



BRIEF REPORT

Unprecedented early-summer heat stress and forecast of coral bleaching on the Great Barrier Reef, 2021-2022 [version 1; peer review: 2 approved with reservations]

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Abstract

The Great Barrier Reef (GBR) is predicted to undergo its sixth mass coral bleaching event during the Southern Hemisphere summer of 2021-2022. Coral bleaching-level heat stress over the GBR is forecast to start earlier than any previous year in the satellite record (1985-present). The National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch (CRW) near real-time satellite-based heat stress products were used to investigate early-summer sea surface temperature (SST) and heat stress conditions on the GBR during late 2021. As of 14 December 2021, values of instantaneous heat stress (Coral Bleaching HotSpots) and accumulated heat stress over a 12-week running window (Degree Heating Weeks) on the GBR were unprecedented in the satellite record. Further, 89% of GBR satellite reef pixels for this date in 2021 had a positive seven-day SST trend of greater than 0.2 degrees Celsius/week. Background temperatures (the minimum temperature over the previous 29 days) were alarmingly high, with 87% of GBR reef pixels on 14 December 2021 being greater than the maximum SST over that same 29-day period for any year from 1985-2020. The GBR is starting the 2021-2022 summer season with more accumulated heat than ever before, which could have disastrous consequences for the health, recovery, and future of this critical reef system.

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Background temperature, Bleaching, Coral, Degree Heating Week, Great Barrier Reef, heat stress, La Niña, satellite monitoring

Any reports and responses or comments on the article can be found at the end of the article.



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Introduction

The Great Barrier Reef (GBR) has endured five mass coral bleaching events, three of which took place between 2016 and 2020. Coral bleaching occurs when stress disrupts the symbiosis between corals and their endosymbiotic algae (zooxanthellae), causing the corals to expel zooxanthellae; this can lead to coral mortality if stress is prolonged or severe (Brown, 1997). Mass coral bleaching, which is bleaching at a scale of an entire reef system or geographic realm, has only been linked to the stress of excess sea surface temperatures (SST), and this is expected to happen when heat stress in a region exceeds a certain intensity or duration (Glynn, 1984; Hoegh-Guldberg, 1999; Skirving *et al.*, 2019). The U.S. National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch (CRW) program has developed a number of satellite-based SST products that are used to monitor oceanic heat stress, including on coral reefs. The Degree Heating Week (DHW) is an accumulation of instantaneous heat stress (Coral Bleaching HotSpots, or just HotSpots) over a 12-week running window (Skirving *et al.*, 2020). A DHW value of 4 degree Celsius-weeks (C-weeks) or greater is capable of causing sufficient stress for corals to bleach significantly (Hughes *et al.*, 2018; Skirving *et al.*, 2019). In the early-summer months preceding the five documented mass bleaching events, heat stress on the GBR had never exceeded a DHW of 3 degree C-weeks prior to mid-January (with the earliest occurrence in 2002 on 12 January), with peak stress typically occurring between late February and early March. In late 2021, sections of the northern GBR reached a $DHW \geq 3$ degree C-weeks by 13 December, and given the observed conditions at the time of writing (21 December 2021), roughly one third of the GBR is expected to exceed a DHW of 4 degree C-weeks by late January 2022, which is unprecedented.

In addition to the satellite-based measurements, NOAA CRW's modelled Four-Month Coral Bleaching Heat Stress Outlook product, from as early as 2 November 2021, forecast sufficient heat stress to result in a potential sixth mass coral bleaching event on the GBR during the 2021-2022 summer season. The anticipated mass bleaching event was not only forecast to occur during atypical climatic conditions (i.e., this would be the first mass coral bleaching on the GBR during a La Niña), but was also forecast to be the earliest onset of a summer-time heat stress event for the GBR to date. During the eleven-year period covered by CRW's Outlook product (2011-2021), the GBR has experienced three of its five known mass bleaching events, one of which (2020) occurred as a result of the most extensive heat stress event the region has suffered (Hughes *et al.*, 2021). Here, we will describe the early-summer SST and heat stress conditions on the GBR in 2021 (November-December), modelled forecasts of heat stress, and how these compare to observations made in previous years, including the relationship between coral bleaching and the El Niño-Southern Oscillation (ENSO) state.

Results and discussion

Early-summer heat stress conditions of late 2021 compared to previous years

On 14 December 2021, 59% of the 5 km-resolution satellite-based reef pixels ($0.05^\circ \times 0.05^\circ$ satellite pixels that coincide with reefs) on the GBR had HotSpots greater than 0.5°C , with 34% being greater than 1.0°C . This is more extensive and severe than the HotSpots measured on 14 December during any year since 1985. The accumulation of HotSpots as DHWs for the same date reached a $DHW > 2$ degree C-weeks for 14% of GBR reef pixels. DHWs greater than 2 degree C-weeks have accounted for more than 0.1% of the GBR reef pixels by 14 December during only three other years (2008: 1.2%, 2010: 10.8%, 2018: 5.4%), none of which were as high as by 14 December 2021 (13.7%, Table 1). The seven-day SST trend as of 14 December 2021, indicated that SST had increased by at least 0.2 degrees C/week for 89% of GBR reef pixels, with 75% greater than 0.5 degrees C/week. The extent and magnitude of these SST trends are not atypical, and were greater during the same period for several other years, notably 1990 and 1993. However, compared to previous years, the early-summer combination of increasing SST trends with unprecedented levels of extensive HotSpots and DHWs are priming the GBR region for coral bleaching-level DHWs later during the 2021-2022 summer.

It is possible that the underlying catalyst for the developing anomalous SST conditions lies in the background temperature. In this context, we define the background temperature as the minimum temperature during the previous 29 days (period of a tidal cycle). The background temperatures on the GBR for 14 December 2021 were overwhelmingly the highest across the entire satellite SST record (i.e., compared with the minimum temperature for each pixel within the 29 days prior to and including 14 December of all years from 1985 to 2020). In fact, for 87% of GBR reef pixels, the minimum temperature at each of these pixels from 16 November to 14 December 2021 was greater than the maximum temperature at the corresponding pixel for any day between 16 November and 14 December from 1985 to 2020 (Figure 1). This is even more noteworthy considering that during November 2021, Queensland, Australia experienced rainfall 136% above the 1961-1990 average, making it the wettest (and most likely the most intensively cloud covered with minimal surface solar heating) November since 2010 (Australian Bureau of Meteorology). Despite this, the SST and corresponding heat stress conditions on the GBR by mid-December 2021 exceeded, in intensity and extent, that seen for any prior year, including bleaching years (Table 1). This suggests that excessive heat energy is being caused by sources other than direct solar heating. Annual SST trends will need to be considered to understand why early-summer 2021 stands out as the warmest on record for the GBR (Figure 2).

Table 1. Summary of annual heat stress conditions from 1985 to 2021. For each year, as of 14 December, the El Niño Southern Oscillation (ENSO) status (October-December) including the NINO3.4 temperature (degrees C); if there was an occurrence of a mass bleaching event on the Great Barrier Reef (GBR) during the following summer; the percentage of the 5,274 GBR 5 km satellite pixels that had a HotSpot > 1; the percentage of GBR pixels with a Degree Heating Week (DHW) > 2; and the mean background temperature for all GBR pixels. Cells within the table containing ‘--’ indicate a value of between 0.0% to 0.1% of the GBR pixels. [Note: La Niña conditions present in December 2016 did not persist past January 2017; bleaching did not commence until February 2017.]

Year (14 December)	ENSO status (NINO3.4 temperature)	Bleaching year	HotSpot >1 (%)	DHW >2 (%)	Mean background temperature (degrees C)
2021	La Niña (-1.0)	TBD	33.5	13.7	27.4
2020	La Niña (-1.3)	No	3.4	--	26.7
2019	Neutral (0.5)	Yes	0.3	--	25.9
2018	El Niño (0.9)	No	11.6	5.4	26.7
2017	La Niña (-0.8)	No	0.2	--	26.5
2016	La Niña (-0.7)	Yes	--	--	26.9
2015	El Niño (2.6)	Yes	--	--	26.4
2014	El Niño (0.6)	No	0.4	--	26.0
2013	Neutral (-0.2)	No	--	--	26.3
2012	Neutral (0.1)	No	--	--	25.7
2011	La Niña (-1.1)	No	1.3	--	26.3
2010	La Niña (-1.6)	No	25.5	10.8	26.7
2009	El Niño (1.4)	No	--	--	26.0
2008	La Niña (-0.6)	No	18.2	1.2	26.5
2007	La Niña (-1.5)	No	--	--	26.3
2006	El Niño (0.9)	No	--	--	25.6
2005	La Niña (-0.6)	No	2.4	--	26.7
2004	El Niño (0.7)	No	0.3	--	26.3
2003	Neutral (0.4)	No	--	--	25.9
2002	El Niño (1.3)	No	5.4	--	25.8
2001	Neutral (-0.3)	Yes	--	--	26.5
2000	La Niña (-0.7)	No	--	--	26.4
1999	La Niña (-1.5)	No	--	--	25.9
1998	La Niña (-1.5)	No	--	--	26.5
1997	El Niño (2.4)	Yes	--	--	25.6
1996	Neutral (-0.4)	No	--	--	25.7
1995	La Niña (-1.0)	No	--	--	26.5
1994	El Niño (1.0)	No	--	--	26.0
1993	Neutral (0.0)	No	--	--	25.6
1992	Neutral (-0.3)	No	--	--	24.9
1991	El Niño (1.2)	No	--	--	25.7
1990	Neutral (0.4)	No	2.4	--	25.5
1989	Neutral (-0.2)	No	--	--	26.4
1988	La Niña (-1.8)	No	--	--	26.1
1987	El Niño (1.3)	No	--	--	26.3
1986	El Niño (1.1)	No	9.1	--	26.5
1985	Neutral (-0.3)	No	--	--	26.0

Bleaching Outlook for the 2021-2022 summer season on the GBR

The NOAA CRW modelled weekly global Four-Month Coral Bleaching Heat Stress Outlook product has been generating weekly forecasts of bleaching-level heat stress conducive to mass coral bleaching since July 2011 (Eakin et al., 2012; Liu et al., 2018). Using SST forecasts from the NOAA/National Weather Service/National Centers for Environmental Prediction’s Climate Forecast System Version 2 (CFSv2) (Saha et al., 2014), the CRW Outlook product predicts the likelihood of coral bleaching-level heat stress, on subseasonal-to-seasonal scales, up to four months into the future. The CFSv2 is an operational, dynamical, fully coupled ocean-land-atmosphere seasonal climate global forecast model system. CRW’s CFS-based Four-Month Coral Bleaching Outlook is detailed in Eakin et al. (2012) and Liu et al. (2018). Weekly Outlooks generate forecasts of heat stress (HotSpot and DHW) for each of the subsequent 20 weeks at a spatial resolution of 0.5° × 0.5° (approximately 50 km × 50 km). The Outlook product forecasts each 50 km ocean pixel to be in one of five stress level categories, with a corresponding potential bleaching intensity, listed in Table 2. Note that the Outlook system applies a much more complicated algorithm (described in Liu et al., 2018) based on the relationship between CRW’s satellite HotSpots and DHWs as well as modelled HotSpots and DHWs. Forecasts are available in ten pre-set probabilistic levels ranging from 10% to 100% in increments of 10%. Henceforth, when referring to Outlook forecasts, we are referring to the 90% probabilistic Outlook level.

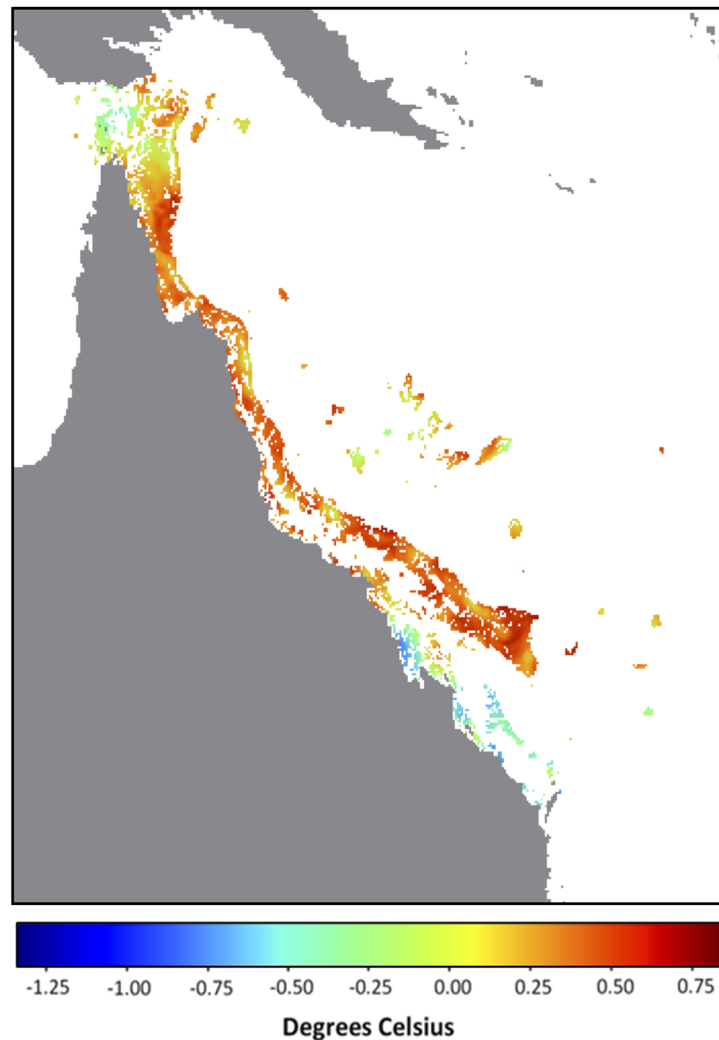


Figure 1. December 2021 Background temperature compared with November – December all-time maximum temperature. Map of Great Barrier Reef 5 km-resolution satellite pixels ($0.05^\circ \times 0.05^\circ$) denoting the difference between the background temperature for 14 December 2021 (minimum SST observed over the previous 29 days, 16 November - 14 December) and the all-time (1985-2020) maximum temperature between 16 November and 14 December. Values indicate difference in degrees Celsius; positive values and warm colours indicate reef pixels in which the 2021 background temperature is higher than the all-time maximum.

On 14 December 2021, NOAA CRW's near real-time satellite monitoring indicated that nearly the entirety of the GBR (98% of all GBR reef pixels) was at Bleaching Watch or higher, with 42% of all GBR reef pixels, including large portions of the far northern GBR, under Bleaching Warning. At a more conservative probability of 90%, Outlook forecasts for 23 January 2022, generated on 21 December 2021, predicted 20% of GBR reef pixels to be at Bleaching Alert Level 1, the majority of these north of Celebration Reef (13.283°S). By 13 February 2022, 45% of GBR reef pixels were predicted to be at Bleaching Alert Level 1 or higher. Bleaching Alert Level 2 conditions were forecast for 14% of the GBR pixels by this date. CRW's Outlook has been forecasting heat stress for the upcoming GBR summer season earlier than ever observed previously; these forecasts are supported by the [Australian Bureau of Meteorology](#) as well as subsequent CRW satellite observations.

GBR bleaching and ENSO state

It is noteworthy that CRW's Outlook has forecast unprecedented heat stress for summer 2021-2022 on the GBR despite the presence of a La Niña. If the Outlook forecasts prove to be accurate, this will be the first mass coral bleaching event on the GBR during a La Niña. Two mass bleaching events on the GBR occurred during El Niño events (1998 and 2016), and three (2002, 2017, and 2020) during 'neutral' phases of the ENSO. The GBR bleaching event of 2017 occurred

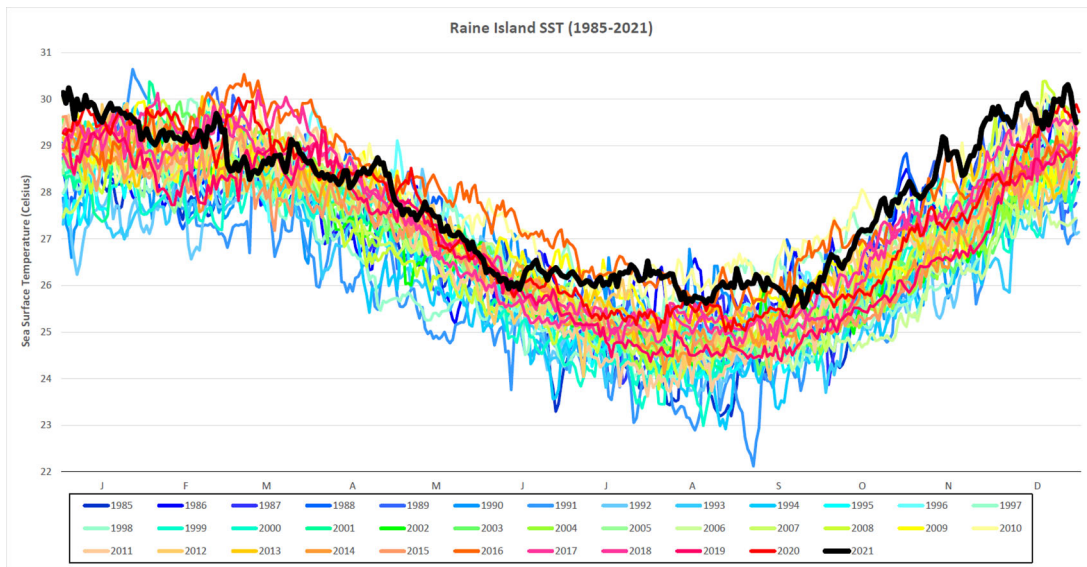


Figure 2. Daily SST for Raine Island from 1985-2021. Daily SST (degrees Celsius) from 1985-2021 for a single 5 km-resolution satellite pixel ($0.05^\circ \times 0.05^\circ$) located in the northern Great Barrier Reef, Raine Island (11.589°S , 144.035°E). SST for 2021 is in black and in bold.

Table 2. Description of Stress Level categories used in Coral Reef Watch’s (CRW) satellite monitoring and modelled Four-Month Coral Bleaching Outlook products. ‘Definition for satellite monitoring’ column details the conditions necessary to meet each Stress Level category. The ‘Potential bleaching intensity’ column details the expected outcome for corals subject to each Stress Level.

Stress Level category	Definition for satellite monitoring	Potential bleaching intensity
No Stress	HotSpot ≤ 0	No bleaching
Bleaching Watch	$0 < \text{HotSpot} < 1$	--
Bleaching Warning	$1 \leq \text{HotSpot}$ and $0 < \text{DHW} < 4$	Possible bleaching
Bleaching Alert Level 1	$1 \leq \text{HotSpot}$ and $4 \leq \text{DHW} < 8$	Significant bleaching likely
Bleaching Alert Level 2	$1 \leq \text{HotSpot}$ and $8 \leq \text{DHW}$	Severe bleaching and significant mortality likely

immediately following a La Niña period, but the ENSO had shifted back to a ‘neutral’ phase before bleaching commenced. Since 1985, there have been 13 La Niña, 13 ‘neutral’ and 11 El Niño states during the January/February/March period according to the Oceanic Niño Index produced by NOAA (NOAA National Weather Service Climate Prediction Center).

The ENSO conditions for 2022 are predicted to remain in a La Niña state throughout at least January by all seven of the major international climate models. Four of these models continue the event into February, and one forecasts the La Niña to last through to April (Australian Bureau of Meteorology; Columbia Climate School International Research Institute for Climate and Society). A La Niña is typically associated with atmospheric instability over the GBR, which is conducive to increased cloud cover, precipitation and higher winds (Braganza, 2008; Chung and Power, 2017). The second most severe early-summer SST conditions observed on the GBR occurred in 2010 (Table 1), as part of the 2010-2011 GBR summer season, which also coincided with a La Niña. However, these warm ocean conditions contributed to northeast Australia experiencing high cloud cover and extreme rainfall (Evans and Boyer-Souchet, 2012; Ummenhofer et al., 2015). This resulted in reduced heat stress on the GBR (Leahy et al., 2013; Zhao et al., 2021), although the resultant flooding contributed to other forms of coral stress (e.g. Jones and Berkelmans, 2014). CRW’s Outlook forecasts account for the effects of La Niña. However, like other seasonal forecasts, the Outlook does not have an ability to predict the development of cyclones or very large storms. As a result, effects of these major storms cannot be included within the Outlook forecasts until they have occurred. This is an important factor to consider since cyclones have been a major mitigating and feedback factor for heat stress on the GBR in the

past. While cyclones could remove some heat from the system, it is unclear whether their impact would be enough to help the GBR avoid another mass bleaching event in early 2022 due to the significant amount of early-summer heat already present on the reef and surrounding seas. As of 21 December 2021, CRW's Outlook predicts bleaching on the GBR to commence by early January and to be widespread along the GBR by 30 January 2022.

Conclusions

The lead-up to the 2021-2022 summer season on the GBR was uniquely warm. The extent and magnitudes of HotSpots and DHWs on GBR satellite reef pixels exceed those observed during this period in any previous year on record (1985-2020). The presence of a La Niña, and more specifically high cloud cover, could provide the GBR with some relief from heat stress (Zhao *et al.*, 2021). Whether that would be enough to avoid bleaching-level heat stress across large sections of the GBR in January/February/March 2022 remains to be seen. For more than 85% of the GBR, the background temperatures (minimum SST over previous 29 days) for 14 December 2021 were higher than the maximum temperatures observed over the same 29-day period for any year since 1985. Therefore, it is likely that the predicted marine heatwave has been largely driven by the long-term shifts in oceanic conditions. Future studies must investigate the oceanic and climatic patterns contributing to the exceptionally warm early-summer conditions in the Coral Sea for late 2021. There is a potential for future summers to get warmer earlier and to stay warmer for longer. If this becomes a trend, it could be detrimental to the health, recovery and survival of corals on the GBR.

Methods

SST data and heat stress metrics (HotSpots, DHWs, and seven-day SST trends) were derived from the daily global 5 km (0.05° × 0.05°) NOAA CRW [Heat Stress Monitoring Product Suite version 3.1 dataset](#). To determine which pixels correspond with coral reefs, a global 5 km reef-pixel dataset was used to overlay the SST and heat stress metric datasets (Heron *et al.*, 2016). All data extraction and analyses were performed in Python version 3.6.9.

The initial occurrence of DHW values greater than 3 and 4 degree C-weeks on the GBR were determined by analysing daily DHWs on GBR reef pixels for each 12-month period, starting on 1 July (Southern Hemisphere winter), within the satellite record (1985-2021). The initial occurrence for each year was defined as the dates that the target DHW values (3 and 4 degree C-weeks) or greater were observed on a GBR reef pixel. The proportion of GBR reef pixels having HotSpot values greater than 0.5 °C and 1.0 °C, as well as with DHW values greater than 2 degree C-weeks was determined for 14 December of each year in the satellite record. The seven-day SST trend of GBR reef pixels for 14 December of each year was also extracted and compared.

We defined the background temperature for a given date as the minimum SST for a pixel over the 29 days prior to and including the given date, which is the period of a full tidal cycle. The background temperature for 14 December (minimum SST from 16 November to 14 December) for each year, 1985-2021, was determined for each GBR reef pixel. The all-time maximum SST from 1985-2020 over the same 29-day period was also determined for each GBR pixel. This was then used to compare background temperatures among years as well as to determine the proportion of GBR pixels in which the background temperature on 14 December 2021 was greater than the maximum SST between 16 November and 14 December for all years from 1985-2020.

Data availability

Sea surface temperature data and heat stress metrics used in this report are available from https://coralreefwatch.noaa.gov/product/5km_v3.1 and are archived at the NOAA National Centers for Environmental Information. Data repositories for the individual metrics used here are listed below.

CoralTemp (Sea Surface Temperature) version 3.1: https://www.star.nesdis.noaa.gov/pub/sod/mecb/crw/data/5km/v3.1_op/nc/v1.0/daily/sst/

HotSpot version 3.1: https://www.star.nesdis.noaa.gov/pub/sod/mecb/crw/data/5km/v3.1_op/nc/v1.0/daily/hs/

Degree Heating Week version 3.1: https://www.star.nesdis.noaa.gov/pub/sod/mecb/crw/data/5km/v3.1_op/nc/v1.0/daily/dhw/

7-day Sea Surface Temperature Trend version 3.1: https://www.star.nesdis.noaa.gov/pub/sod/mecb/crw/data/5km/v3.1_op/nc/v1.0/daily/sst-trend-7d/

Four-Month Coral Bleaching Outlook version 5: <https://www.star.nesdis.noaa.gov/pub/sod/mecb/crw/data/outlook/v5/nc/v1/outlook/>

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The authors characterized the thermal conditions of the GBR using CRW's near real-time satellite-based heat stress products. They described an unprecedented event that hit the historical records in the onset of bleaching conditions and its magnitude.

Taking as a reference the Stress Level categories, used in Coral Reef Watch (CRW), they forecast a mass coral bleaching in the next season. While the description is detailed, the study is limited by focusing only on thermal exposure; NOAA's DHW tends to overpredict events of bleaching.

Considering other factors is becoming necessary because at a regional and local scale there are several factors that could change the predictions and avoid overpredictions (error type I). For example, turbidity can exacerbate (if linked to water quality, e.g., Wooldridge 2020¹) or mitigate the effects (if linked to the reduction of light stress, e.g., Sully and Van Woesik 2020², Gonzalez-Espinosa and Donner 2021³). However, even though there is evidence that the susceptibility of coral communities to mass bleaching from thermal stress is constrained to the local biological and environmental contexts, and multivariate prediction methods that incorporate other environmental variables (e.g., solar radiation, or light attenuation) and other temperature metrics (e.g. heating rate, high-frequency variability, bimodality) have suggested an improvement in predicting the spatial variability in bleaching intensity for individual events (Maina et al., 2008⁴; McClanahan et al., 2019⁵; Safaie et al., 2018⁶; Sully & van Woesik, 2020²), the algorithms used to predict bleaching (as an operational tool) remain focused only on temperature.

Finally, I would be cautious with the assumption that mass bleaching "has only been linked to the stress of excess sea surface temperatures" because even though the elevated temperature is often reported as the primary cause of observed mass coral bleaching, it is the interaction between temperature and other environmental variables that modulate bleaching responses. A quick exploratory analysis of other environmental variables (e.g., description or time series of turbidity, cloudiness, etc) could be included in the discussion.

On the other hand, since this study is focused on describing the thermal exposure using a single

metric approach then it successfully reports the unprecedented conditions in the historical record.

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Is the work clearly and accurately presented and does it cite the current literature?

Partly

Is the study design appropriate and is the work technically sound?

Partly

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?

Partly

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Coral reef ecology, multiple drivers.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 17 May 2022

Blake Spady

We greatly appreciate the time and effort that the reviewer has provided to deliver the valued feedback and suggestions for our manuscript. Please find our response to each comment below.

Comment 1:

The authors characterized the thermal conditions of the GBR using CRW's near real-time satellite-based heat stress products. They described an unprecedented event that hit the historical records in the onset of bleaching conditions and its magnitude.

Taking as a reference the Stress Level categories, used in Coral Reef Watch (CRW), they forecast a mass coral bleaching in the next season. While the description is detailed, the study is limited by focusing only on thermal exposure; NOAA's DHW tends to overpredict events of bleaching.

Response 1:

The present study is a description of unprecedented early-summer sea surface temperature (SST) conditions, and a description of forecast SST conditions. Our aim was to alert managers, scientists, and other stakeholders, who work on the Great Barrier Reef (GBR) to these conditions and forecasts. While a critique of the Degree Heating Week (DHW) algorithm in general may not be unwarranted, this manuscript is not a justification of, or investigation into the DHW algorithm. Here, we focus firstly on the comparison of satellite SST among years from 1985-2021, then look into the heat stress conditions by simply utilising the DHW metric as a tool to describe and compare the observed and forecasted heat stress accumulation on the GBR. For a location with known overprediction by DHW, the comparison of DHW values with previous years is still valid in describing unprecedented SST conditions. This article describes recorded unprecedented early-summer conditions, and alerts readers to the forecast of anomalous heat stress accumulation on the GBR for the 2021-2022 summer season.

Comment 2:

Considering other factors is becoming necessary because at a regional and local scale there are several factors that could change the predictions and avoid overpredictions (error type I). For example, turbidity can exacerbate (if linked to water quality, e.g., Wooldridge 2020¹) or mitigate the effects (if linked to the reduction of light stress, e.g., Sully and Van Woosik 2020², Gonzalez-Espinosa and Donner 2021³). However, even though there is evidence that the susceptibility of coral communities to mass bleaching from thermal stress is constrained to the local biological and environmental contexts, and multivariate prediction methods that incorporate other environmental variables (e.g., solar radiation, or light attenuation) and other temperature metrics (e.g. heating rate, high-frequency variability, bimodality) have suggested an improvement in predicting the spatial variability in bleaching intensity for individual events (Maina et al., 2008⁴; McClanahan et al., 2019⁵; Safaie et al., 2018⁶; Sully & van Woosik, 2020²), the algorithms used to predict bleaching (as an operational tool) remain focused only on temperature.

Response 2:

While several factors can be responsible for coral bleaching at regional and local scales, there is a strong relationship between large-scale bleaching (i.e. mass coral bleaching) and

thermal stress accumulation. The focus of this study is strictly on the description of large-scale accumulated heat stress, leading to mass coral bleaching, not on small-scale or local bleaching events.

In this study, we found that the NOAA Coral Reef Watch (CRW) Four-Month Coral Bleaching Heat Stress Outlook product had forecast heat stress accumulation for 45% of the 5,274 GBR pixels (0.05 x 0.05 degrees) to match or exceed that which has been demonstrated to result in mass bleaching events on the GBR in the past (since 1985). We therefore found it appropriate to alert managers, scientists and other stakeholders working on the GBR that these thermal conditions were forecasted, and that if the forecast conditions were correct, there would be a high probability of a mass bleaching event taking place in these areas. The CRW Outlook product forecast described in this manuscript provides a likelihood of thermal stress accumulation levels, categorized in relation to potential bleaching.

As you mention, the algorithms currently available to predict mass coral bleaching remain focused only on temperature. The aim of this study was not to improve upon those algorithms, nor to create a new predictive tool. Our goal was to provide a timely report of the unprecedented early-summer SST conditions as well as a warning of SST conditions forecast for the GBR, in the context of a potential mass bleaching event. However, it is worth highlighting that the 2021-2022 summer season has since passed, and CRW's 21 December 2021 forecast of accumulated heat stress levels has been confirmed by subsequent near real-time satellite SST data to be largely accurate. Further, the effects of this heat stress have been confirmed, via aerial and in-water surveys, to have resulted in a mass coral bleaching event that encompassed the far northern and central GBR.

Comment 3:

Finally, I would be cautious with the assumption that mass bleaching "has only been linked to the stress of excess sea surface temperatures" because even though the elevated temperature is often reported as the primary cause of observed mass coral bleaching, it is the interaction between temperature and other environmental variables that modulate bleaching responses. A quick exploratory analysis of other environmental variables (e.g., description or time series of turbidity, cloudiness, etc) could be included in the discussion.

On the other hand, since this study is focused on describing the thermal exposure using a single metric approach then it successfully reports the unprecedented conditions in the historical record.

Response 3:

Thank you for this comment. We agree that the quoted statement could have been more carefully phrased. We have edited this section of the text to now read:

"Mass coral bleaching (large-scale bleaching of an entire reef system or geographic realm) has, with few exceptions, always been linked to the stress of excess sea surface temperatures (SST), and this is expected to happen when heat stress in a region exceeds a certain intensity or duration (Glynn, 1984; Hoegh-Guldberg, 1999; Skirving *et al.*, 2019)."

We appreciate your suggestion of an exploratory analysis of other environmental variables

influencing coral bleaching, however, this is beyond the scope of our study. This study, as you acknowledge, is focused on describing a single metric (thermal stress accumulation) in relation to the GBR for the 2021-2022 summer season.

Competing Interests: No competing interests were disclosed.

Reviewer Report 14 April 2022

<https://doi.org/10.5256/f1000research.120142.r129136>

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Timothy R. McClanahan 

Global Marine Programs, Wildlife Conservation Society, Bronx, NY, USA

Coral bleaching is a biological response poorly predicted by excess heat

The paper describes the excess temperature or Degree-heating Weeks (DHW) in the Great Barrier Reef (GBR) up to December 2021. They show that excess heat is above historical records, which is increasingly becoming a common report as climate change warms the oceans. The authors predict a mass bleaching in subsequent months. The paper is descriptive and uses NOAA predictions based on thresholds that have not been modified since established in 2012, despite a literature providing ways to improve the algorithms (van Hooijdonk et al. 2013; DeCarlo 2020). NOAA provides these predictions on a global basis and here they present it for the GBR during an unusual ocean state, or La Nina year.

Coral bleaching is a biological response and therefore there are several problems with using global algorithmic predictions based on thermal exposure alone. Corals constitute many species and associated life histories that have evolved in different thermal and stress environments. Responses to excess heat is complex and seems to be changing over time and greatly influenced by geography and other environmental factors (Sully et al. 2020; McClanahan et al. 2019, 2020a,b). Therefore, the DHW for predicting bleaching has high variance and low skill or predictive ability (van Hooijdonk and Huber 2009; DeCarlo 2020). Therefore, many studies in this same region find various responses and not high bleaching when thresholds have been passed (Kim et al. 2019; DeCarlo and Harrison 2020). Other examples are that an early peak temperature can prompt an acclimation response that can prevent or reduce bleaching (Ainsworth et al. 2016). Bleaching is typically a late-summer response, and an early peak is not always an indicator of late-season bleaching. Other studies show that other forces like light and nutrients can modify the response. Some differences have been attributed to cloudiness and light, which may have been more important modifier than is broadly recognized in the past events (McGowan and Theobald 2017). Other studies in this region suggest that high nutrients due to ocean currents and upwelling will increase bleaching responses (DeCarlo et al. 2019). Finally, GBR corals are displaying decreasing sensitivity to thermal stress, which is likely to result in more false positives in prediction looking

into the future (Hughes et al. 2019).

In short, there are many unknowns surrounding the coral bleaching phenomenon, which makes it quite difficult to predict bleaching even from early summer warming. Even some of the best studies of predictive skill suggest the highest values rarely exceed 35% for DHW due to both many false negatives and positives (Logan et al. 2012). Moreover, the number of false alarms appears to be increasing since 2000, which is likely due to the original algorithm weakening as corals change and adapt to thermal exposures (DeCarlo 2020). When predicting bleaching for such a large area as the GBR, the skill increases, but this is not surprising and tells us less about bleaching reoccurrence, but rather that there is high spatial variability likely to capture bleaching as the area of prediction increases. The frequency of bleaching at constant spatial cell sizes is not increasing over time (Skirving et al. 2019). The frequency may appear to be increasing if increasing numbers of observers are recording bleaching in large areas, such as national boundaries (Hughes et al. 2018). In sum, there is no discrete or generic global threshold for coral bleaching or mortality but rather high spatial and changing variability. The duration and spatial extent of bleaching is what is increasing and likely leading to more phenomena known as heat waves (Skirving et al. 2019).

This Coral Reef Watch excess heat has global coverage that would encompass many areas influenced by the La Nina, not just the GBR. The key issue that needs to be addressed is the excess heat on western ocean boundaries during a protracted inter-annual La Nina. How has the whole Pacific responded and where is the excess heat in this year relative to other La Nina years? I see this large-scale geography as the important aspect of this period in terms of novel responses and predictions. Are there some other processes influencing this La Nina relative to the previous years? This sort of detective work would be highly appreciated and continue to add to the context and nuances around climate change and inter-annual ocean oscillations.

The authors need to place their work in the context of the findings and ocean states above. The current version lacks the context and nuance demanded by a critical reading of the scientific literature on bleaching. Catastrophic framing should be avoided, especially without acknowledging the full context or other possible factors or interpretations. The science of bleaching has moved on considerably since some of these early warning DHW algorithms were developed (DeCarlo 2020). The algorithms need to change to accommodate this increase in knowledge and to include other variables that are available from satellite data (Gonzalez-Espinosa and Donner 2021; McClanahan and Azali 2021).

In short, this is a report about excess temperature and not the biological response of corals. Coral bleaching is as much about coral sensitivity as it is about excess heat, and this requires more than satellite data to evaluate.

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Is the work clearly and accurately presented and does it cite the current literature?

No

Is the study design appropriate and is the work technically sound?

Partly

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?

No

Are all the source data underlying the results available to ensure full reproducibility?

Partly

Are the conclusions drawn adequately supported by the results?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Coral reef ecology

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 17 May 2022

Blake Spady

We would like to express our gratitude for the valuable and thoughtful feedback provided by the reviewer. Please find our response to each comment below.

Comment 1:

Coral bleaching is a biological response poorly predicted by excess heat

The paper describes the excess temperature or Degree-heating Weeks (DHW) in the Great Barrier Reef (GBR) up to December 2021. They show that excess heat is above historical records, which is increasingly becoming a common report as climate change warms the oceans. The authors predict a mass bleaching in subsequent months. The paper is descriptive and uses NOAA predictions based on thresholds that have not been modified since established in 2012, despite a literature providing ways to improve the algorithms (van Hooijdonk et al. 2013; DeCarlo 2020). NOAA provides these predictions on a global basis and here they present it for the GBR during an unusual ocean state, or La Nina year.

Response 1:

It is correct that coral bleaching is a biological response, and several factors aside from thermal exposure can be responsible for this process. However, in this paper we are focusing only on mass coral bleaching events, which have a much stronger relationship to thermal stress than bleaching more generally. Your statement that this paper is descriptive is exactly correct; the purpose of this paper was to describe the unprecedented early-summer anomalous sea surface temperature (SST) conditions on the Great Barrier Reef (GBR). Further, we sought to alert managers and scientists on the GBR to these conditions as well as to the forecasted SST conditions for the remainder of the summer season. While it is valid to critique the Degree Heating Week (DHW) algorithm in general, this paper is not a justification of, or investigation into that algorithm. The DHW algorithm utilised in this paper is a widely used tool which quantifies SST heat accumulation over time. Here, we simply use that metric to describe the conditions observed and those forecasted for the remainder of the season. It may also be worth noting that the forecast made on 21 December 2021 of bleaching-level heat stress described within this paper has since been supported by subsequent measurements and observations. The levels of heat stress

accumulation predicted through to 13 February 2022 has been confirmed to be largely accurate by the near real-time satellite data. Further, the connection of this heat stress accumulation to an outbreak of mass bleaching has been supported by subsequent field observations. In March 2022, large sections of the far northern GBR and central GBR, the same general areas described here, were observed and described by several third-party sources to have undergone a significant mass bleaching event.

Comment 2:

Coral bleaching is a biological response and therefore there are several problems with using global algorithmic predictions based on thermal exposure alone. Corals constitute many species and associated life histories that have evolved in different thermal and stress environments. Responses to excess heat is complex and seems to be changing over time and greatly influenced by geography and other environmental factors (Sully et al. 2020; McClanahan et al. 2019, 2020a,b). Therefore, the DHW for predicting bleaching has high variance and low skill or predictive ability (van Hooijdonk and Huber 2009; DeCarlo 2020). Therefore, many studies in this same region find various responses and not high bleaching when thresholds have been passed (Kim et al. 2019; DeCarlo and Harrison 2020). Other examples are that an early peak temperature can prompt an acclimation response that can prevent or reduce bleaching (Ainsworth et al. 2016). Bleaching is typically a late-summer response, and an early peak is not always an indicator of late-season bleaching. Other studies show that other forces like light and nutrients can modify the response. Some differences have been attributed to cloudiness and light, which may have been more important modifier than is broadly recognized in the past events (McGowan and Theobald 2017). Other studies in this region suggest that high nutrients due to ocean currents and upwelling will increase bleaching responses (DeCarlo et al. 2019). Finally, GBR corals are displaying decreasing sensitivity to thermal stress, which is likely to result in more false positives in prediction looking into the future (Hughes et al. 2019).

Response 2:

We concede that the biological response of coral bleaching is a complicated multi-variate process and we don't claim here that the DHW algorithm alone has the capacity to predict bleaching in all forms, uniformly across all regions, or equally effectively at all spatial scales. However, at large scales (i.e. mass bleaching events), the DHW algorithm used here has been effective at demonstrating a strong correlation between heat-stress accumulation and significant coral bleaching. Considering that correlation, the aim of this paper was again to alert scientists and managers to an unprecedented thermal anomaly observed in the early-summer 2021-2022 on the GBR, and to raise awareness of the potential of a large-scale bleaching event. We agree with your statement of "*Bleaching is typically a late-summer response, and an early peak is not always an indicator of late-season bleaching.*" It is for that reason that we found it necessary to highlight this event as it was unfolding. At the time of writing this paper we had seen an unprecedented build-up of thermal stress on the GBR, and the forecast at the time did not indicate that this was an early peak, but that heat accumulation would continue to build through January and into February. It was also found that the forecasted sum of this accumulated heat was that which has been shown to result in mass bleaching events on the GBR in the past. While the field observations of mass coral bleaching along the northern half of the GBR in March 2022 cannot confirm that bleaching had occurred prior to February 2022, the data we had in mid-December 2021 indicated that this would be a possibility. Therefore, we sought to alert those working specifically on the

GBR of this potential.

Comment 3:

In short, there are many unknowns surrounding the coral bleaching phenomenon, which makes it quite difficult to predict bleaching even from early summer warming. Even some of the best studies of predictive skill suggest the highest values rarely exceed 35% for DHW due to both many false negatives and positives (Logan et al. 2012). Moreover, the number of false alarms appears to be increasing since 2000, which is likely due to the original algorithm weakening as corals change and adapt to thermal exposures (DeCarlo 2020). When predicting bleaching for such a large area as the GBR, the skill increases, but this is not surprising and tells us less about bleaching reoccurrence, but rather that there is high spatial variability likely to capture bleaching as the area of prediction increases. The frequency of bleaching at constant spatial cell sizes is not increasing over time (Skirving et al. 2019). The frequency may appear to be increasing if increasing numbers of observers are recording bleaching in large areas, such as national boundaries (Hughes et al. 2018). In sum, there is no discrete or generic global threshold for coral bleaching or mortality but rather high spatial and changing variability. The duration and spatial extent of bleaching is what is increasing and likely leading to more phenomena known as heat waves (Skirving et al. 2019).

Response 3:

We must stress that the predictions made within this paper were more specifically of the Alert Levels detailed in **Table 2**, which are categorisations of thermal stress related to potential bleaching. Further, we stress that the early-summer heat stress detailed is not what we used to predict this accumulated heat stress. The predictions of heat stress made in this paper were derived from the NOAA Coral Reef Watch modelled weekly global Four-Month Coral Bleaching Heat Stress Outlook product (CRW Outlook product). The CRW Outlook product uses SST forecasts generated by the NOAA/National Weather Service/National Centers for Environmental Prediction's Climate Forecast System Version 2 (CFSv2) to generate weekly predictions of the likelihood of heat stress within the Alert Levels (referenced above) up to 20 weeks into the future. The intent of this paper was not to use the early-summer heat stress as a predictive indicator of conditions over the following months, but to describe both the unprecedented early-summer conditions as well as to describe the forecast of accumulated heat stress for the upcoming summer months. As you mention here, and as we allude to in our response to **Comment 2**, the predictive skill of the DHW algorithm increases at larger spatial scales. For that reason, we find the use of the DHW algorithm justified and appropriate in this context. The forecast of accumulated heat stress described here covered 45% of the 5,274 GBR pixels (0.05 x 0.05 degrees), or approximately 59,332 km². This gave us relatively high confidence that, if the forecast was correct, significant portions of this large area would experience heat stress related bleaching. We fully agree that there is no discrete or generic global threshold for coral bleaching, however, we also know that thermal stress is almost always related to mass coral bleaching and that once a certain level of thermal stress is exceeded, a bleaching event is likely.

Comment 4:

This Coral Reef Watch excess heat has global coverage that would encompass many areas influenced by the La Nina, not just the GBR. The key issue that needs to be addressed is the excess

heat on western ocean boundaries during a protracted inter-annual La Nina. How has the whole Pacific responded and where is the excess heat in this year relative to other La Nina years? I see this large-scale geography as the important aspect of this period in terms of novel responses and predictions. Are there some other processes influencing this La Nina relative to the previous years? This sort of detective work would be highly appreciated and continue to add to the context and nuances around climate change and inter-annual ocean oscillations.

Response 4:

Thank you for this comment. We agree that this is indeed a key issue and an interesting academic pursuit. The scope of this paper, as you mention in **Comment 1**, is descriptive in nature. Our aim here was to inform managers and scientists who work on the GBR of the facts revealed by the data, and not to investigate the precise causes and effects of these observations. We encourage readers of this manuscript to pursue the answers to these questions, as it is beyond the scope of this study.

Comment 5:

The authors need to place their work in the context of the findings and ocean states above. The current version lacks the context and nuance demanded by a critical reading of the scientific literature on bleaching. Catastrophic framing should be avoided, especially without acknowledging the full context or other possible factors or interpretations. The science of bleaching has moved on considerably since some of these early warning DHW algorithms were developed (DeCarlo 2020). The algorithms need to change to accommodate this increase in knowledge and to include other variables that are available from satellite data (Gonzalez-Espinosa and Donner 2021; McClanahan and Azali 2021).

In short, this is a report about excess temperature and not the biological response of corals. Coral bleaching is as much about coral sensitivity as it is about excess heat, and this requires more than satellite data to evaluate.

Response 5:

Thank you. As mentioned in our response to **Comment 4**, this paper is purely descriptive. Therefore, it is beyond the scope of this study to relate the findings from the thermal event described here to the ocean conditions and ocean states elsewhere in the Pacific. We do agree that catastrophic framing should be avoided. However, we do not feel that our framing of the predictions of bleaching-level heat stress is "catastrophic". We make no predictions or mention of subsequent coral mortality, recovery, or of the ecological impacts of the predicted potential bleaching event. Further, we must reiterate that while we framed our predictions as being "potential" within the paper, it is important to note that the 2021-2022 summer season on the GBR has since passed and our predictions have been confirmed to be largely accurate based on both satellite data and in-water and aerial surveys of the GBR. Precisely how accurate these predictions were cannot yet be determined, but it is clear that a mass coral bleaching event took place in the 2021-2022 summer season within the areas that we forecasted bleaching-level heat stress on 21 December 2021. We can appreciate your critiques of the DHW algorithm, but we must also stress that this paper is not an investigation into, nor a justification of that algorithm. This paper was only ever intended to be a timely report of excess SST on the GBR, as well as a modelled outlook of forecasted SST conditions in the context of coral stress. As such we

merely use the DHW algorithm as a tool to describe these conditions and compare historical conditions among years.

Competing Interests: No competing interests were disclosed.

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