9.67	9.18	7 Mar 2024	Observed
	Brunei	41	1.91	1.57	1.16	0.15	4.43	7.76	2.51	29 Jun 2024	Observed
	Chile (Easter Island)	1	1.14	0.00	0.00	0.00	4.47	0.00	5.49	31 Mar 2000 (13.58)	Low confidence
	China	204	8.93	15.99	9.80	11.83	12.41	13.17	4.31	8 Sep 2020	Observed
	Colombia (Pacific)	10	8.40	4.67	4.73	4.78	20.83	19.18	19.94	24 Jul 2023	Observed
	**Cook Islands	152	4.01	0.49	1.69	0.16	2.88	12.13	2.71	13 Apr 2017 (12.26)	Observed
	Costa Rica (Pacific)	47	1.09	6.18	0.00	0.31	11.34	17.64	10.94	8 Apr 2024	Observed
	Ecuador (Galapagos)	74	5.10	4.25	4.32	4.48	17.33	14.29	15.59	6 May 1998 (36.96)	Observed
	El Salvador	6	5.15	1.29	5.70	0.16	13.63	5.69	6.31	27 Sep 2023	Observed
	**Federated States of Micronesia	967	1.79	11.65	6.71	3.73	2.80	14.20	6.40	22 Oct 2024	Observed
	**Fiji	1328	6.11	1.87	1.52	5.32	8.38	7.79	4.78	17 Mar 2014 (8.96)	Observed
	France (Pacific)	1075	0.00	3.26	5.76	10.83	6.49	7.24	3.16	2 Apr 2016 (11.09)	Observed
	French Polynesia	1261	1.57	0.30	0.00	0.00	0.00	7.27	0.31	9 Apr 2024	Observed
	Indonesia	9369	2.65	4.21	1.86	3.05	3.95	6.96	4.45	18 May 2016 (7.81)	Observed
	Japan	460	0.60	4.81	0.76	10.59	2.02	17.58	11.51	14 Sep 2024	Observed
	**Kiribati	382	13.52	8.86	0.00	0.00	15.54	12.43	0.00	1 Nov 2023	Observed
	Malaysia	823	3.49	4.48	0.75	0.77	4.03	7.39	2.44	11 Jun 2024	Observed
	**Marshall Islands	793	6.18	2.48	0.15	0.00	2.27	7.64	3.14	5 Nov 2024	Observed
	Mexico (Pacific)	26	1.13	5.39	8.33	1.24	17.99	7.07	9.23	20 Oct 2023	Observed
	**Nauru	5	15.70	13.35	0.00	0.00	4.14	6.40	0.00	27 Dec 2014 (16.99)	High confidence
	**Niue	16	0.98	0.31	0.00	0.15	0.00	2.04	1.68	22 Mar 1988 (7.13)	Unlikely
	**Palau	142	1.21	4.68	3.69	6.45	2.43	9.16	3.26	22 Oct 2024	Observed
	Panama (Pacific)	90	1.48	0.79	0.15	0.91	14.30	10.37	9.24	8 Oct 2023	Observed
	**Papua New Guinea	3439	4.89	4.09	11.44	16.01	17.16	11.20	16.77	6 Jan 2023	Observed
	Philippines	5051	4.44	6.54	1.77	2.92	3.21	8.36	2.19	13 Jul 2020	Observed
	**Samoa	88	4.71	7.97	0.00	0.00	0.59	15.27	2.51	19 May 2024	Observed
	**Singapore	374	0.30	0.59	0.14	0.33	0.51	5.04	0.62	15 Jun 2010 (5.59)	Observed
	**Solomon Islands	1400	0.61	2.28	4.82	2.41	2.75	4.74	11.46	21 Feb 2025	Observed
	Taiwan	153	5.27	12.36	7.87	11.09	10.28	18.67	4.55	16 Sep 2024	Observed
	Thailand	430	5.32	3.56	1.22	1.21	2.89	12.70	1.28	7 Jun 2024	Observed
	**Timor-Leste	183	5.66	6.19	4.51	4.51	2.83	4.47	3.44	3 Jan 2020	Low confidence
	**Tonga	323	0.14	0.78	1.22	6.73	11.52	4.75	4.75	1 Apr 2000 (13.14)	Low confidence
	**Tuvalu	58	0.91	0.91	0.00	0.00	5.67	13.38	0.00	3 Jun 2024	Observed
	United States (Pacific)	650	10.02	4.95	0.60	6.82	1.40	3.59	10.23	3 Oct 2014 (11.65)	Observed
	**Vanuatu	476	2.20	2.94	2.62	6.30	6.73	9.99	4.74	15 Mar 2024	Observed
	Vietnam	210	9.67	7.82	7.20	7.56	6.62	12.32	4.08	4 Jun 2024	Observed
	Wallis and Futuna	35	1.94	4.81	0.16	0.00	0.63	15.25	2.31	13 May 2024	Observed
Indian	Australia (Indian)	1237	4.13	5.88	7.53	7.81	5.38	8.44	20.95	6 Mar 2025	Observed
	Bahrain	189	1.79	4.68	10.16	7.58	9.72	7.32	6.08	9 Sep 1986 (12.14)	Observed
	**Comoros	86	2.15	2.20	0.30	0.00	0.63	6.30	0.44	14 Apr 2024	Observed
	Djibouti	98	0.45	1.32	2.27	4.74	12.35	9.28	2.50	12 Oct 2023	Observed
	Egypt	674	7.73	11.12	7.25	3.23	12.10	26.64	11.19	28 Sep 2024	Observed
	Eritrea	452	0.15	5.32	6.65	5.50	18.89	7.33	2.08	16 Oct 2023	High confidence
	France (Indian)	17	12.36	1.64	6.96	0.93	2.03	9.30	16.98	6 Apr 2025	Observed
	India	395	2.60	12.02	3.92	2.40	3.23	11.52	4.72	21 May 2020	Observed
	Iran	106	1.94	5.08	5.76	0.84	6.51	8.93	2.09	1 Aug 2024	Observed
	Israel	5	4.77	7.18	5.16	1.11	6.06	23.66	6.45	17 Sep 2024	Observed
	Jordan	5	4.77	7.18	5.16	1.11	6.06	23.66	6.45	17 Sep 2024	Observed
	Kenya	127	3.25	8.44	0.16	2.31	1.85	12.89	5.17	16 Apr 2024	Observed
	Kuwait	29	4.27	17.96	18.46	15.05	19.35	22.26	9.84	12 Sep 2024	Observed
	Madagascar	865	5.93	6.03	7.36	2.35	5.04	14.17	10.85	5 May 2024	Observed
	**Maldives	1024	0.96	1.29	0.15	0.15	0.15	5.93	0.15	9 May 2016 (7.23)	Observed
	**Mauritius	129	8.70	6.14	2.70	2.88	1.42	11.34	13.22	18 May 2016 (14.83)	Observed
	Mayotte	104	4.66	2.44	1.47	0.93	1.79	9.59	4.41	22 Apr 2024	Observed
	Mozambique	430	2.90	5.64	1.94	1.61	2.96	9.83	5.32	14 Apr 2024	Observed
	Myanmar	425	5.18	5.23	6.12	3.49	5.22	9.43	5.79	4 Jun 2024	High confidence
	Oman	74	1.76	3.14	11.23	2.86	10.26	14.31	7.25	2 Aug 2024	Observed
	Qatar	15	0.97	2.06	6.75	4.05	5.91	2.82	4.06	9 Sep 1986 (9.62)	Observed
	Saudi Arabia	1095	5.92	14.22	6.66	7.55	16.21	23.68	9.93	17 Sep 2024	Observed
	**Seychelles	273	6.11	4.75	3.21	1.07	2.67	15.25	4.88	26 Apr 2024	Observed
	Somalia	79	1.11	4.56	0.00	0.60	2.77	8.50	4.94	17 Apr 2024	High confidence
	Sri Lanka	123	2.70	4.15	0.68	1.06	1.57	8.70	0.17	16 May 2016 (9.53)	Observed
	Sudan	227	0.50	6.76	2.62	2.79	13.77	11.11	5.60	13 Oct 2023	High confidence
	Tanzania	529	3.50	7.79	0.78	1.91	1.78	13.48	2.92	5 Apr 2024	Observed
	United Arab Emirates	277	0.76	1.18	4.33	1.15	5.66	4.21	2.07	9 Sep 1986 (7.66)	Observed
	United Kingdom (Indian)	500	3.67	0.29	0.00	0.77	1.85	6.27	4.47	15 May 2016 (15.80)	Observed
	Yemen	203	0.00	0.29	2.28	3.98	14.29	7.17	2.19	20 Oct 2023	High confidence

Coral reef-containing countries organised by ocean basin, the number of reef-containing 5-km pixels within their jurisdiction, the 80th percentile annual maximum DHW value (2019–2025) among reef locations within the corresponding political boundaries, the date of peak heat stress

Table 2 (continued)

accumulation (based on the 80th percentile annual maximum DHW) within the satellite record, and the assessment of mass coral bleaching during the ongoing global stress period. The 80th percentile max DHWs are color-coded to match that of the corresponding heat stress levels of NOAA CRW's Bleaching Alert Area product (DHW, °C-weeks: ≥ 4–light red; ≥ 8–dark red; ≥ 12–brown; ≥ 16–light purple; ≥ 20–dark purple). Dates of record heat stress accumulation are shaded salmon if this date was within the ongoing global stress period; dates prior to this period are not shaded and display the 80th percentile annual max DHW value for that date in parentheses. Assessments of mass coral bleaching are categorised as either 'Observed' when there are reliable in situ reports of widespread bleaching for that country or a confidence level of inferred bleaching ('High confidence', 'Low confidence' and 'Unlikely'; coloured yellow, light grey and bright green, respectively), determined based on the satellite-derived heat stress accumulations in the country (see Methods). Countries listed with a double asterisk are identified as sovereign Small Island and Developing States (SIDS). *Values for 2025 are up to 17 December

warming has not been demonstrated (Carballo-Bolaños et al. 2019; Crabbe 2019; Hoegh-Guldberg et al. 2023). In addition to advantageous thermal and adaptive histories, some coral colonies, with the aid of several factors including, but not limited to, heat-tolerant symbionts (Sampayo et al. 2008), food availability (Grottoli et al. 2006; Connolly et al. 2012), and/or favourable oceanography (Green et al. 2019; Radice et al. 2019; Reid et al. 2020), demonstrate a capacity to recover from heat stress capable of causing mortality under alternate circumstances (Romero-Torres et al. 2020). Despite this, based on past studies there is an expected heat stress accumulation threshold for near-complete, reef-wide coral mortality (> 80% of corals) of ≥ 20 °C-weeks (Glynn 1984; Vargas-Ángel et al. 2019; Baum et al. 2023), albeit with one known exception in the northern Red Sea (Osman et al. 2018; Kochman and Fine 2025). This level of heat stress accumulation was surpassed in > 26% of reef locations within the Atlantic Ocean basin since 2018 (primarily in 2023), a region that has already experienced multiple devastating disturbance events over the past 40–50 years (Gardner et al. 2003; Jackson et al. 2014; Cramer et al. 2021). 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). Summertime SST anomalies on the Great Barrier Reef in 2024 were the warmest in four centuries (Henley et al. 2024). The most extreme heat exposures occurred in the Caribbean, the southern Atlantic, the Red Sea, the Persian Gulf, Western Australia, and the eastern and western Pacific. Reports of observed bleaching were relatively fewer from 2020 to 2022 than in the remainder of the global stress period, possibly due to reduced monitoring efforts throughout 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 (Montano et al. 2022). The satellite data show a continuous period of global coral heat stress despite reduced monitoring. The 3rd highest peak in global annual bleaching stress extent did indeed occur during 2020–2022 (Fig. 2).

We are unable to conclude that reduced monitoring during COVID-19 restrictions contributed to a delayed declaration of GCBE4. Despite maximum annual bleaching stress extents during 2019–2022 exceeding both GCBE1 and GCBE2, the lack of a 'global event' designation during this period could be due to shifts in reef compositions/tolerances, public perceptions, or a combination of these. It is not possible to predict the comprehensive impacts of recent heat stress on reefs, especially repeat disturbance events, due to the complexity of its interaction with their ecological memory from past exposure (Hughes et al. 2019b). Repeat heat stress exposure has been shown in some locations to significantly increase thermal tolerance (e.g. Hughes et al. 2021; Lachs et al. 2023), though these relationships are likely multifaceted (Hughes et al. 2019b; Wall et al. 2021). Similarly, the public memory often complicates our view of comparable ecological events over time, as we risk becoming desensitised to impacts that may have caused distress decades earlier. This phenomenon, known as 'shifting baseline syndrome' (Pauly 1995), has been shown to affect coral reef scientists, making comparisons across time problematic (Braverman 2020). Heavily trafficked locations where near-annual bleaching has become commonplace, such as the Florida Keys (Manzello et al. 2025), risk a shift in public perception over time. However, it is worth noting that there is evidence that Florida Keys reef scientists specifically are not subject to shifting baseline syndrome, likely due to increased education, monitoring, and experience counteracting a potential shifted perspective (Muldrow et al. 2020). As this potential omnipresent state of global heat stress continues, both of these phenomena are likely to be more difficult to understand or predict without significant scrutiny. Regardless of shifts in reef tolerance or public perception, the increased frequency of repeated exposure to heat stress is threatening the long-term persistence of reef systems (Hughes et al. 2018a; Smale et al. 2019).

Since August 2014, there has been only a roughly eight-month gap during which conditions for a global stress period were not met, and it is currently uncertain when, or if, these conditions might end. More than half of the world's reef locations experienced multiple bleaching-level heat stress events since late 2018. By the end of GCBE3, the average time between severe bleaching events globally was only 6 years (Hughes et al. 2018a). Within the 7.3-year period of continuous global stress thus far, 64% of the world's reef locations accumulated DHW ≥ 4 °C-weeks at least twice, whereas over 30% experienced this level of heat stress four times or more. Furthermore, nearly one-third of the world's reef locations experienced ≥ 8 °C-weeks at least twice during this period. Of the 102 reef-containing countries, 85 experienced bleaching-level heat stress as their 80th percentile annual max DHW during at least three years, and 84 countries experienced their record highest 80th percentile max DHW in the past approximately seven years (Table 2). One of the most notable examples of repeated heat stress and mass bleaching occurred on the Great Barrier Reef, which experienced mass coral bleaching in at least five of the last seven austral summers (2020, 2021, 2022, 2024 and 2025) (Great Barrier Reef Marine Park Authority et al. 2024, 2025; Emslie et al. 2025; Spady et al. 2025), with a trend of an increasingly early onset of heat stress (Spady et al. 2022). Among other major reef systems, since 2018, mass coral bleaching was observed during at least three boreal summers in both the Caribbean (2019, 2023 and 2024) and in the Red Sea (2020, 2023 and 2024) (Table S1). Repeated heat stress events can have long-lasting and species-specific effects, even in those colonies that appear healthy visually (Brown et al. 2023), raising concerns about the capacity for reef resilience under future marine heatwaves (Castillo et al. 2012; Neal et al. 2017; Schoepf et al. 2019). With an expectation of longer-lasting heat stress events and potentially annual marine heat extremes (Hughes et al. 2018a), corals will face increased pressure for genetically driven adaptation and, if unable to do so, their survival under accelerating warming is increasingly unlikely (Hoegh-Guldberg 1999; Dixon et al. 2022).

Conclusions

More than 25 years ago, it was predicted that most coral reefs would experience near-annual bleaching events exceeding the extent of GCBE1 by 2040 (Hoegh-Guldberg 1999); the results presented here support this as being an accurate, if not conservative, estimate. For the past seven years, global heat stress conditions on coral reefs have consistently surpassed those contributing to GCBE1. Over that same period, the average frequency of bleaching-level heat stress accumulation was every two years for one-fourth of the world's reef areas. Based on our analyses, most reef-containing nations likely experienced mass coral bleaching at least once since 2018, with some confirmations for the first time on important reef systems that would have previously been considered 'thermal refugia' (e.g. reef locations within the Solomon Islands, Raja Ampat, southern Great Barrier Reef) (Cacciapaglia and Van Woesik 2015). This illustrates that the predicted loss of local-scale refugia (Dixon et al. 2022) is well underway, as the global number of recorded bleaching events continues to rapidly increase (Hughes et al. 2018a).

The chronic presence of bleaching-level heat stress since August 2018, as of this writing, was most severe and widespread during 2023–2025, coinciding with the declared fourth global-scale coral bleaching event. While the declaration of a 'global-scale coral bleaching event' is important for public perception and awareness, our analyses and comparisons of SST trends and heat stress accumulations suggest that a more appropriate designation may be the beginning of the 'era of near-annual bleaching'. The Global Coral Heat Stress Index, detailed here, can help highlight periods within this new era during which global bleaching risk is relatively severe or moderate, providing a general understanding of the state of global stress for stakeholders worldwide. Regardless of the scale or intensity of global heat stress, the risk of near-annual bleaching has remained high for much of the world for nearly the entirety of the last decade. Whilst future work is essential to assess the resulting ecological impacts of recent stress (i.e. coral bleaching, mortality and disease), and to understand the follow-on effects to social and economic systems, the record extent and severity of this heat stress suggest that the consequences are likely to be dire.

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Data Availability Sea surface temperature and heat stress metrics used in this study were derived from the NOAA CRW daily global 5-km satellite coral bleaching heat stress monitoring product suite (https://coralreefwatch.noaa.gov/).

Declarations

Conflict of interest The authors declare no competing interests.

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