Coral Reefs (2025) 44:1275–1285
https://doi.org/10.1007/s00338-025-02690-1

RESEARCH

Satellite-based analysis of an unverified mass coral bleaching event on the Great Barrier Reef in 2021

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Received: 9 October 2024 / Accepted: 2 June 2025 / Published online: 17 June 2025
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Abstract The Great Barrier Reef (GBR), Australia, has experienced more frequent heat stress events since the region's first recorded mass coral bleaching event in 1998. Seven confirmed mass coral bleaching events have occurred on the GBR, including five events since 2016. Due to the large scale of the GBR, comprehensive visual bleaching surveys are challenging, particularly as heat stress events accumulate more frequently in remote regions. One such event lacking extensive bleaching surveys occurred on the northern GBR in 2021, suggesting a need for alternative monitoring options. Satellite-based heat stress monitoring products recorded significant bleaching-level heat stress (4 °C-weeks) on 67% of the northern GBR in 2021, comparable in extent to previously confirmed events. Here, we demonstrate a strong correlation between satellite-based heat stress metrics and mass bleaching on the GBR, and indicate that the GBR has likely experienced at least eight mass bleaching events from 1998 to 2024, three of which were consecutive events affecting the northern GBR from 2020 to 2022. In-water surveys and time-series observations of individual corals at Lizard Island confirm partial and fully bleached corals (> 50% coral cover bleached) were common in shallow and deep habitats in 2021. From 1998 to 2015, there were two widespread bleaching events; this increased to one event every 1.5 years from 2016 to 2024, indicating that the GBR is approaching an annual bleaching scenario. As heat stress events become more common, bleaching thresholds from satellite-based monitoring products remain accurate and should continue to be used to predict and understand the potential impacts from thermal stress to reef ecosystems.

Keywords Coral reefs · Degree Heating Week · Heat stress · Mass bleaching · Remote sensing · Sea surface temperature

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00338-025-02690-1.

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Introduction

As of 2024, there have been seven verified mass coral bleaching events on the Great Barrier Reef (GBR), Australia: 1998, 2002, 2016, 2017, 2020, 2022 and 2024 (Great Barrier Reef Marine Park Authority et al. 2022, 2024; Cantin et al. 2024). During summer seasons with significant heat stress accumulation on the GBR, government authorities, managers, and scientists perform extensive surveys of the reef for signs of coral bleaching and mortality. Surveyors

are largely informed of when and where to assess the reef by satellite sea surface temperature (SST) metrics, including the US National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch (CRW) daily global 5 km satellite coral bleaching heat stress monitoring products (Skirving et al. 2020).

Mass coral bleaching is typically associated with widespread heat stress that exceeds a certain intensity and/or accumulation threshold (Glynn 1984; Glynn and D'Croz 1990; Hoegh-Guldberg 1999). NOAA CRW's Degree Heating Week (DHW; °C-week) is a measure of accumulated instantaneous heat stress, or Coral Bleaching HotSpots, over a 12-week running window (Liu et al. 2014, 2017; Skirving et al. 2020). Considerable evidence has confirmed that the DHW threshold of 4 °C-weeks is sufficient to cause significant coral bleaching (Liu et al. 2014; Skirving et al. 2019), particularly on the GBR, as bleaching prevalence increased dramatically at 2.5 °C-weeks during the 2016 bleaching event (Hughes et al. 2017). The magnitude of heat stress accumulation also strongly correlates to the severity of the bleaching response on the GBR, with severe bleaching likely at > 6 °C-weeks and mortality common at a heat stress accumulation of > 8 °C-weeks (Hughes et al. 2017).

In 2021, NOAA CRW's DHW product detected significant heat stress accumulation in the northern GBR (north of 15°S) and Torres Strait (hereafter collectively referred to as the northern GBR; see Fig. 1), at a level that had been both previously and subsequently documented to cause mass coral bleaching in the region (≥ 4 °C-weeks). However, the immense scale of the GBR along with the increased frequency of heat stress events within remote regions have presented substantial complications for extensive in situ survey confirmation of bleaching during all periods of heat stress. A comprehensive verification of the impacts of this heat stress throughout the northern GBR in 2021, via in situ surveys, was not conducted due to stakeholder decisions described later in this paper. Therefore, there is a need to assess the

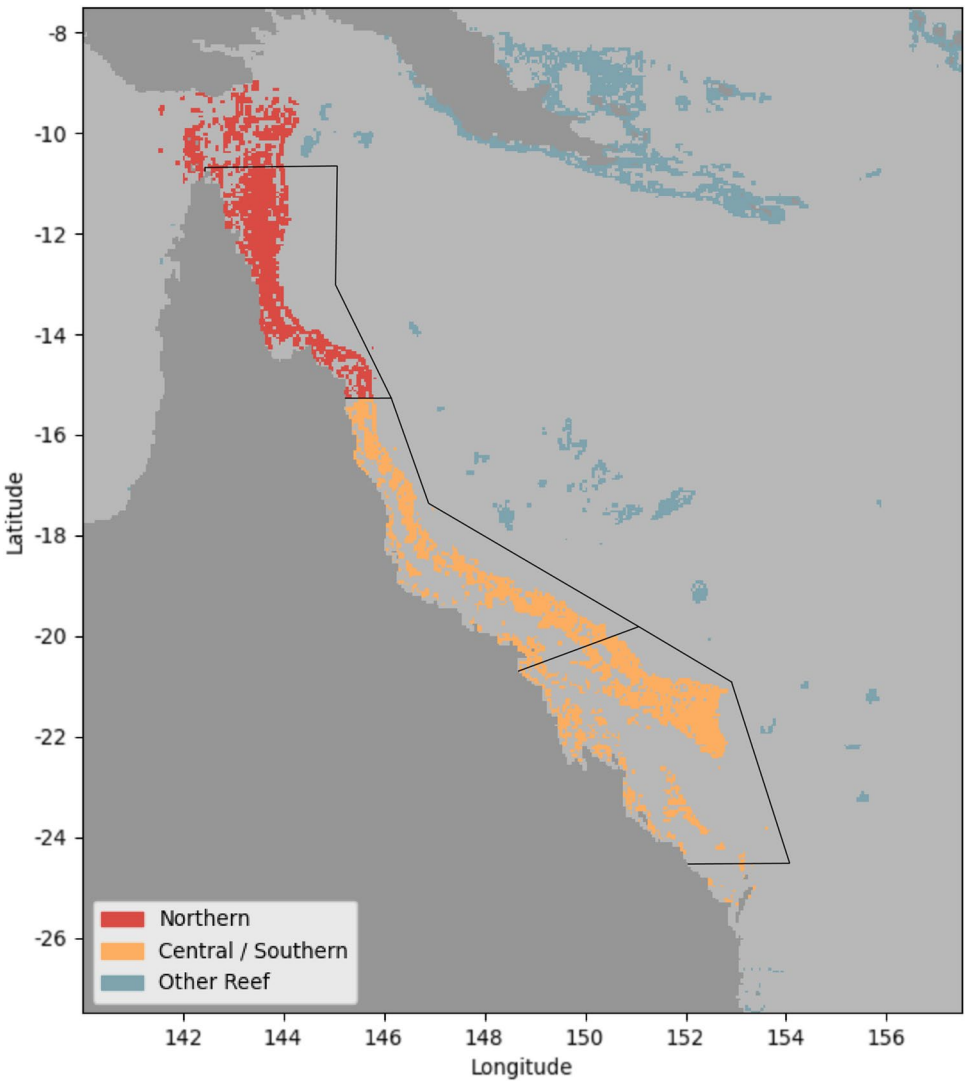

Fig. 1 Map of 5 × 5 km reef pixels used in analyses of the northern GBR (red). Central/Southern GBR pixels (yellow) were combined with the northern GBR pixels only for analyses of the entire reef system. Light blue reef pixels were not included in the analyses. Black borders indicate the spatial bounds of the Northern, Central, and Southern GBR as classified by the Australian Institute of Marine Science's Long-Term Monitoring Program

extent of coral bleaching on the GBR via satellite monitoring data, assisted by limited in situ surveys.

In this study, we investigate the capacity of NOAA CRW's DHW product to reliably and consistently detect the onset and presence, as opposed to the severity, of a mass bleaching event on the GBR. We evaluate if a heat stress threshold of 4 °C-weeks effectively corresponds to confirmations of significant bleaching during recent verified GBR mass bleaching events. We also statistically compare the extent of this level of heat stress accumulation in 2021 with known bleaching and non-bleaching years, for the entire GBR as well as for the northern GBR separately. An overview of limited bleaching surveys available during 2021 is detailed as further support for comparison with the satellite data, including comprehensive local-scale surveys from Lizard Island during heat stress accumulation and following peak heat stress. The results from these analyses are used to determine if satellite-based products are a valid option for effectively understanding the impacts of the accumulated heat stress on a reef system as extensive as the GBR. Further, we conclude if a mass bleaching event was likely to have occurred on the GBR in 2021, and therefore if, as of 2024, eight mass bleaching events can be defensibly declared on the GBR.

Methods

Heat stress metrics for the GBR were derived from the NOAA CRW daily global 5 km satellite coral bleaching heat stress monitoring product suite (https://coralreefwatch.noaa.gov/). As heat stress on the GBR is accumulating increasingly early in recent years (Spady et al. 2022), rather than using the annual maximum DHW provided from NOAA CRW, this study uses maximum daily DHW values from 1st November of the previous year to 30th June of the listed year for each corresponding Austral summer season (following Skirving et al. 2019). This period was used to avoid associating DHW values that had accumulated late in a calendar year with an event from earlier in the same calendar year (e.g., to avoid heat stress accumulated in December 2021, which corresponded to the 2022 bleaching event, to be associated with the heat stress event that occurred in early 2021).

Early seasonal warming occurred in the Northern GBR in December 2020, which initiated in-water research into bleaching dynamics at Lizard Island from February–March 2021. Two sites at Lizard Island near Watsons Bay; Turtle Beach (14.65071°S, 145.45009°E) and Osprey reef (14.66779°S, 145.44189°E) were surveyed at two depths (Shallow: 4–6 m and Deep: 10–12 m). Coral colony level bleaching severity was recorded in-water and from imagery captured from individual coral colonies within 1×1 m quadrats, and three replicate 4×10 m permanent survey plots spread throughout each site and depth. Colony level bleaching severity was scored on a categorical scale from 1 to 6, following the methods used during broadscale coral bleaching monitoring campaigns throughout the GBR (Marshall and Baird 2000; Hughes et al. 2017). Categories used include: Category 1—no bleaching; Category 3—minor partial bleaching (1–50% colony area bleached white); Category 4—major partial bleaching (50–95% colony area bleached white); Category 5—severe fully bleached (100% colony area bleached white), and Category 6—recently dead (severely bleached white colonies with recent partial or full colony mortality). Initial bleaching severity observations were collected from February 21–28th, 2021; colonies were monitored for bleaching severity progression after cyclone Niran in March and assessed again for survival and recovery in September 2021.

Aerial estimated percent bleaching observations for 2016, 2017, and 2020 were extracted from the version 3 dataset from González et al. (2022) (https://data.mendeley.com/datasets/tncdys47mh/3); aerial estimated percent bleaching observations for 2022 were provided by the Australian Institute of Marine Science (AIMS). At the time of writing, survey data from and following the 2024 event were not yet available, though a significant mass bleaching event had been confirmed (Great Barrier Reef Marine Park Authority et al. 2024). Therefore, in situ observational data from the year 2024 were not included in this analysis. Analyses were undertaken using only values at coral reef locations compiled at 5 km resolution by NOAA CRW from multiple data sources (Heron et al. 2016). Statistical analyses between groups of years for the differences in proportion of reef pixels that had reached DHW ≥ 4 were performed via binomial generalized linear models (GLM) with a complementary log–log link. All analyses were performed in Python v3.6.

Results and discussion

Degree Heating Week and mass bleaching on the Great Barrier Reef

The NOAA CRW DHW product has shown a high capacity for accurately determining the onset of mass bleaching events on the GBR. During recent confirmed mass coral bleaching events (2016, 2017, 2020, 2022 and 2024), between 46 and 79% of the 4684 reef pixels on the GBR (including those within the Torres Strait; see Fig. 1) reached DHW ≥ 4. Among surveyed reefs in each of the four years with available data (numbering between 645 and 1133 reefs; survey data for 2024 not yet available), a maximum DHW of ≥ 4 °C-weeks correlated to observations of coral bleaching in 93%, 95%, 79% and 91% of reefs for the years 2016, 2017, 2020 and 2022, respectively. Overall, among these four

documented events, the probability of bleaching detection using a DHW threshold of 4°C-weeks was 88%. It is therefore reasonable to consider DHW ≥ 4 as 'bleaching-level heat stress' on the GBR. Although a formal analysis cannot be conducted to compare the satellite-based heat stress with the in situ observations for 2024 until the data have been released, general reports from the Great Barrier Reef Marine Park Authority (GBRMPA) have confirmed a mass bleaching event throughout the GBR (Cantin et al. 2024). These reports of bleaching severity and extent do align with the spatial spread and intensity of heat stress accumulation as measured by the NOAA CRW DHW product (Great Barrier Reef Marine Park Authority et al. 2024).

The frequency of bleaching-level heat stress on the GBR has dramatically increased over the last nearly four decades. In the 30 years from 1986 to 2015, only six summer seasons experienced a DHW ≥ 4 on greater than 10% of GBR reef pixels. Further, during 19 of these 30 summer seasons on the GBR, fewer than 1% of reef pixels experienced a DHW ≥ 4. However, in the nine summer seasons from 2016 to 2024, six had greater than 10% of GBR reef pixels experiencing DHW ≥ 4. Additionally, none of the nine most recent summer seasons experienced DHW ≥ 4 on fewer than 1% of reef pixels, as was common from 1986 to 2015. Bleaching-level heat stress has also become more extensive during anomalous summers on the GBR since the first documented event in 1998 (Fig. 2). Heat stress accumulation of ≥ 4 °C-weeks during the mass coral bleaching events of 1998 and 2002 affected less than 20% of the GBR reef pixels. Regional heat stress events (as opposed to widespread events) were more common prior to 2016, including a documented regional bleaching event in the Southern GBR in 2006 (Maynard et al. 2008), as well as evidence via satellite DHW of regional events in highly remote regions of the Torres Strait during 2003, 2009, 2010, and 2011. The summer of 2004 showed evidence of mild simultaneous regional heat stress events within both the Southern GBR and Torres Strait. However, beginning in 2016, instances of bleaching-level heat stress were much more extensive than previously recorded, often affecting all four regions of the GBR and Torres Strait. Six of the previous nine years from 2016–2024 had bleaching-level heat stress on 27–81% of reef pixels,

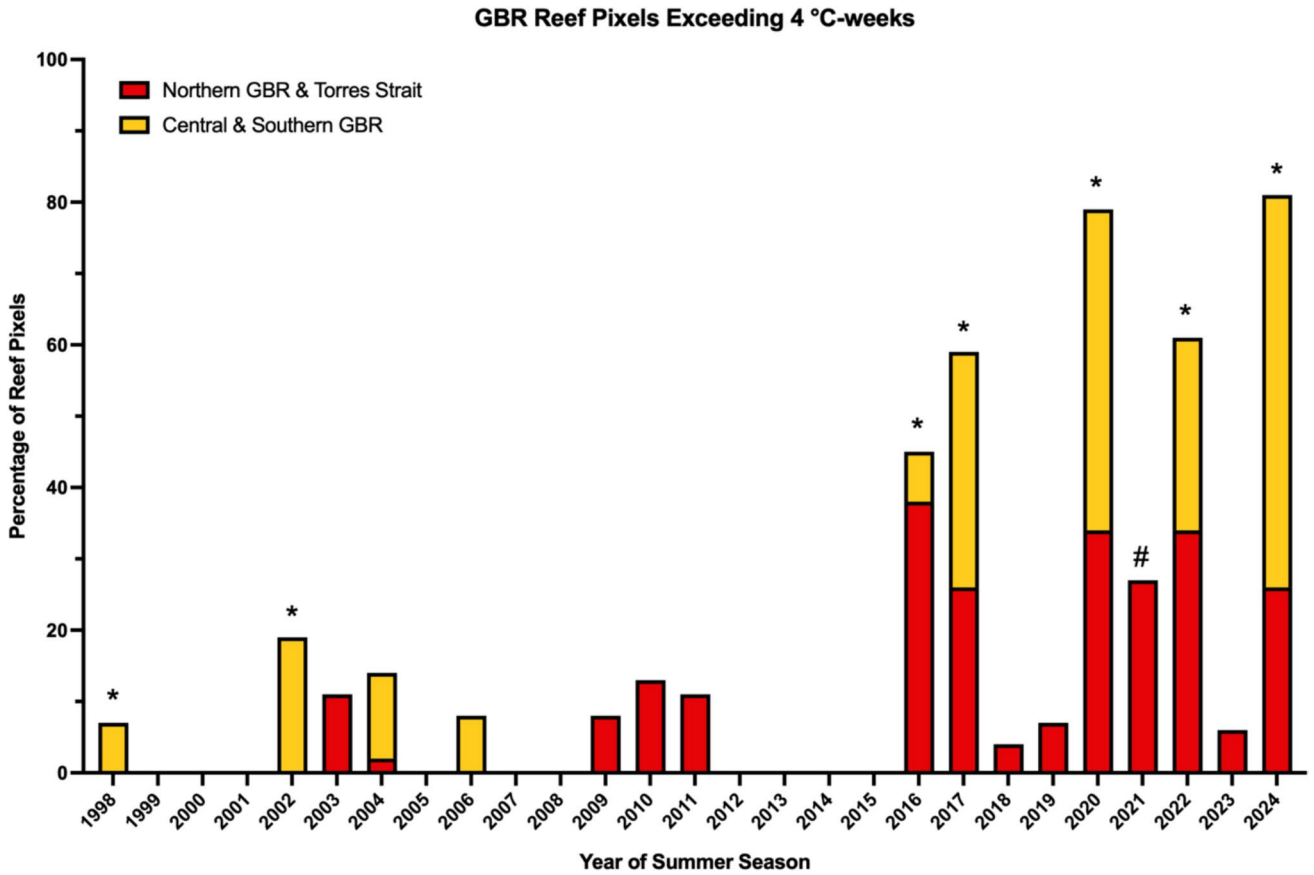

Fig. 2 Percentage of total coral reef pixels on the GBR with a maximum DHW ≥ 4 during the Austral summer seasons from 1998 to 2024 within the Northern GBR and Torres Strait regions (red) and Central/Southern regions (yellow). Asterisks (*) above bars indicate years in which there were field survey-verified mass bleaching events on the GBR; the heat stress event of 2021 is denoted by a hash (#). The maximum DHW was determined over the period of 1st November of the previous year to 30th June of the labeled year

commonly including large portions of the Northern GBR and Torres Strait.

As heat stress events become more recurrent and extensive on the GBR, the logistics required to continually monitor and capture bleaching intensity at its peak across a large reef ecosystem the size of the GBR has become increasingly challenging. Long-term monitoring programs continue to operate throughout the GBR to detect the annual changes in coral cover from one year to the next. However, surveying the GBR for bleaching during a heat stress event requires the cooperation of multiple agencies and organizations, hundreds of hours of field work and subsequent analyses, and extensive funding. When a heat stress event is expected to cause significant mortality or shifts in reef composition, the expenditure of these resources is more easily justifiable. However, during the more frequently occurring heat stress events that are not expected to result in a significant direct impact through widespread mortality of corals, especially in remote regions such as the reefs north of Cooktown, Queensland, utilizing these considerable resources may not be the most efficient or cost-effective monitoring method.

Comparative analysis of an unverified mass bleaching event

Prior to 2016, no field survey-verified mass bleaching event had been documented on the northern GBR, although between 18 and 32% of the 1913 reef pixels within this region experienced DHW ≥ 4 during 1987, 2003, 2009, 2010 and 2011. However, these events paled in comparison with 2016, when 94.2% of the reef pixels in this region accumulated heat stress of DHW ≥ 4, and 64.2% of reef pixels accumulated heat stress of DHW ≥ 8. Since then, 2017, 2020, 2021, 2022 and 2024 were standout years, having DHW ≥ 4 on 64.3%, 83.7%, 66.8%, 82.6%, and 64.1% of reef pixels, respectively (Table 1). The extent of northern GBR reef pixels with a maximum DHW ≥ 4 during the 2021 event significantly exceeded that measured during years in which mass bleaching did not occur in the region, and was comparable to that measured on the northern GBR during the five recent confirmed mass bleaching events of 2016, 2017, 2020, 2022 and 2024. We compared, between groups of years, the proportion of reef pixels in the northern GBR that had a maximum DHW ≥ 4 (Table S1). The proportion of reef pixels in this region at DHW ≥ 4 in the recent confirmed bleaching years (2016, 2017, 2020, 2022 and 2024) was significantly higher than in known, non-bleaching years (1986–2015, 2018, 2019, and 2023) (GLM; coeff = −3.297, S.E. = 0.932, $p < 0.001$). The proportion of northern GBR reef pixels that reached DHW ≥ 4 in 2021 was also significantly higher than those same known, non-bleaching years (GLM; coeff = −2.986, S.E. = 1.488, $p = 0.045$). There was no significant difference between the proportion of reef pixels in the northern GBR reaching DHW ≥ 4 in 2021 as compared with recent confirmed bleaching years (GLM; coeff = 0.311, S.E. = 1.402, $p = 0.825$).

When successive mass coral bleaching events occur within one to three years of each other on the GBR, the

Table 1 Percentage of the 1913 reef pixels in the northern GBR that reached or exceeded a maximum DHW of 4, 6, and 8 °C-weeks for each year within the satellite record (1986–2024)

Year	DHW ≥ 4 (%)	DHW ≥ 6 (%)	DHW ≥ 8 (%)
1986	0	0	0
1987	18.5	0.4	0
1988	0.1	0	0
1989	0.2	0	0
1990	0	0	0
1991	0	0	0
1992	0	0	0
1993	0	0	0
1994	5.5	0.4	0
1995	0	0	0
1996	1.2	0	0
1997	0	0	0
1998	0	0	0
1999	0	0	0
2000	0	0	0
2001	0	0	0
2002	1.0	0	0
2003	26.2	3.6	0
2004	4.2	0	0
2005	0	0	0
2006	0	0	0
2007	0	0	0
2008	0	0	0
2009	18.8	0.4	0
2010	31.9	4.1	0.2
2011	27.4	0.5	0
2012	0.5	0	0
2013	0	0	0
2014	0	0	0
2015	0	0	0
2016	**94.2**	**85.4**	**63.2**
2017	**64.3**	**45.6**	**32.1**
2018	9.8	1.0	0
2019	18.1	4.1	0
2020	**83.7**	**60.8**	**29.8**
2021	*66.8*	*29.1*	*3.1*
2022	**82.6**	**36.9**	**10.4**
2023	15.1	3.2	0
2024	**64.1**	**23.7**	**6.7**

Years in which mass bleaching was confirmed in the northern GBR via aerial surveys are highlighted in bold emphasis; 2021 is highlighted in italic emphasis

thermal threshold for severe bleaching (> 30% bleaching) in corals was reported to have increased, potentially due to stress-hardening, acclimatization, or selective mortality of sensitive species and/or genotypes (Hughes et al. 2021). The reefs experiencing three consecutive heat stress events in the northern GBR in 2020, 2021 and 2022 might have shown increased resistance and/or resilience to bleaching-level heat stress during the 2022 summer season (analysis not performed here). However, additional local, regional, and global co-variates and/or stressors can work independently, or in concert to influence coral bleaching prevalence on a reef, independent of recent bleaching history.

Of the 146 northern GBR reef pixels surveyed during the 2022 event, 79% were observed to have bleached. There were 1580 reef pixels on the northern GBR in 2022 that experienced DHW ≥ 4, and 75% of these (1183 pixels) also experienced DHW ≥ 4 during the summers of 2020 and 2021 (Fig. 3), therefore experiencing three consecutive summer seasons of significant heat stress. The surveyed reefs were expected to be most resilient to heat stress during the 2022 event (Hughes et al. 2021), yet significant bleaching was observed during this third consecutive event, indicating that the northern GBR reefs remained sensitive to heat stress during the summer of 2021. We find it logical to conclude via inductive reasoning that reefs, which experienced similar levels of heat stress during three consecutive years, and confirmed mass coral bleaching was strongly correlated with DHW ≥ 4 in the first and third year, also experienced mass coral bleaching under these conditions in the second year (2021).

Within the northern GBR, maximum DHWs of at least 4 °C-weeks in 2021 were comparable in extent to the 2016, 2017, 2020, 2022 and 2024 events; however, the severity of accumulated heat stress during the 2021 event was less. Maximum DHWs on the northern GBR in 2021 reached DHW ≥ 6 on 29% of reef pixels, compared with 37–85% of pixels in 2016, 2017, 2020 and 2022. While the extent of heat stress exceeding this severity threshold may have been lower in 2021 than these four confirmed mass bleaching events, it is noteworthy that a maximum DHW ≥ 6 has not exceeded 4.2% of pixels in this region within the satellite record (1986–2024) for any year except 2016, 2017, 2020, 2021, 2022 and 2024. Heat stress levels at which coral mortality is generally expected to be at higher risk (DHW ≥ 8) was observed on between ~ 7% (2024) and ~ 63% (2016) of the reef pixels in the northern GBR during the five, recent confirmed mass bleaching events. In 2021, 3.1% of the northern GBR reef pixels reached DHW ≥ 8. While this is comparatively low, outside of the five recent confirmed events, this percentage is the highest in the satellite record. Only the summer of 2010 had any reef pixels reaching DHW ≥ 8 (3 of 1913 pixels) in the northern GBR (Table 1).

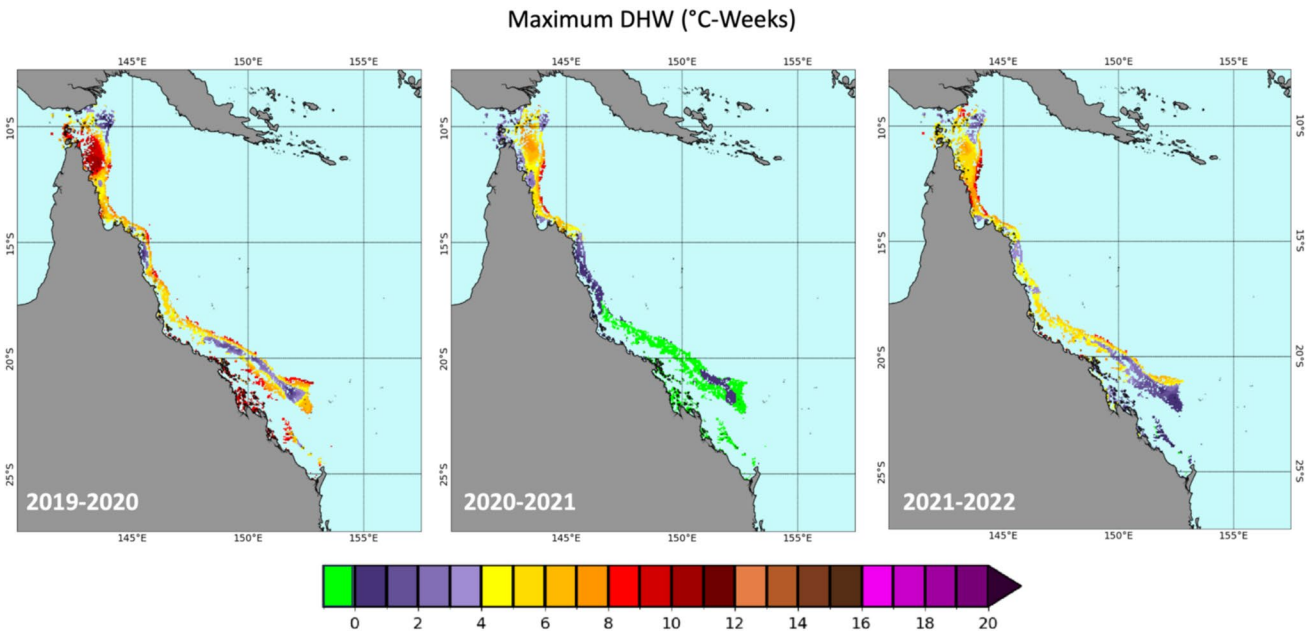

Fig. 3 Maximum DHWs (from 1st November–30th June each Austral summer season) on the GBR for the field survey-confirmed mass bleaching events of 2019–2020 [left] and 2021–2022 [right], along with maximum DHWs for the unverified event of 2020–2021 [center]. Only the 4684 GBR reef pixels used in this study are visible on these maps. Reef pixels that did not exceed 0 °C-weeks are represented in green. DHW ≥ 4 is considered sufficient to result in significant coral bleaching (Liu et al. 2014; Skirving et al. 2019)

In situ bleaching surveys on the GBR during 2021

Lizard Island is located at the bottom edge of the Northern GBR regional boundary and the southern edge of the intense heat stress footprint in 2021. Lizard Island reached a maximum accumulated heat stress value of 4.92 °C-weeks on 2nd March, 2021. Early onset of severely bleached corals were reported by the Lizard Island Research Station managers to begin in December 2020, with increased prevalence at multiple reef sites by 30th January, 2021. During the last week of February, SST anomalies were increasing in the region and in-water surveys confirmed that minor (category 3) to major partial bleaching (category 4) was common for > 50% of the hard coral community and 10–25% of the soft coral community at both shallow (4–6 m) and deeper reef slopes (10–12 m) around the island (Fig. 4). Cyclone Niran developed south of the area and dissipated further heat stress development, which likely also prevented further progression of bleaching severity and mortality at this site. These in-water observations confirm that bleaching was common among coral reef communities exposed to > 4 ˚C-weeks in 2021.

In-water surveys were conducted on 54 northern GBR reefs from October to December, 2020, prior to significant

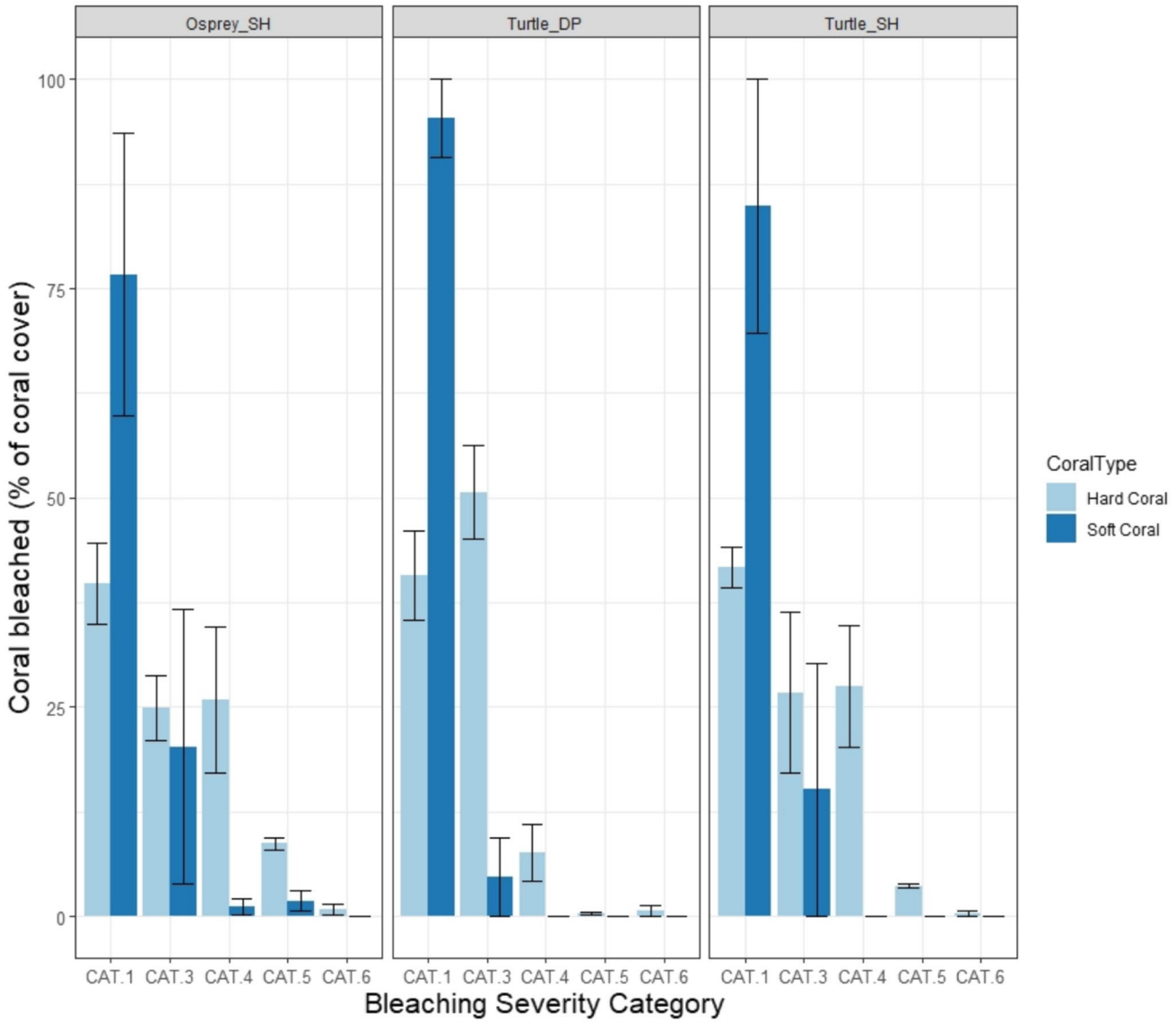

Fig. 4 Coral bleaching severity frequency distributions (% coral cover) for hard and soft corals at Lizard Island (Turtle Shallow (4–6 m); Turtle Deep (10–12 m) and Osprey Reef Shallow (4–6 m) in late February. Proportion of coral colonies (% of coral cover) by bleaching severity category (No Bleaching (Cat1)), minor partial bleaching (Cat.3), major partial bleaching (Cat.4), severe fully bleached (Cat.5) and recently dead (Cat.6)

bleaching-level heat stress (as of 31st December 2020, all northern GBR reef pixels had DHW < 3); low levels of hard coral bleaching was reported on 30% of surveyed reefs (Emslie 2022). Preliminary aerial surveys of reefs from Cooktown to Cape Melville occurred on 26–27th March, 2021, allowing for at least 38 days of recovery since peak heat stress in the inshore and mid-shelf sections of this sub-region on 16th February. While no official record was taken during these preliminary surveys, personal communications with GBRMPA officials revealed that there were consistent observations of inshore reefs having 10–30% bleaching in this area and mid-shelf reefs having 1–30% bleaching. There were no observations of bleaching on the outer shelf reefs in this area, most of which had been afforded 66 days of recovery since peak heat stress on 18th January. One additional independent observation occurred during heat stress accumulation, much closer to the date of peak heat stress. This observation, submitted through the Eye on the Reef network (sighting no. 36330)—including video evidence, found approximately 65% of corals showing signs of heat stress (3% recent mortality, 17% severely bleached, 15% partially bleached, and 30% paling) at North Direction Island, during which heat stress accumulation had reached slightly under 4 °C-weeks. Unfortunately, the sparse in situ observations, which lack spatial homogeneity and optimal timing, are not sufficient to fully describe the biological response of the northern GBR during the 2021 heat stress event.

Confirmation of large-scale (mass) coral bleaching events are typically, and usually reliably performed via visual in-water or aerial surveys. However, as heat stress events on the GBR have become more frequent and have encompassed more remote sections of the reef, it is becoming cost-effective to restrict comprehensive visual surveys of the marine park only to years in which significant mortality and/or shifts in reef composition are expected. The heat stress event of 2021 directly followed the documented mass bleaching of 2020. After performing the preliminary aerial bleaching surveys detailed above, coral reef stakeholders on the GBR concluded that the effect of the event was not likely to have resulted in significant die-offs of corals (as was observed in the previous events of 2016, 2017, and 2020). It was therefore decided that extensive bleaching surveys would not be conducted.

Based on both the satellite heat stress metrics and the limited available in situ data, it appears probable that mortality comparable to the previous three documented events was unlikely to have occurred on the GBR in 2021. However, the physiological toll and consequences of sub-lethal bleaching on a reef can be significant. Short- and long-term effects of sub-lethal temperature stress and coral bleaching include reduced growth, reduced reproductive output, altered population trajectories, and susceptibility to predation (Edmunds 2005; Cox 2007; Edmunds and Lenihan 2010; Levitan et al. 2014; Briggs et al. 2024), as well as an increased susceptibility to coral disease (Lesser 2004; Bruno et al. 2007; Lesser et al. 2007). Additionally, sub-lethal bleaching can rapidly trigger ecological effects, including on the obligate coral symbiont crustaceans and gobiid fishes, which can be reduced or removed completely following the onset of bleaching (Baker et al. 2008). The frequent bleaching of reefs, regardless of intensity, are important events worth documenting, understanding, and reporting. As such, alternative approaches to quantify bleaching impacts to the reef are necessary; the use of remote sensing techniques is crucial in understanding these events.

Monitoring heat stress events in the absence of in situ surveys

NOAA CRW's daily global 5 km satellite coral bleaching heat stress monitoring product suite has accurately monitored and predicted heat stress events leading to all seven confirmed mass bleaching events on the GBR, including those events affecting the northern GBR. These products were also used to highlight the potential for a mass bleaching event on the GBR in 2022, months before peak heat stress occurred in the region, during anomalous early-summer heat stress accumulation (Spady et al. 2022). In 2021, NOAA CRW monitored and predicted a mass bleaching event on the northern GBR in near real-time. In mid-December 2020, CRW's Regional Virtual Stations (https://coralreefwatch.noaa.gov/product/vs) for both the Far Northern GBR and Torres Strait (encompassing the reefs north of 15°S latitude), which summarize heat stress metrics for predefined geographic regions, triggered a Bleaching Warning as DHWs in each region approached 4 °C-weeks. The main purpose of this product is to alert stakeholders of a region to the potential risk of bleaching, as well as to provide a mechanism to compare current and past events. While this tool is only an indicator of regional heat stress, it has proven to be highly valuable in alerting managers to significant bleaching-level heat stress for all corresponding mass bleaching events on the northern GBR, including 2021 (Fig. 5).

In early January 2021, DHWs exceeded the 4 °C-weeks threshold (Bleaching Alert Level 1) and by late January exceeded the 8 °C-weeks threshold (Bleaching Alert Level 2). By late February/early March, the Far Northern GBR Regional Virtual Station reached a maximum DHW of 11.34 °C-weeks before heat stress began to dissipate in the region. The Torres Strait saw a maximum DHW of 8.98 °C-weeks in early February before heat stress began to dissipate. The 2021 event occurred slightly earlier in both regions than the 2020 event, though it was shorter-lived and less severe. During the 2021–2022 summer season, heat stress occurred earlier in the season (late November/early December) than ever previously observed within

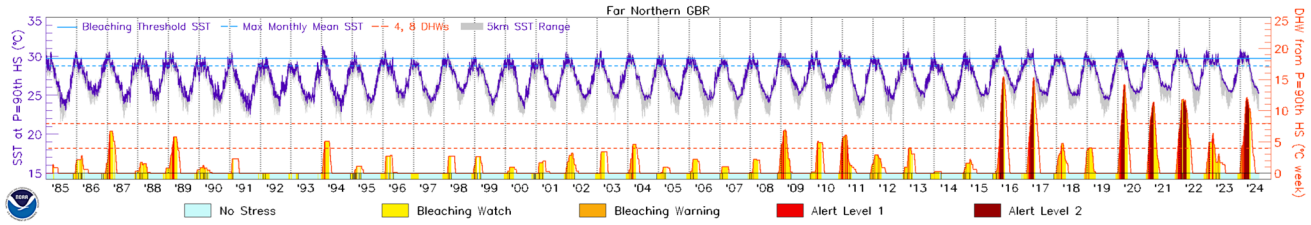

Fig. 5 Summary of the Far Northern GBR satellite Regional Virtual Station from 1985–2024. Purple line (associated with left *y*-axis) shows the daily sea surface temperature. Red line (associated with right *y*-axis) shows daily DHW accumulation. Color of shading underneath curves for DHW accumulation denote the associated bleaching alert level for the region. The Far Northern GBR region reached Bleaching Alert Level 2 (suggesting a risk of reef-wide bleaching with mortality of heat-sensitive corals) only during the summer seasons of 2016, 2017, 2020, 2021, 2022 and 2024

the satellite record and reached a maximum heat stress of 11.81 °C-weeks and 10.76 °C-weeks in the Far Northern GBR and Torres Strait regions, respectively. The onset of heat stress during the 2021–2022 summer season manifested with an unprecedented 33.5% of the entire GBR (the vast majority of which occurred within the northern GBR) having HotSpots ≥ 1 °C (the threshold for accumulating DHW) by mid-December, 2021 (Spady et al. 2022). This increasingly early onset from 2020 to 2022 is consistent with the notion of prolonged anomalous warming events in the region.

The ability to not only predict, but also to continuously monitor and analyze data retrospectively, is an invaluable tool for understanding heat stress events and their evolution over time on coral reefs, including those without in situ monitoring. Consistent in situ monitoring techniques and data, along with historical validation, have provided increased confidence for the use of satellite SSTs to identify large-scale heat stress events that lead to mass coral bleaching. While verifying DHW-based predictions of coral bleaching with in situ observations is ideal, the results shown here demonstrate that a mass coral bleaching event can be monitored and described in lieu of in situ observations on the GBR as current predicted risk thresholds continue to align with patterns of bleaching. That such a significant mass coral bleaching event, on the world's most iconic coral reef, was not comprehensively documented on the GBR during the 2020–2021 summer season highlights the critical importance of continued and consistent satellite monitoring of coral reefs.

Conclusions

The effectiveness of satellite-based heat stress monitoring, specifically NOAA CRW's DHW product, on the GBR has been sufficiently validated in relation to the onset of bleaching for every year in which comprehensive bleaching surveys have been conducted. Coral bleaching-level heat stress on the northern GBR in 2021 was comparable in extent to the heat stress that significantly correlated with the five recent confirmed mass bleaching events in the region (2016, 2017, 2020, 2022 and 2024). Further, this level of heat stress in the northern GBR during the 2021 event was between 3.9 and 1.4 times more extensive than the documented events along the southern and central regions of the GBR in 1998 and 2002, respectively. Despite this, to our knowledge, there is no discussion in the literature of 2021 being a significant bleaching event on the GBR. It is important to note that this study does not attempt to quantify the severity of bleaching that may have occurred during the 2021 heat stress event, rather it finds that the northern GBR experienced the likely onset of a regional mass bleaching event and therefore, significant stress. Through the combination of satellite-based SST measurements of accumulated heat stress and in-water bleaching severity observations, we have sufficient evidence to support that a regional mass bleaching event occurred in the northern region of the GBR in 2021.

Based on the analysis presented here, as of 2024, the GBR has suffered at least eight mass bleaching events, three of which were consecutive events on the northern GBR from 2020 to 2022. The risk of annual bleaching has been steadily increasing globally (Hughes et al. 2018), and the GBR has now suffered six mass bleaching events over the past nine years. Without sufficient rest between stress events for recovery, growth and recruitment, annual bleaching could result in a significant loss of coral diversity and an overall decline of reefs in general (Grottoli et al. 2014). With the inclusion of 2021 as a regional mass coral bleaching event within the GBR, near-annual coral bleaching appears more likely to be the new expectation for the GBR. As managers and science organizations face increased challenges and resource requirements for extensive surveys during heat stress events, satellite-based heat stress products provide a validated capability to accurately describe the effects of climate change and future heat stress events on coral reefs. However, ongoing monitoring of coral community composition, abundance and bleaching response thresholds will undoubtedly enhance

future predictions of bleaching and mortality risk, as well as if adaptation will change these predictive thresholds.

Acknowledgements The National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch (CRW) program was supported by funding from the NOAA Coral Reef Conservation Program. NOAA CRW and ReefSense staff were supported by the NOAA grant NA19NES4320002 (Cooperative Institute for Satellite Earth System Studies) at the University of Maryland/Earth System Science Interdisciplinary Center. Part of this work was performed and funded under ST13301CQ0050/1332KP22FNEED0042. Australian Institute of Marine Science (AIMS) fieldwork at Lizard Island in 2021 was supported by funding from the Great Barrier Reef Foundation toward the Reef Restoration and Adaptation Program. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect the views of NOAA or the Department of Commerce.

Author contributions All authors contributed to the study conception and design; formal analysis performed by BLS and PJM; visualisation and figures created by BLS, EFG, NC and AN; first draft of manuscript prepared by BLS and EFG; all authors contributed to the writing and editing of subsequent drafts of the manuscript; supervision of study by DPM.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions.

Data availability Heat stress metrics for the GBR were derived from the NOAA CRW daily global 5 km satellite coral bleaching heat stress monitoring product suite (https://coralreefwatch.noaa.gov/). Aerial estimated percent bleaching observations for 2016, 2017, and 2020 were extracted from the version 3 dataset from González et al. (2022) (https://data.mendeley.com/datasets/tncdys47mh/3).

Declarations

Competing Interests The authors declare no competing interests.

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