Inconsistent coral bleaching risk indicators between temperature data sources

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Key Points:

- Temperature data sources did not provide consistent risk indicators for coral bleaching
- Across five reefs, coral bleaching risk indicators differed in their ability to predict the observed coral bleaching events
- Temperature data in daily and monthly temporal resolutions differed in the accuracy of coral bleaching risk indicators

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

J. M. Maina,
joseph.mbui@mq.edu.au

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Author Contributions:

Conceptualization: V. H. F. Neo, J. Zinke, T. Fung, C. J. Merchant, J. M. Maina
Data curation: V. H. F. Neo, J. Zinke, K. J. A. Zawada, H. Krawczyk, J. M. Maina
Formal analysis: V. H. F. Neo, J. Zinke, T. Fung
Investigation: V. H. F. Neo
Methodology: V. H. F. Neo, J. Zinke, T. Fung, C. J. Merchant, J. M. Maina

Inconsistent Coral Bleaching Risk Indicators Between Temperature Data Sources

V. H. F. Neo[1], J. Zinke[2,3,4], T. Fung[5], C. J. Merchant[6,7], K. J. A. Zawada[8], H. Krawczyk[2], and J. M. Maina[1]

[1]School of Natural Sciences, Macquarie University, Sydney, NSW, Australia, [2]School of Geography, Geology and the Environment, University of Leicester, Leicester, UK, [3]Molecular and Life Sciences, Curtin University, Bentley, WA, Australia, [4]Australian Institute of Marine Science, Townsville, QLD, Australia, [5]School of Mathematical & Physical Sciences, Macquarie University, Sydney, NSW, Australia, [6]Department of Meteorology, University of Reading, Reading, UK, [7]National Centre for Earth Observation, University of Reading, Reading, UK, [8]Centre for Compassionate Conservation, TD School, University of Technology Sydney, Sydney, NSW, Australia

Abstract Coral reefs are facing severe threats and are at risk of accelerated decline due to climate change-induced changes in their environment. Ongoing efforts to understand the mechanisms of coral response to warming rely on multiple sources of temperature data. Yet, it remains uncertain whether the Sea Surface Temperature (SST) data used for coral reef studies are consistent among different data products, despite potential implications for conservation. A better understanding of the consistency among the different SST data applied to coral reefs may facilitate the fusion of data into a standard product. This will improve monitoring and understanding of the impact of global warming on coral reefs. Four types of SST data across North-Western and South-Western Australia are compared to assess their differences and ability to observe high thermal stress during historical coral bleaching events. The four SST data sources included those derived from Global Circulation Models, NOAA CoralTemp SST product, ESA CCI SST product, and coral core derived SST. Coral bleaching risk indicators, Degree Heating Week (DHW), and Degree Heating Month (DHM) were calculated using these sources and compared for consistency. DHW and DHM were inconsistent among data sets and did not accurately reflect high thermal stress metrics during moderate and severe bleaching events. Some reefs did not experience bleaching in spite of high DHWs and DHMs, suggesting a mismatch in data scales, or perhaps other oceanographic factors and coral adaptation. By exploring the differences and similarities among these four data sources, this study highlights the need to compare existing indicators of thermal stress from different data sets.

Plain Language Summary Climate change and warming have resulted in global coral bleaching events, severely compromising our environment's health. Monitoring the changes in ocean temperatures around them is essential to maximizing our efforts to protect them. Different ocean temperature data products exist and are being used without understanding their differences. To highlight these differences, the present study compares historical warming from climate models and remote and in situ sensors and known bleaching events on five reefs across Western Australia.

1. Introduction

Climate-driven ocean warming has significantly impacted coral reefs since 1979, when the first large-scale bleaching was reported (Barton & Casey, 2005). As ocean temperatures increase beyond tolerant thresholds for corals' endosymbiotic zooxanthellae, corals are forced to expel them and consequently lose the nutrients they require, which may lead to coral bleaching and death (Ainsworth & Brown, 2021). Extensive research efforts geared toward understanding the mechanisms of coral bleaching, human intervention strategies, and the natural adaptive capacity of coral reefs have not prevented an increase in the frequency and intensity of coral bleaching over the last decade (Fox et al., 2021; Sully et al., 2019). The increasing frequency and intensity of marine heatwaves have caused new bleaching occurrences in reefs with no previous reported bleaching (Fox et al., 2021; Hughes et al., 2017; McClanahan et al., 2019). However, the resilience and adaptation of corals are also highly dynamic and complex, with a higher thermal tolerance at low latitudes and a higher rate of bleaching events in subtropical regions, despite the higher absolute temperatures in the tropics (McClanahan et al., 2020; Sully et al., 2019). There are gaps in our understanding of coral response to increasing temperatures and current practices for

Supervision: J. Zinke, J. M. Maina
Visualization: V. H. F. Neo, T. Fung
Writing – original draft: V. H. F. Neo, J. Zinke
Writing – review & editing: V. H. F. Neo, J. Zinke, T. Fung, C. J. Merchant, J. M. Maina

monitoring and thermal stress metrics for bleaching risks. For example, coral bleaching risk is mapped using thermal stress indicators derived from existing SST monitoring platforms. However, a lack of comprehension of inherent characteristics among different data sources could lead to inconsistent coral bleaching risks reported (Darling et al., 2019; McClanahan et al., 2020; Sully et al., 2019). Hence, a clearer understanding of how thermal stress metrics vary between data sources is required to narrow these uncertainties between data sources.

Many anthropogenic and climate change-related oceanographic impacts, such as cyclones, solar insolation, and rising sea surface temperatures (SSTs), cause disturbances to corals and their endosymbiotic algae (Ainsworth & Brown, 2021; Darling et al., 2019; Hughes et al., 2017; Lough et al., 2018; McClanahan et al., 2020). In spite of natural cycles of warming and cooling in the past, SST anomalies have been widely linked and considered the most important cause of coral bleaching events in the last few decades (Gilmour et al., 2021; Safaie et al., 2018). Coral reefs have thrived in warmer climates, such as during the Eocene period, where SST was much higher than current and forecasted ocean temperatures for 2100 (Bijl et al., 2010; Descombes et al., 2015; Hollis et al., 2009). Hence, coral bleaching in recent years is attributed to the increased frequency and intensity of SST anomalies compared to the climatological conditions suitable for modern corals. Bleaching events result in subsequent species selection of more stress-tolerant phenotypes such as the massive, boulder-shaped corals (e.g., *Porites and Favia spp*.) that bleach at higher temperatures than the branching corals (e.g., *Acropora spp*) with lower thermal resilience, thus increasing thermal thresholds of coral ecosystems and modifying the diversity of coral communities (Clarke et al., 2017; Gilmour et al., 2021; Kubicek et al., 2019; McClanahan et al., 2020; Sully et al., 2019). A differential survival rate of corals has been observed during recent extreme heat events, such as the major El Niño associated events in 2002/2003, 2009/2010, and 2015/2016, compared to historical ones, suggesting that selective mortality through successive heatwaves might help shape coral community responses to future warming (Fox et al., 2021). Nonetheless, recent studies report alarming rates of global coral bleaching events (Hughes et al., 2018). As the frequency and history of thermal anomalies and wider diurnal temperature ranges have been linked to attenuating the severity of bleaching events, it is crucial to understand both site-level historical thermal stress and temperature patterns (Gilmour et al., 2021; Sully et al., 2019).

SST can be observed in a variety of ways, each with different precision, accuracy, spatial, and temporal characteristics. Changes over time can be recorded using remote sensing, data loggers, coral core geochemical proxies, or general circulation models (GCMs; AIMS, 2017; Eyring et al., 2016; Minnett et al., 2019; Zinke et al., 2018). Satellite SST products are based on measurements of the thermal emission from the Earth's oceans and atmosphere by radiometers, which undergo an inverse process to infer the SST, after which they may be spatially gridded for convenience (Anding & Kauth, 1970; Merchant & Embury, 2014; Minnett et al., 2019). Using a series of real-time and reprocessed night-only Geo-Polar satellites, the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch (CRW) project generated one of the most commonly used SST products for monitoring coral bleaching risks (Eakin et al., 2010; Liu et al., 2013; Maturi et al., 2017; Robert-Jones et al., 2012). CRW uses a common indicator of coral reef thermal stress, Degree Heating Weeks (DHWs; Eakin et al., 2010), which are derived from daily CoralTemp SST data processed to a ∼5 km grid, where the feature resolution of analyses may be coarser (Reynolds et al., 2013). Another indicator of coral reef thermal stress used by coral reef scientists where daily SST data is unavailable, Degree Heating Months (DHMs), is derived from monthly SST data (Barton & Casey, 2005). The European Space Agency's (ESA) Climate Change Initiative (CCI) SST analysis combines satellite data from Advanced Very High-Resolution Radiometers (AVHRRs) and Along Track Scanning Radiometers (ATSRs) to create a daily gap-filled SST at ∼5 km spatial grid (Merchant et al., 2019). The CCI analysis provides an estimate at 20 cm depth based on adjusting skin SST measurements to this standardized depth and at a standardized time of day to improve observational stability. Thus, CoralTemp and CCI analyses have similar underlying observations and matching spatial and temporal gridding but are processed using different algorithms (Merchant et al., 2019; Minnett et al., 2019). The differences in methods and objectives between different satellite products imply that thermal stress indicators and associated bleaching risks will differ (Merchant et al., 2019).

Since corals sense changes in their surrounding environment during their multi-decadal to century long growth, measured values of the coral's skeletal geochemical composition (e.g., Sr/Ca, Li/Mg) have been shown to reliably record SST variations (e.g., D'Olivo et al., 2018; Sayani et al., 2019; Thompson, 2021). Coral palaeoclimatologists have developed a number of geochemical proxies for SST that can be used to quantitatively convert the proxy signal to historical ocean temperatures in their immediate surroundings by means of regression (e.g., D'Olivo et al., 2018; Pfeiffer et al., 2009; Sayani et al., 2019). The Strontium to Calcium ratio (Sr/Ca)-derived temperature has emerged as the most robust of the SST sensitive proxies in coral core studies (e.g., Pfeiffer et al., 2009; Sayani et al., 2019; Zinke et al., 2018). Coral Sr/Ca-derived SST is relatively less affected by atmospheric conditions at the immediate sea surface and spatial interpolation as in remote sensing data measured from space (Clarke et al., 2019). Furthermore, because the temperature proxies are recorded at depths relevant to corals, they do not suffer from depth mismatch uncertainties. Reconstructing temperatures from the past decades using these proxies can provide tremendous insights into past climate variability and historical temperatures (Lauchstedt et al., 2017; Zinke et al., 2018). While techniques for extracting paleoclimatic temperature data from coral core geochemical proxies can reconstruct SST at high temporal resolution, the spatial detail is limited to the core location (Lauchstedt et al., 2017; Zinke et al., 2018, 2015, 2014). Apart from in situ geochemical data from coral proxies, data loggers on moorings, floats (drifting buoys and Argo), and gliders can provide in situ temperature measurements directly from their environment (AIMS, 2017; ARGO, 2020; Bailey et al., 2019). Data loggers can be useful for daily measurements but are representative only of much smaller areas than satellite data. Despite the relatively low spatial resolution of approximately 50–100 km, several times higher than a reef-scale, GCMs hind-forecast SST and account for future greenhouse gas emissions and other factors affecting climate change and rates of ocean warming. Historical SST data are also available long-term from periods prior to satellite and data logger coverage, yet at even larger spatial scales. The different strengths and weaknesses of alternative sources of SST data make comparing SST data sets an essential component of improving the monitoring and projections of SST warming using SST-derived indicators of thermal stress.

Rarely are the inherent strength and limitations of the different SST data sources acknowledged in the applications of SST products. Inconsistencies in bleaching risks reported are to be expected due to different data acquisition and processing methods in SST products (Yang et al., 2021). A better understanding of the consistency of the thermal stress metrics derived from the different temperature data sources is necessary. First, we compare consistency via the common indicators of thermal stress derived from four different data sources: NOAA CoralTemp and CCI satellite products, coral core-derived SST proxy (Sr/Ca), and the Australian Community Climate and Earth-System Simulator (ACCESS) GCM. We compare the values of each derived common indicator of thermal stress with known values associated with coral bleaching between the four data sets, focusing on North-Western and South-Western Australia. Since the late 1990s, there have been fewer reports of severe bleaching in temperate high-latitude coral reefs in Australia than in tropical to sub-tropical low to mid-latitude reefs (Abdo et al., 2012; Babcock et al., 2021). Thus, the coast of North-Western and South-Western Australia are ideal case studies as their coral reefs have different thermal histories and susceptibility to warming.

2. Materials and Methods

2.1. Study Area

Nineteen sites on five reefs in North-Western to South-Western Australia were selected based on the availability of temperature data from satellite products and coral derived proxies (Figure 1; Table S1 in Supporting Information S1). Sites at Cocos Keeling Island are in the northernmost part of the island at an average depth of 5.4 m, with a high coral cover and two species of endemic corals (Brewer et al., 2009; Hennekam et al., 2018). Browse Island and Scott Reef are in low latitudes and less than 1° apart in latitude off the Kimberley coast in the southeast Indian Ocean (Bessey et al., 2020; van Oppen et al., 2011). Shallow platform reefs surround Browse Island with coral cover in intertidal benthic slopes and upper reef slopes below 10 m. It lies within the 200 m isobath off the Kimberley coast (Bessey et al., 2020). Scott Reef system can be categorized into three atolls and has more than 300 species of corals (Gilmour et al., 2013; Green et al., 2019; van Oppen et al., 2011). During the 1998 marine heatwave in Scott Reef, less resilient corals such as *Acroporidae* at depths of less than 20 m encountered mortality (Gilmour et al., 2013). Despite the catastrophic bleaching event, with almost 70%–90% of corals bleached, coral recovery was quick and returned to its pre-bleaching state within 12 yr due to subsequent recruitment and high rates of survival (83%–93% annually) of branching (*Acropora*) and massive (*Goniastrea*) coral larvae (Gilmour et al., 2013). Shortly after recovery, the 2015 and 2016 marine heatwaves caused more than 60% of coral cover in Scott Reef to bleach severely again (Green et al., 2019).

Ningaloo Reef sites and southernmost high latitude coral reefs in Houtman Abrolhos Islands (Sites HAB05B and HAB10A) are located at an average depth of 3.3, 3.5, and 8.5 m, respectively (Clarke et al., 2017; Zinke et al., 2015, 2014). During the marine heatwaves from 2010 to 2011, the first known severe coral bleaching and mortality were reported in these two reefs, albeit to different extents within different parts of the reef (Abdo et al., 2012; Babcock et al., 2021; Markey et al., 2016). Following the bleaching event caused by temperatures of 4.2°C above mean maximum daily temperatures, coral mortality in the Houtman Abrolhos was more than 50%, and recovery was consequently affected by the limited connectivity of the isolated island (Abdo et al., 2012).

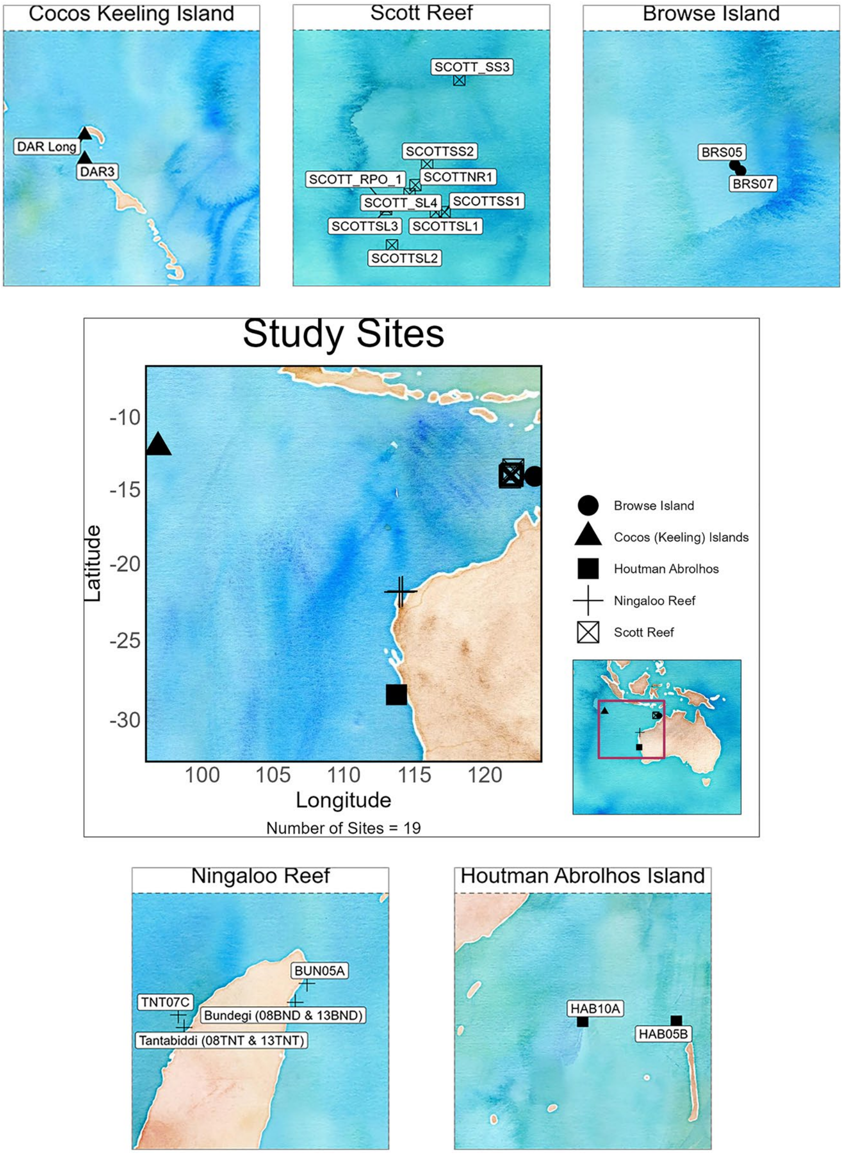

Figure 1. Study Sites along the North-Western and South-Western coasts of Australia. Sites are shaped according to the reef. The total number of sites is 19. The individual sites and coordinates are in Table S1 in Supporting Information S1 (Kahle & Wickham, 2023; R Core Team, 2021; core coordinates and sources summarized in Table S1 in Supporting Information S1).

2.2. Satellite-Derived SST Products

SST data is based on four decades of measurements from radiometers on multiple satellites that have been synthesized into convenient products. Daily gap-filled SSTs from ESA CCI were downloaded from the open-source platform (http://surftemp.net/timeseries/index.html) for each site coordinate (Merchant & Embury, 2020, Merchant et al., 2019; Table S1 in Supporting Information S1). The CCI SST analysis is based on the series of single-view sensor AVHRRs and the dual-view ATSRs (Merchant et al., 2019). The product covers the years 1981–2020 and is gridded daily at a spatial resolution of 0.05° (~5 km) (Merchant et al., 2019). SST daily time series data were extracted for each site from NOAA CoralTemp SST Version 3.1 product (Table S1 in Supporting Information S1). NOAA CoralTemp Version 3.1 Level 4 SST product is a daily gap-filled SST product based on a series of night-only real-time Geo-Polar satellites, reprocessed and gridded to a spatial resolution of 5 km (Maturi et al., 2017; Roberts-Jones et al., 2012). The CCI and NOAA CoralTemp products differ in SST retrieval methods and algorithms and in radiance measurements from the single-view AVHRR and dual-view ATSR sensors. Satellites' here refer to both, otherwise referred to as NOAA CoralTemp or CCI throughout the manuscript.

2.3. Reconstruction of SST From Coral Core Sr/Ca Ratios

Coral core derived Sr/Ca and oxygen isotope proxies are available from previous studies involving coral core geochemical proxy extraction (Clarke et al., 2017; Hennekam et al., 2018; Zinke et al., 2015, 2014). In these studies, coral cores were collected from multiple study sites located within four of the five reefs in Western Australia, namely Cocos Keeling Islands, Browse Island, Ningaloo Reef, and Houtman Abrolhos Islands (Clarke et al., 2017; Hennekam et al., 2018; Zinke et al., 2015, 2014; Figure 1; Tables S1 and S2 in Supporting Information S1). We used the Sr/Ca ratio in the skeletal carbonate of corals as a proxy for SST (Zinke et al., 2015). Due to the possible confounding effect of salinity on isotope incorporation (Dee et al., 2015), oxygen isotope ratios were not used as proxies in this study. Coral core Sr/Ca data were available for all sites except for the nine sites in Scott Reef (Table S3 in Supporting Information S1). Coral core Sr/Ca ratio was available for Cocos Keeling, Browse Island, Ningaloo Reef, and Houtman Abrolhos Island (Clarke et al., 2017; Hennekam et al., 2018; Zinke et al., 2015, 2014). All Sr/Ca ratios were derived from different coral cores, except for two sets of data derived from the same coral core in a different year. The two sets of Sr/Ca ratios are from Ningaloo Reef Bundegi sites (08BND and 13BND) and Ningaloo Reef Tantabiddi sites (08TNT and 13TNT) (Figure 1; Tables S1 and S2 in Supporting Information S1). Unpublished coral Sr/Ca ratios from Browse Island for two cores were also used in this study due to the proximity of Browse Island to Scott Reef which lacks coral proxy data. The Browse island site location, core extraction methods, and Sr/Ca data are described in Supporting Information (Text S1, Figures S1 and S5 in Supporting Information S1). All other Sr/Ca data were taken from publicly available data (https://www.ncei.noaa.gov/products/paleoclimatology; Table S3 in Supporting Information S1).

In situ logger data for the corresponding location were not available or had short time series (1–4 yr; Figure S3 in Supporting Information S1). Consequently, Sr/Ca time series was calibrated using NOAA CoralTemp and CCI SST analyses to reconstruct two coral core-derived monthly SST data sets (Figures S2a–S2x in Supporting Information S1). The former, including other low-resolution variants of NOAA AVHRR data (e.g., Reynolds Reanalyses at 25 km spatial resolution), is routinely applied in coral proxy-based SST reconstructions. Sr/Ca ratios are inversely correlated with SST. While it is commonly assumed that there is a linear relationship between Sr/Ca proxy values and SST values, a nonlinear pattern, mainly quadratic, were observed in some of the residual diagnostic. We then fitted a generalized additive model for Sr/Ca proxy values against SST values using restricted maximum likelihood and compared their respective goodness of fit measures to confirm that there are quadratic patterns in some series. Neglecting proper diagnostic procedures and relying solely on linear assumptions can obscure underlying mechanisms that may be responsible for nonlinear relationships. When corals bleach, calcification is disrupted, leading to interruption in growth, slower growth or a bleaching scarring (Clarke et al., 2019). High Sr/Ca ratios record such calcification disruption caused by bleaching or thermal stress in a high-density stress band during the summer maximum. As a result of the high Sr/Ca, the reconstructed SST during the bleaching event is falsely lower (higher residuals between Sr/Ca-SST and CCI SSST). There was an observation of this at Bundegi in 2011 in addition to what may have occurred in 1998. Those findings were shown and explained by Clarke et al. (2019, 2017), also for other sites near Ningaloo on the Onslow shelf. In this context, nonlinear fits of temperature against geochemical parameters were applied here. Note that model selection procedures were used to ensure the most suitable calibration model is applied for each Sr/Ca time series, which means a quadratic model is used only when needed. The quadratic or linear model was then used to reconstruct the SST time series from coral Sr/Ca proxy values (Figures S2a–S2x in Supporting Information S1). Following the calibration, monthly geochemical proxy-derived SST time series were used to calculate thermal stress indicators (DHMs).

Uncertainty in monthly Sr/Ca-SST results from the measurement uncertainty in Sr/Ca and the regression uncertainty on the slope between Sr/Ca versus SST. Sr/Ca measurement uncertainty in this study for all Sr/Ca records is 0.008 mmol/mol (1 sigma) which equates to approximately 0.13°C assuming a Sr/Ca versus SST slope of −0.06 mmol/mol per 1°C. The regression uncertainty can be taken from the slope uncertainty which is 0.02 mmol/mol, taking into account the full range of slope values reported in the literature (Corrège, 2006), which equates to 0.33°C. Both uncertainty estimates were added and uncertainties propagated as the square root of the sum of squares. This results in a Sr/Ca-SST uncertainty of 0.36°C for each monthly value in this study.

2.4. General Circulation Models

To observe differences in long-term trends among data sets, we used projected SST data based on historical and the low mitigation climate scenario (RCP SSP5 8.5) from the ACCESS GCM (Eyring et al., 2016). SST time series from the GCM were downloaded at a daily time step from a historical run (1980–2015) and from the future projection for 2016–2030. Data was downloaded from the World Climate Research Program climate data archives in NetCDF format. For each site, SST time series data of approximately 50 km resolution were extracted using the corresponding latitude and longitude coordinates (Table S1 in Supporting Information S1).

2.5. Thermal Stress Metrics

Each SST data set was used to calculate two coral bleaching indicator metrics, DHWs and DHMs. DHW (expressed in the unit °C-weeks) is the sum of all degrees above a locally determined heat stress threshold over a rolling 12-week period (Liu et al., 2018). The local heat stress threshold is determined by calculating the long-term mean temperature for each month and finding the maximum value, called the maximum monthly mean (MMM), the heat stress threshold is the MMM plus 1°C. For a 12-week period, every degree above the MMM + 1°C heat stress threshold—known as a temperature anomaly—is totaled. For example, if the heat stress threshold is 30°C, and the local SST for a given day is 32°C, then the temperature anomaly is 2. DHW are calculated by summing all daily anomaly values in a 7 days window and dividing by 7 to represent DHW in °C-weeks. DHMs are calculated in a similar way but use monthly SST data instead of daily, are totaled over a 3-month rolling window, and are expressed in the unit °C-months.

MMMs for each location and data combination were calculated as per Strong et al. (1997). NOAAs MMMs are centered to the year 1988 by capturing the data from 1985 to 1990 plus 1993 only as per Heron et al. (2015). The years 1991 and 1992 data were omitted due to widespread atmospheric interference from volcanic eruptions. MMMs were calculated using both the NOAA data—which matched NOAAs own climatology layers—and the CCI data.

DHWs were calculated using daily CCI, NOAA CoralTemp, and GCM SST data, whereas DHMs were calculated using monthly CCI, NOAA CoralTemp, GCM, and calibrated Sr/Ca data. As the monthly temporal resolution of the calibrated Sr/Ca data was insufficient for calculating daily DHW, it could not be used for DHW calculation. Similarly, calibrated Sr/Ca ratios available for Ningaloo Reef and the Houtman Abrolhos at annual resolution were not used for DHM calculations. A DHW and DHM time series was generated for each site to compare the differences between the multiple data sources.

2.6. Comparing Thermal Stress Metrics and Bleaching Risks Among Data Sets

To compare if consistent bleaching risks are observed simultaneously in different SST sources, we calculated and compared their observed thermal stress exposure (DHW and DHM). DHWs between four and below eight, and DHMs between one and below two, are used to represent moderate bleaching risks, while DHW values of eight and above and DHM values of two and above are used to represent severe bleaching risks (Barton & Casey, 2005; Kayanne, 2016; Liu et al., 2018). Using the CCI, GCM, and NOAA CoralTemp SST data, we calculated the cumulative number of moderate bleaching and severe bleaching risks between 1985 and 2020 in each data set. The Chi-Square goodness of fit test was used to test for the consistency of the cumulative number of bleaching risks across data sets from derived DHWs or DHMs that were compared to known standard values for indicators of bleaching risks. As some sites lack long-term data (Table S2 in Supporting Information S1), values based on calibrated Sr/Ca were excluded from this statistical analysis.

2.7. Comparing Historical Thermal Stress and Bleaching Risks With Observed Coral Bleaching

Based on the CCI, NOAA CoralTemp, and GCM SST data, and DHM from the CCI, NOAA CoralTemp, GCM, and Sr/Ca-derived SST, we compared bleaching risks with observed coral bleaching records from Hughes et al. (2018). The database contained bleaching records from 1980 to 2016 (Table S4 in Supporting Information S1). To quantify the accuracy of the coral stress indicators from different data sets in predicting the observed historical coral bleaching, we generated confusion matrices using the cvms package in R (Olsen et al., 2021). In this context, a confusion matrix applies several tests, including predictive accuracy (Balanced Accuracy and AUC), true positive rate (Sensitivity), and true negative rate (Specificity), to evaluate coral bleaching predictability from the different measures of thermal stress and bleaching risks (Olsen et al., 2021). A test with a sensitivity of 0.7 or 70% can detect 70% of bleaching but miss 30%. In this case, we are dealing with a false negative. In a test with 70% specificity, 70% of bleaching events will be detected, but 30% will be miscalled. In this case, 30% will seem as if they bleached, but they didn't. This is called a false positive. These tests were chosen as they assess the overall predictability and the rate at which positive and negative events are correctly predicted. Balanced accuracy averages the true positives and true negatives. Using the established bleaching risk thresholds for DHWs and DHMs, we created a presence/absence matrix of bleaching risks (Barton & Casey, 2005; Liu et al., 2018). Sensitivity and specificity tests were conducted for thermal stress-generated bleaching risks against observed bleaching events to compare the efficacy of the bleaching risk among data sets. As there were no known bleaching observations on Browse Island where calibrated Sr/Ca data was available, no data for Browse Island Sr/Ca-derived DHM were included in the confusion matrix.

3. Results

3.1. Comparing Thermal Stress Metrics and Bleaching Risks Among Data Sets

Comparing temperature stress metrics for occurrence and magnitude based on CCI, NOAA CoralTemp, and GCM revealed significant differences among them (Figures 2a and 2b; Tables S4a–S4d in Supporting Information S1). These metrics measure thermal exposure in the preceding days and represent thermal stress when values surpass a threshold. Between the years 1985–2020, a period when DHWs were available across CCI, NOAA CoralTemp, and GCM data sets, the highest DHWs was reported at different years in different sites. The highest DHWs were observed in 2016 for low latitude Cocos Keeling, Browse Island, and Scott Reef sites (Figure 2a); in 2013 for Ningaloo Reef sites (Figure 2b); and in 2011 for southernmost Houtman Abrolhos sites (Figure 2b). According to the three data sets, DHWs at some sites differed. CCI reported the highest DHWs in Cocos Keeling (DAR Long) site in 2016 as more than eight DHW, compared to NOAA CoralTemp's four to eight and GCM's less than four. Based on the chi-square goodness of fit test conducted to determine significant differences (95% confidence) in the cumulative number of high DHWs between the three data sets from 1985 to 2020, inconsistencies in DHWs were found, as statistical significance ($p < 0.05$) was reported at all eight sites (Tables S4a–S4b in Supporting Information S1).

Similar discrepancies in DHWs were also observed in other sites. Even within the same reef, Ningaloo Reef Bundegi (08BND, 13BND) sites (Figure 2b) displayed different DHW measurements compared to that in Ningaloo Reef Tantabiddi (08TNT, 13TNT) sites (Figure 2b). The DHW was highest at Ningaloo Reef Bundegi (08BND, 13BND) sites (Figure 2b) in 2013 and measured by NOAA CoralTemp-derived DHW, while the DHW was highest at Ningaloo Reef Tantabiddi (08TNT, 13TNT) sites (Figure 2b) in 2013 but measured by CCI derived-DHW. Both sites differ by less than 0.5° in latitude. Besides thermal histories, future DHW projections from GCM appear to show more thermal anomalies (high DHWs) in the lower latitude sites (Figure 2a) compared to higher latitudes sites in Ningaloo Reef or Houtman Abrolhos islands (Figure 2b).

Generally, satellites, GCM, and Sr/Ca-derived DHMs show inconsistency in onset, occurrence and magnitude across time, simultaneously displaying both low (less than 1) and high (more than 1) DHMs at the same time points (Figures 3 and 4; Tables S4c–S4d and Figures S6a–S6l in Supporting Information S1). Due to a lack of monthly coral core data from Scott Reef and Houtman Abrolhos islands, DHMs derived from Sr/Ca were only available from Cocos Keeling Island, Browse Island, and Ningaloo Reef. Consistently, the highest DHMs between 1985 and 2020 were measured by either CCI or NOAA CoralTemp in 2016 at lower latitude sites on Cocos Keeling Island, Scott Reef, Browse Island, and Ningaloo Reef Bundegi sites (08BND and 13BND). Notably, Ningaloo Reef Tantabiddi sites (08TNT and 13TNT) reported the highest DHM value in a different year in 2011, despite their proximity to Ningaloo Reef Bundegi sites. In contrast, DHMs in Tantabiddi sites in 2016 were below one, indicating there was no thermal stress despite being an ENSO year. Among Houtman Abrolhos sites at higher latitudes, 2011 was also reported as having the highest CCI-derived DHM. However, this is expected as Ningaloo reef, and Houtman Abrolhos island are known to be affected by marine heatwaves during La Niña conditions, which in this case occurred in 2011 (Abdo et al., 2012; Babcock et al., 2021; Feng et al., 2013). Sr/Ca-derived DHMs were generally lower than all other data types, except at Browse Island (BRS05 and BRS07) sites and Ningaloo Reef (08BND) sites (Figures S6a–S6h in Supporting Information S1). All three sites BRS05, BRS07, and 08BND reported high DHMs in 2005, 2003, and 2008 respectively (Figures S6c–S6e in Supporting Information S1). Conversely, the low CCI, NOAA CoralTemp, and GCM-derived DHMs do not agree with the high Sr/Ca-derived DHM reported in these years (Figures 3 and 4; Figures S6c–S6e in Supporting Information S1). Generally, satellite data and GCM measurements showed different DHMs at different time intervals

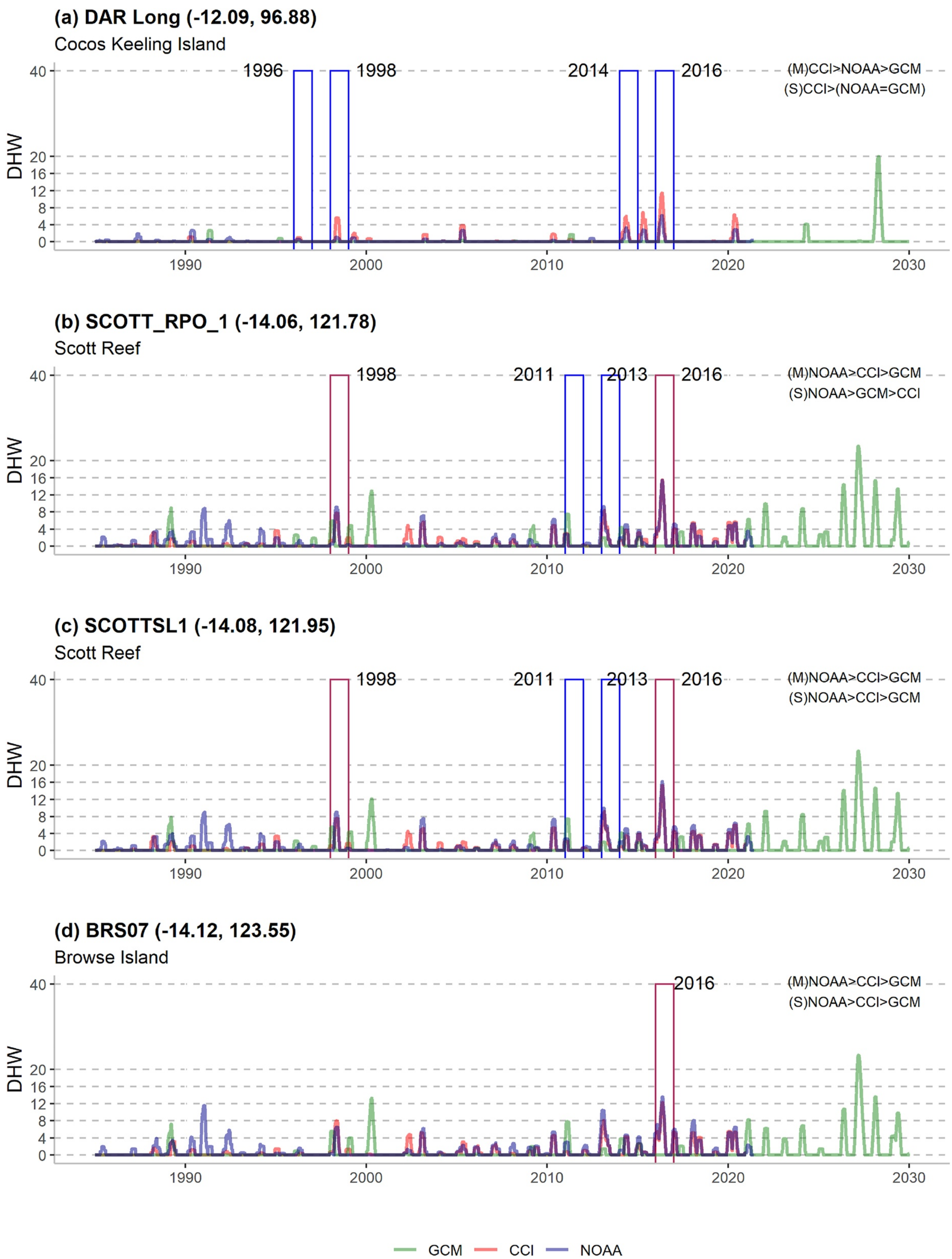
(a) DAR Long (-12.09, 96.88)
Cocos Keeling Island
1996
1998
2014
2016
(M)CCI>NOAA>GCM
(S)CCI>(NOAA=GCM)
(b) SCOTT_RPO_1 (-14.06, 121.78)
Scott Reef
1998
2011
2013
2016
(M)NOAA>CCI>GCM
(S)NOAA>GCM>CCI
(c) SCOTTSL1 (-14.08, 121.95)
Scott Reef
1998
2011
2013
2016
(M)NOAA>CCI>GCM
(S)NOAA>CCI>GCM
(d) BRS07 (-14.12, 123.55)
Browse Island
2016
(M)NOAA>CCI>GCM
(S)NOAA>CCI>GCM
DHW
1990
2000
2010
2020
2030
GCM
CCI
NOAA

Figure 2.

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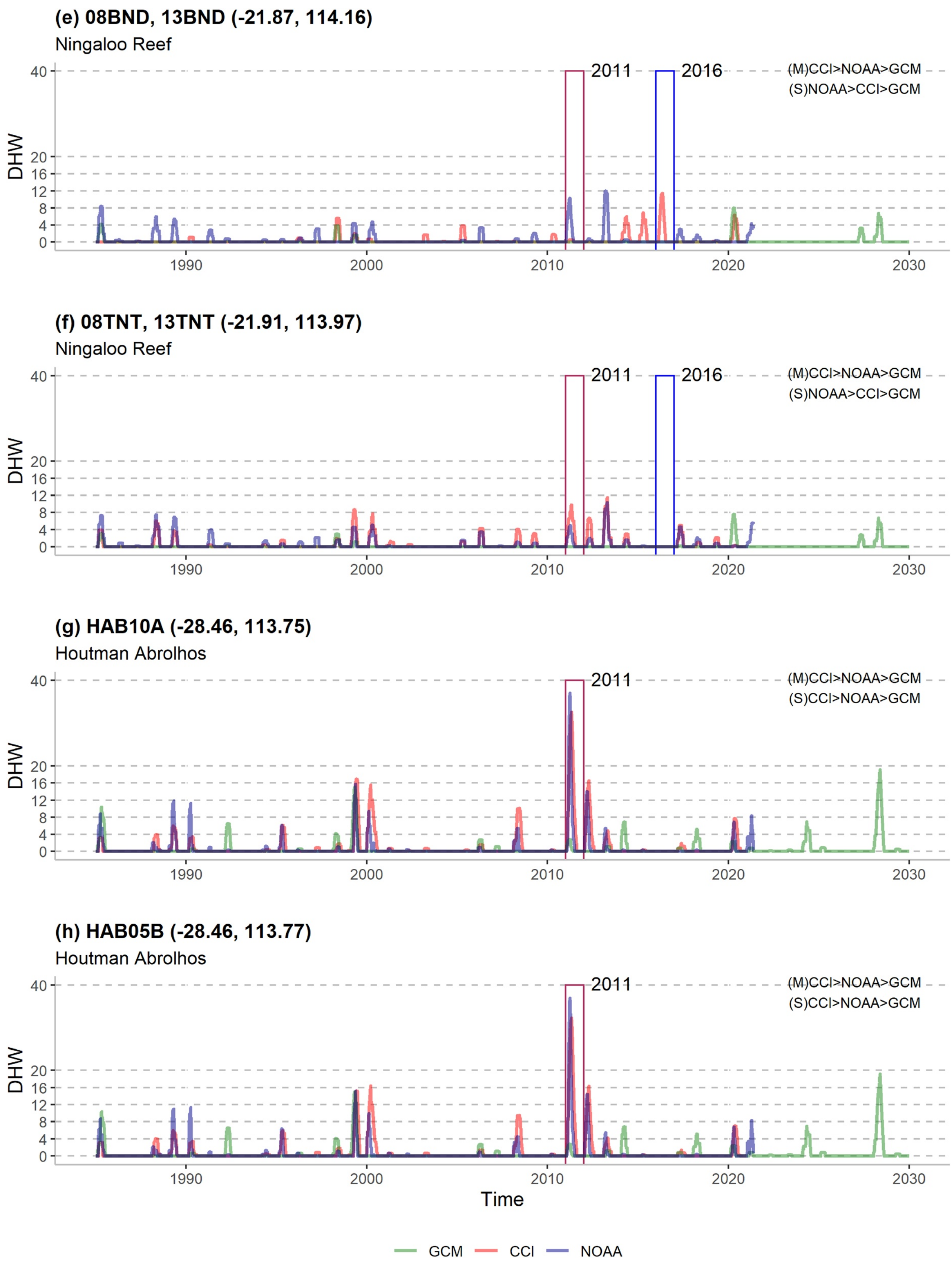

Figure 2. (Continued)

(Figures S6a–S6h in Supporting Information S1). Based on the chi-square goodness of fit test conducted to determine significant differences (at a 5% significance level) in the cumulative number of high DHMs between the three data sets, inconsistencies in DHMs were found, as statistical significance ($p < 0.05$) were reported at most sites, except in Ningaloo Reef Tantabiddi sites (Tables S4c–S4d in Supporting Information S1).

3.2. Comparing Historical Thermal Stress and Bleaching Risks With Observed Coral Bleaching

Coral bleaching risk has been associated with DHW and DHM values exceeding certain thresholds, indicating thermal stress exposure (Barton & Casey, 2005; Liu et al., 2018). Using the established thresholds, DHWs reported by the satellites and GCM were translated to moderate, severe or no bleaching risks during years where historical bleaching records exist for a particular reef (Figures 2a and 2b, Table S4 in Supporting Information S1). We found that observed bleaching records were inconsistent with thermal stress exposure and bleaching risks based on DHW and/or DHM values from all four data sets (Figures 2–4; Figures S6a–S6l in Supporting Information S1).

Overall, bleaching risks from satellites and GCM-derived DHWs did not correspond to known historical bleaching events. The satellite and GCM bleaching risks for Cocos Keeling (DAR Long) site (Figure 2a) varied in four historical moderate bleaching events, where only moderate bleaching risks in 1998 and 2014 were reported. In other sites with moderate and severe historical bleaching observations, such as Scott Reef (SCOTT_RPO_1 and SCOTTSL1) sites (Figure 2a), bleaching risks were reported for severe bleaching events in the years 1998 and 2016 but not moderate bleaching events in 2011 and 2013. On the same sites, the increase in DHWs was almost double between the first and second severe bleaching events in 1998 and 2016. Furthermore, DHWs were higher during the two subsequent historical moderate bleaching events in 2011 and 2013 than during the severe bleaching event in 1998. A similar phenomenon was also observed in Ningaloo Reef Bundegi (08BND, 13BND) sites (Figure 2b), where DHW measured in 2016 during the moderate bleaching event was higher than DHW measured in 2011 during the severe bleaching event. Where only moderate bleaching events were reported, such as in Cocos Keeling (DAR Long) site (Figure 2a; the years 1996, 1998, 2014, and 2016), DHWs were consistently higher in every subsequent bleaching event observed, except in Ningaloo Reef Tantabiddi (08TNT, 13TNT) site (Figure 2b). High DHWs of >4 DHW were also observed at time points where no historical bleaching was reported (Figures 2a and 2b).

Similarly, DHMs reported by the satellites, GCM, and Sr/Ca were converted to either moderate, severe, or no bleaching risks during years where historical bleaching was observed in that particular reef (Figures 3 and 4; Figures S6a–S6l and Table S4 in Supporting Information S1). Overall, bleaching risks obtained from CCI, NOAA CoralTemp, GCM, and Sr/Ca were not consistent with observed historical bleaching events (Figures 3 and 4; Figures S6a–S6l and Table S4 in Supporting Information S1). Bleaching risks from all data types failed to identify moderate bleaching risks in any of the four historical moderate bleaching events in the Cocos Keeling (DAR Long) site (Figure 3a; Figure S6A in Supporting Information S1). Similarly, the moderate bleaching event of Ningaloo Reef Bundegi and Tantabiddi (08BND, 13BND, 08TNT, and 13TNT) sites in 2016 (Figures 3a–3b; Figures S6e–S6h in Supporting Information S1), following a severe bleaching event in 2011, was accompanied by DHMs above the bleaching risk threshold in Ningaloo Reef Bundegi (08BND and 13BND) sites (Figures 3a and 3b) or below the bleaching risk threshold on Ningaloo Reef (08TNT and 13TNT) Tantabiddi sites (Figure 3b; Figures S6g–S6h in Supporting Information S1). On Scott Reef, both the moderate bleaching event of 2013 and the severe bleaching event of 2016 were accompanied by higher DHMs than the severe bleaching event of 1998, with the value doubling in 2016. DHM derived from CCI, NOAA CoralTemp, and GCM increased with every subsequent known bleaching event of the same severity. In Cocos Keeling and Browse Island, Sr/Ca-derived DHMs were consistently below one DHM or unavailable during known bleaching years. However, based on CCI calibrated Sr/Ca-derived DHM

Figure 2. A Degree Heating Weeks (DHWs) time series based on CCI, NOAA CoralTemp, and GCM SST data products. The sites are arranged from north to south, showing differences in thermal history and future thermal projections between sites. Known bleaching events are highlighted in blue (moderate bleaching) and red (severe bleaching). Data is shown from the years 1985 to 2020 for NOAA CoralTemp and CCI data and from the years 1985 to 2030 for GCM data. Statistically significant ($p < 0.05$) differences in moderate (M) and severe (S) bleaching risk prediction using DHWs based on GCM, NOAA CoralTemp, and CCI data are indicated on the figure panels. (b) DHWs time series based on CCI, NOAA CoralTemp, and GCM SST data products. The sites are arranged from north to south, showing differences in thermal history and future thermal projections between sites. Known bleaching events are highlighted in blue (moderate bleaching) and red (severe bleaching). Data is shown from the years 1985 to 2020 for NOAA CoralTemp and CCI data and from the years 1985 to 2030 for GCM data. Statistically significant ($p < 0.05$) differences in moderate (M) and severe (S) bleaching risk prediction using DHWs based on GCM, NOAA CoralTemp, and CCI data are indicated on the figure panels.

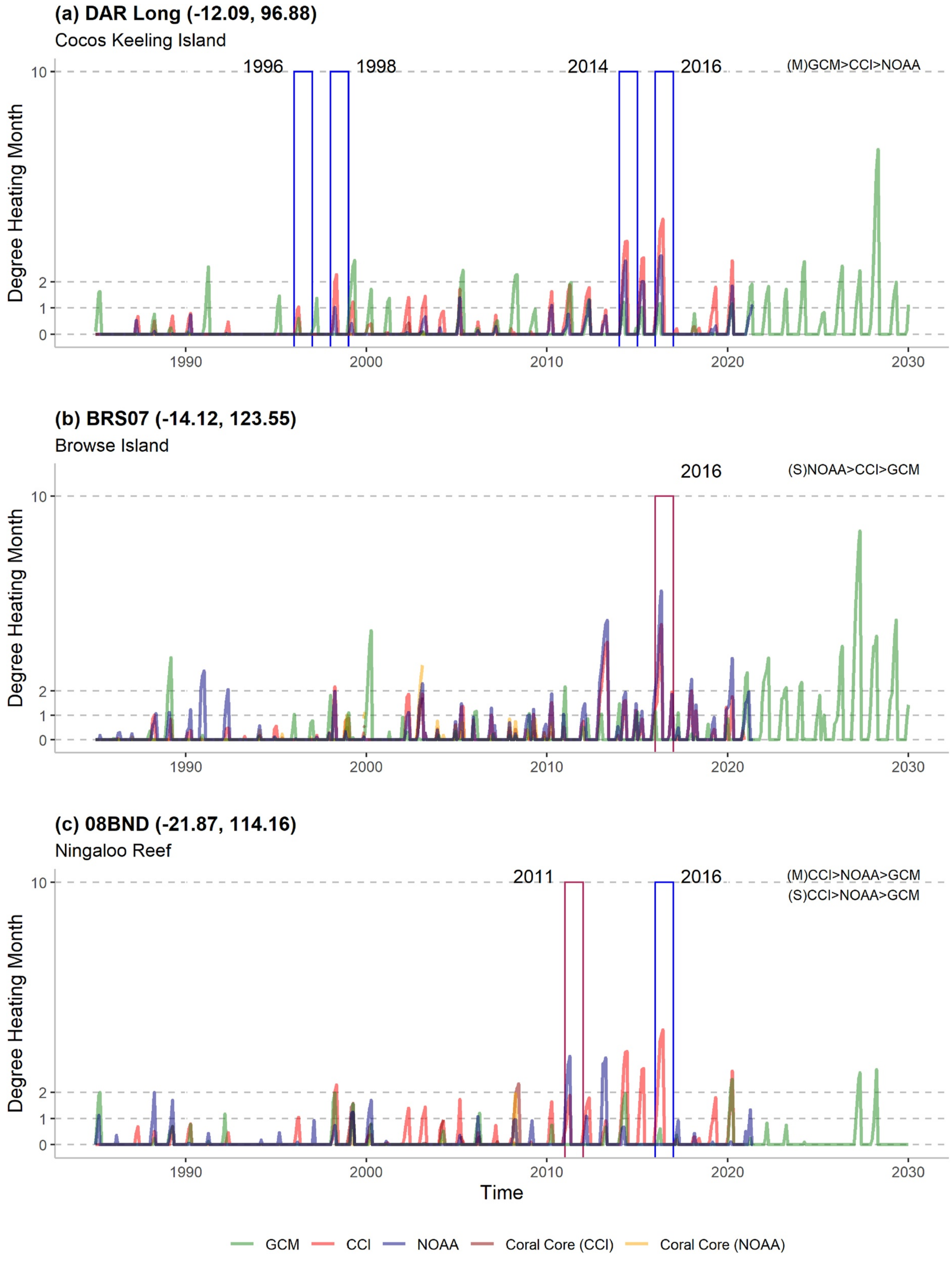
(a) DAR Long (-12.09, 96.88)
Cocos Keeling Island
1996
1998
2014
2016
(M)GCM>CCI>NOAA
(b) BRS07 (-14.12, 123.55)
Browse Island
2016
(S)NOAA>CCI>GCM
(c) 08BND (-21.87, 114.16)
Ningaloo Reef
2011
2016
(M)CCI>NOAA>GCM
(S)CCI>NOAA>GCM
Degree Heating Month
Time
GCM
CCI
NOAA
Coral Core (CCI)
Coral Core (NOAA)

Figure 3.

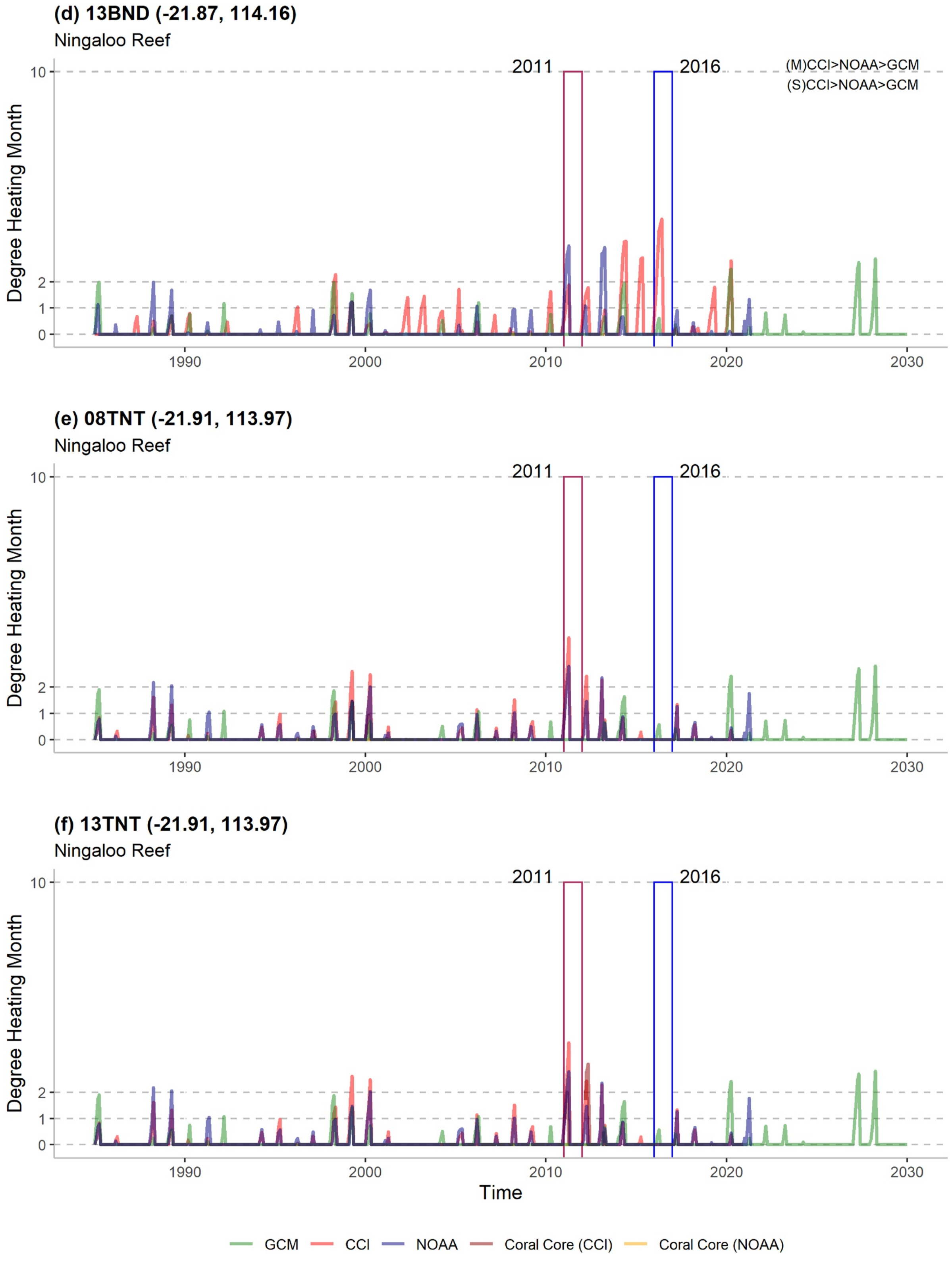

Figure 3. (Continued)

in Ningaloo reef Tantabiddi (13TNT) site (Figure 3b; Figure S6h in Supporting Information S1), a high DHM of above two DHM in the year 2011 corresponds to the known severe bleaching event in the same year. In contrast, NOAA CoralTemp calibrated Sr/Ca-derived DHM in Ningaloo Reef Tantabiddi (13TNT) site (Figure 3b; Figure S6h in Supporting Information S1) did not detect high DHMs in the same year. Within the same reef, Ningaloo Reef Bundegi (08BND) site (Figure 3a; Figure S6e in Supporting Information S1) Sr/Ca-derived DHM recorded DHM anomalies above one DHM during 1999 and 2008 where no known bleaching was recorded. This was reflected by CCI-calibrated Sr/Ca-derived DHM in both years. DHM anomalies were observed by NOAA CoralTemp calibrated Sr/Ca-derived DHM in the same site in 1999 but not in 2008. Surprisingly, the high Sr/Ca-derived DHMs observed at Bundegi site, Ningaloo Reef (08BND) in the years 1999 and 2008 have not been confirmed by Ningaloo Reef (13BND) Bundegi site derived DHM, despite the fact they came from the same corals collected later in the study (Figures 3a–3b; Figures S6e–S6f in Supporting Information S1). High DHMs of more than one DHM were also reported at time points where bleaching was not recorded, as seen in Figures 3 and 4.

3.3. Comparing Thermal Stress-Generated Bleaching Risks With Records of Coral Bleaching

A confusion matrix comparing thermal metrics bleaching risk (from DHWs and DHMs) and observed historical events (previously known coral bleaching events) was generated (Tables 1a–1c). While the DHWs and DHM derived true positives and true negatives are obtained from the same daily resolution data sets from CCI, NOAA CoralTemp, or GCM, there are observable differences. The true positives based on CCI and NOAA CoralTemp derived DHM appears to be higher than that of DHWs in Cocos Keeling Island, Browse Island, Scott Reef, and Houtman Abrolhos Islands. In Ningaloo Reef, CCI-derived DHMs showed higher true positives than those derived from DHWs. Still, NOAA CoralTemp-derived DHMs showed similarities to the true positives to those given by the respective reef's DHWs. Notably, the true positives of GCM-derived DHMs were much higher than those from GCM-derived DHWs in all reefs. In contrast, the true negatives of DHWs derived from CCI, NOAA CoralTemp, and GCM data were consistently higher than that of DHMs, with one exception of NOAA CoralTemp-derived DHW and DHM in Houtman Abrolhos Islands with a slight difference of 0.1. Sr/Ca-derived DHM in Cocos Keeling Islands and Ningaloo Reef showed high accuracy in predicting true negative bleaching events but low accuracy in predicting true positives. All Sr/Ca-derived DHM had zero accuracy in predicting actual bleaching events, except CCI calibrated Sr/Ca-derived DHM in Ningaloo Reef, showing 50% accuracy (Table 1c).

4. Discussion

This study examined the consistency among thermal stress indicators calculated using data from four sources: SST, CCI, NOAA CoralTemp, GCM, and calibrated Sr/Ca. Furthermore, the predictability of reported bleaching risks was assessed by comparing them against records of observed coral bleaching. Because of the inherent differences among SST data products, including spatial and temporal resolutions, observation methods, and retrieval algorithms, there may be inconsistencies among them. Yet there is little understanding of whether these inconsistencies are at the level of time series or derived indicators and their implications for biophysical ecology of coral reefs. Despite the potential implications for conservation, it is not uncommon for coral reef literature to contain bleaching predictions based on different types of data sets. At the same time, significant efforts are currently being expanded toward identifying reefs that can survive climate change are informed by primarily one SST data product (For example, 50 Reefs, Beyer et al., 2018). While these efforts are ongoing, there is a need to test the data sets and metrics used to inform management actions. Understanding the differences can also potentially lead to data fusion solutions that maximize the strength and minimize the weakness of each data set. Data from North-Western to South-Western Australia reefs was used to evaluate predicted bleaching risks and demonstrate inconsistencies with observational data.

Figure 3. (a) Time series of Degree Heating Months (DHMs) based on CCI, NOAA CoralTemp, GCM, and Sr/Ca-derived SST data. Sites are labeled from north to south. Known moderate and severe bleaching events are highlighted in blue and red, respectively. Data is shown from the years 1985 to 2020 for NOAA CoralTemp and CCI data and from the years 1985 to 2030 for GCM data. The Sr/Ca-derived SST (dark red and yellow) differed in timeframes and ranged from 9 to 27 yr. Statistically significant ($p < 0.05$) differences in moderate (M) and severe (S) bleaching risk prediction based on DHMs from GCM, NOAA CoralTemp, and CCI data are displayed on the figure panels. Individual time series are shown in Supporting Data (Figures S6a–S6h in Supporting Information S1). (b) Time series of DHMs based on CCI, NOAA CoralTemp, GCM, and Sr/Ca-derived SST data. Sites are labeled from north to south. Known moderate and severe bleaching events are highlighted in blue and red, respectively. Data is shown from the years 1985 to 2020 for NOAA CoralTemp and CCI data and from the years 1985 to 2030 for GCM data. The Sr/Ca-derived SST (dark red and yellow) differed in timeframes and ranged from 9 to 27 yr. Statistically significant ($p < 0.05$) differences in moderate (M) and severe (S) bleaching risk prediction based on DHMs from GCM, NOAA CoralTemp, and CCI data are displayed on the figure panels. Individual time series are shown in Supporting Data (Figures S6a–S6h in Supporting Information S1).

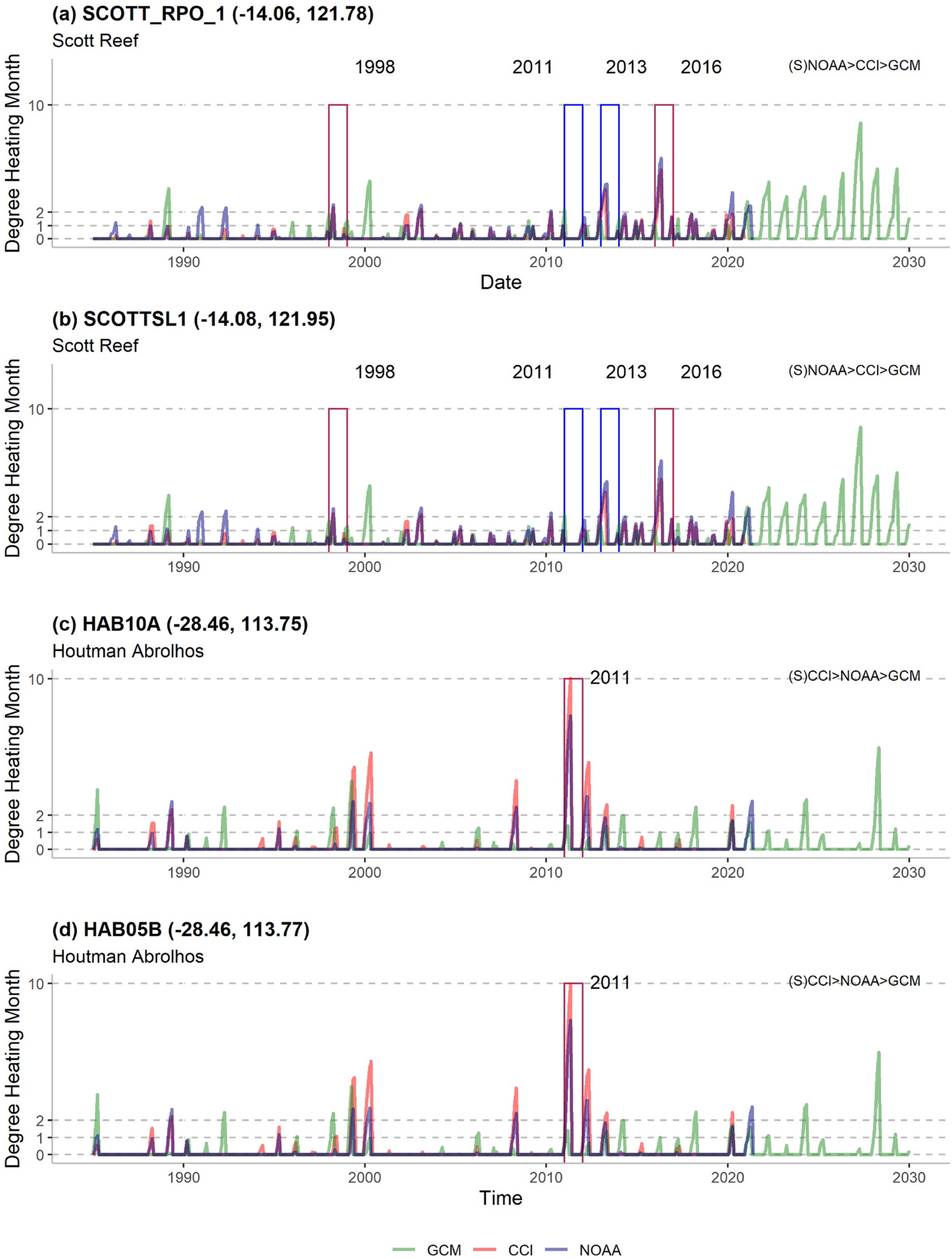

Figure 4. Degree Heating Month time series for CCI, NOAA CoralTemp, and GCM-derived SST data. Sites are labeled from north to south. Known moderate and severe bleaching events are highlighted in blue and red, respectively. Data is shown from the years 1985 to 2020 for NOAA CoralTemp and CCI data and from the years 1985 to 2030 for GCM data. Statistically significant ($p < 0.05$) differences in moderate (M) and severe (S) bleaching risks prediction based on DHMs from GCM, NOAA CoralTemp, and CCI data are displayed on the figure panels. Individual time series are shown in Supporting Data (Figures S6i–S6l in Supporting Information S1).

Table 1
Confusion Matrices Comparing Bleaching Risk With Observed Bleaching For: (A) Degree Heating Weeks; (B) Degree Heating Months (DHMs) From CCI, GCM, and NOAA CoralTemp; and (C) DHMs From Sr/Ca-Derived Sea Surface Temperature (SST)

(a)

	CCI DHW				NOAA CoralTemp DHW				GCM DHW			
Reef	Balanced accuracy	Sensitivity	Specificity	AUC	Balanced accuracy	Sensitivity	Specificity	AUC	Balanced accuracy	Sensitivity	Specificity	AUC
Cocos (Keeling) Islands	0.84	0.75	0.94	0.84	0.63	0.25	1.00	0.63	0.50	0.00	1.00	0.50
Browse Island	0.90	1.00	0.80	0.90	0.82	1.00	0.65	0.82	0.44	0.00	0.89	0.44
Scott Reef	0.80	0.75	0.86	0.80	0.70	0.75	0.65	0.70	0.67	0.47	0.87	0.67
Ningaloo Reef	0.60	0.38	0.82	0.60	0.65	0.50	0.79	0.65	0.50	0.00	0.99	0.50
Houtman Abrolhos	0.88	1.00	0.76	0.88	0.85	1.00	0.71	0.85	0.43	0.00	0.86	0.43

(b)

	CCI DHM				NOAA CoralTemp DHM				GCM DHM			
Reef	Balanced accuracy	Sensitivity	Specificity	AUC	Balanced accuracy	Sensitivity	Specificity	AUC	Balanced accuracy	Sensitivity	Specificity	AUC
Cocos (Keeling) Islands	0.86	1.00	0.72	0.86	0.80	0.75	0.86	0.80	0.55	0.50	0.61	0.55
Browse Island	0.83	1.00	0.66	0.83	0.74	1.00	0.48	0.74	0.82	1.00	0.64	0.82
Scott Reef	0.73	0.75	0.70	0.73	0.63	0.75	0.51	0.63	0.80	0.83	0.76	0.80
Ningaloo Reef	0.72	0.75	0.69	0.72	0.62	0.50	0.73	0.62	0.41	0.00	0.83	0.41
Houtman Abrolhos	0.86	1.00	0.71	0.86	0.87	1.00	0.74	0.87	0.88	1.00	0.75	0.88

(c)

	CCI calibrated Sr/Ca derived DHM				NOAA CoralTemp calibrated Sr/Ca derived DHM			
Reef	Balanced accuracy	Sensitivity	Specificity	AUC	Balanced accuracy	Sensitivity	Specificity	AUC
Cocos (Keeling) Islands	0.50	0.00	1.00	0.50	0.50	0.00	1.00	0.50
Ningaloo Reef	0.69	0.50	0.88	0.69	0.49	0.00	0.98	0.49

Note. Sensitivity and specificity represent the true positive and negative rates, respectively. The area under the curve (AUC) represents the ability of the data type to predict true positive and negative events at the reef. In contrast, Balanced Accuracy represents the average sensitivity and specificity value combined.

4.1. Differences in Thermal Stress Metrics and Bleaching Risks Among Data Sets

Commonly used thermal stress indicators and bleaching risk, DHW and DHM, differed among data sets at each time point along the time series. Additionally, the total number of moderate and severe bleaching events accurately predicted by DHW-derived bleaching risks differed between the satellite and GCM data sets at all sites. SST data from different sources and the associated bleaching risk predictions are still subject to substantial uncertainty, as demonstrated here (Figures 2–4; Tables S4a–S4b, Figures S6a–S6l, and Figures S7a–S7b in Supporting Information S1). The total number of DHM-derived moderate and severe bleaching risk events was consistent among the satellite and GCM data sets for some sites but differed significantly in Cocos Keeling Island, Browse Island, Ningaloo Reef, and Scott Reef (Tables S4c–S4d in Supporting Information S1). DHM derived from Sr/Ca-derived SST was relatively low across time and study sites. A possible explanation for this is that coral cores and satellites measure temperatures at different depths, with satellites measuring skin temperature. There may still be some residual effect of this aspect on data following coral proxy calibration to varying degrees (Sayani et al., 2019). However, based on Sr/Ca, thermal stress was observed in Browse Island (BRS05 and BRS07) and Ningaloo Reef Bundegi (08BND) sites (Figures 3a–3b; Figures S6c–S6e in Supporting Information S1) in 2005, 2003, and 2008, respectively. The Sr/Ca-derived SSTs were calibrated using CCI and NOAA CoralTemp data, but thermal stress was not detected at the same sites when using DHM from CCI, NOAA CoralTemp, or GCM data, suggesting that Sr/Ca-derived SSTs reflect aspects of variability that satellite or GCM data cannot capture. Sr/Ca-derived high DHMs in those years may be indicative of accurate local thermal stress levels that are not reflected in CCI, NOAA CoralTemp, or GCM data. There is a need for further investigation on this topic. Overall, there were considerable differences between the DHW and DHMs from all four sources, which suggests caution should be exercised when relying on a single data source for observing thermal stress that identifies bleaching risks (Tables 1a–1c; Tables S4a–S4d and Figures S7a–S7b in Supporting Information S1).

Across a latitudinal gradient, the highest DHW and DHM measurements were observed at different times. During El Nino in 2016, DHM and DHW levels were consistently highest in Cocos Keeling Island, Browse Island, and Scott reef sites, and in subtropical Houtman Abrolhos Island sites during La Nina in 2011. However, the highest DHW occurred in the subtropical Ningaloo Reef in 2013, detected by CCI data from two sites on Ningaloo Reef Bundegi sites (Figure 2b) and by NOAA CoralTemp data from two sites on Ningaloo Reef Tantabiddi sites (Figure 2b). All Ningaloo Reef sites had the highest DHM in 2016 based on CCI data. It is evident from the differences between the site measurements of DHW and DHM derived from the same data set that coral thermal stress metrics need to be evaluated on a temporal scale higher than monthly. Also, the inconsistency between site measurements of DHW and DHM in Ningaloo Reef on Bundegi and Tantabiddi sites could be attributed to the wind exposure causing offshore eddies and localized upwelling, which creates uneven temperature exposure within the same reef (Xu et al., 2016). Ningaloo Reef Bundegi (08BND, 13BND) sites are located in a part of the reef-protected by offshore waves and rely significantly on tides for circulation (Clarke et al., 2017). If the measurement is taken at a different time of the day, there will be discrepancies between satellite measurements. The CCI and NOAA CoralTemp measurements use different satellites at various times of day, and only CCI attempts to adjust to a consistent time of day throughout its record. Not relying on a single remotely sensed data set for daily SST monitoring reveals such differences. It highlights the question of which strategy is optimal for combining satellite observations to quantify coral reef thermal environment. As a highly exposed reef, Tantabiddi Reef may serve as thermal refugia since high-frequency temperature changes caused by wind and waves may prevent coral bleaching, while the sheltered Bundegi Reef might not (Babcock et al., 2021;Safaie et al., 2018; Schoepf et al., 2015; Sully et al., 2019). A detailed thermal history of coral organisms would provide an indication of their environment's changing temperature. However, the highest temporal resolution from coral Sr/Ca proxies is currently monthly, preventing the more accurate DHW metric calculation. Nevertheless, DHM from coral Sr/Ca-SST pre-dating the satellite record may allow for a longer-term thermal stress evaluation across reef locations globally. This would allow us to build records of reef-scale spatially matched thermal stress histories to identify potential climate change refugia. GCM projections project more frequent high DHW and DHMs in low-latitude sites compared to high-latitude sites in the future, projecting tropical and subtropical regions to experience greater temperature anomalies compared to higher-latitude regions. This suggests Ningaloo Reef Tantabiddi sites as a location for future conservation efforts where thermal tolerance can be built from high-frequency temperature changes and with relatively lower absolute temperatures than other sites (Sully et al., 2019). Historical coral proxy-derived DHM assessment may, ultimately, assist in evaluating future thermal stress predictions from downscaled GCM's.

4.2. Inconsistencies in Bleaching Risks Compared to Observed Coral Bleaching

In addition to examining the inconsistencies in thermal stress indicators derived from the four data sources, bleaching risks were classified into severe, moderate, and low or no bleaching risks based on widely used threshold values. Naturally, the inconsistencies in DHW and DHMs between data sources affect the reported coral bleaching risk. Known moderate and severe coral bleaching events were generally not in agreement with bleaching risks derived from DHW and DHM thresholds. In some instances, DHWs and DHMs were determined to be over the severe bleaching threshold, yet there was no bleaching or only moderate bleaching observed. The confusion matrix (Tables 1a–1b) tests the relative predictive ability of data sets against known observed bleaching events. The results, perhaps surprisingly, show lower true positives (sensitivity) in DHW-based coral bleaching risk predictions than those based on DHM. On the other hand, the DHM-based metrics show increased false alarms and lower overall balanced accuracy. GCM-derived DHWs and DHMs, in particular, have low sensitivity in DHW-based metrics, being close to zero in all reefs except in Scott Reef, whereas DHMs were higher in all sites except in Ningaloo Reef. The results indicate that further development with improved sensitivity and specificity is required to improve these metrics, from indicators of thermal stress to accurate predictors of bleaching. As a result of different data sources with different spatial and temporal resolutions and algorithms used to process the data, different outcomes of marine heatwaves or thermal stress and, consequently, bleaching risks will be reported (Hobday et al., 2016; Marin et al., 2021). In the presence of inconsistencies in marine heatwave and SST anomaly calculations by different instruments, DHW and DHM calculations should not be expected to show consistency. Furthermore, the low true positives of GCM-derived DHWs and the high true positives of GCM-derived DHMs suggest that monthly GCM data is more reliable than daily GCM data. Compared to measuring specific events, GCM long-term SST values may be less noisy since they are modeled data, thus providing more reliability in long-term climate observations.

In contrast to other reefs, Ningaloo reef and Cocos Keeling Island had a lower correlation between actual bleaching and thermal stress metrics. This is consistent with earlier studies suggesting that the CRW DHW product overpredicted bleaching (Logan et al., 2014). Localized dynamics are likely important, and a future study could examine the possibility of using SSTs at a higher resolution to detect dynamic factors and other oceanographic factors, such as wind and internal waves, to improve coral bleaching predictability in these locations (Wyatt et al., 2020).

The predictability of coral bleaching using Sr/Ca-derived DHM data (Table 1c) is relatively lower in Ningaloo Reef and Cocos Keeling Island. Sr/Ca-derived DHW and DHM were generally low and below the bleaching risk threshold, with only a few exceptions. CCI calibrated Sr/Ca-derived DHM in Ningaloo Reef Tantabiddi (13TNT) site (Figure 3b; Figure S6h in Supporting Information S1) detected high DHM of above two DHM in the year 2011 when severe bleaching was also recorded. In contrast, NOAA CoralTemp calibrated Sr/Ca did not detect the same DHMs in the same bleaching year. This highlights the uncertainties added to calibrated Sr/Ca where different calibrated data sets may reflect different outcomes with the same Sr/Ca values. Within Ningaloo Reef, CCI calibrated Sr/Ca-derived DHM in Ningaloo Reef Bundegi (08BND) site (Figure 3a; Figure S6e in Supporting Information S1) reflected high DHMs in 1999 and 2008. In contrast, NOAA CoralTemp calibrated Sr/Ca-derived DHM in Ningaloo Reef Bundegi (08BND) site (Figure 3a; Figure S6e in Supporting Information S1) only reflected high DHMs in the year 1999 but not in 2008. The high DHMs reflected using Ningaloo Reef Bundegi (08BND) site (Figure 3a; Figure S6e in Supporting Information S1) Sr/Ca-derived DHM were not reproduced in Ningaloo Reef Bundegi (13BND) site (Figure 3b; Figure S6f in Supporting Information S1), despite the cores being from the same coral colony albeit a different year. This was due to the high temperatures in 2011 affecting Sr/Ca proxy signal incorporation into the skeleton, highlighting the vulnerability of relying solely on a low number of replicated proxy archives that environmental factors could alter (Clarke et al., 2017). Bundegi coral Sr/Ca in 2011 were shown to be affected by high thermal stress related cessation of coral growth and calcification, leading to underprediction of the true SST amplitude (Clarke et al., 2017). Similar bleaching or thermal stress related distortions of the coral core Sr/Ca signals have been reported numerous times (e.g., Clarke et al., 2019; Leupold et al., 2019; Marshall & McCulloch, 2002; Sagar et al., 2016). Such anomalous Sr/Ca signals during known bleaching years may still become valuable signals recording historical thermal stress exposure at the reef scale which would otherwise go undetected by satellite skin temperature. In Cocos Keeling Island, Sr/Ca-derived DHM did not highlight any bleaching risks during the known bleaching events. Comparison with other reefs is not possible due to limited bleaching data available or recorded. Hence, despite being physically exposed to marine heatwaves, there are many limitations to utilizing data from coral cores due to uncertainties during calibration, signals affected by environmental conditions, temporal resolution, and limited spatial coverage.

4.3. Thermal Stress Exposure Increases After Bleaching Events of Similar Severity

An increasing trend was observed in the values of DHW and DHM during subsequent bleaching events of similar severity. In observed moderate and severe bleaching events, DHWs and DHMs were consistently higher in the subsequent moderate and severe bleaching events, sometimes doubling the previous value. This is consistent with some form of coral adaptation to previous thermal anomalies, increasing their resilience to coral bleaching such that higher temperatures are required for the corals to bleach (Schoepf et al., 2015). A bleaching event was observed at Ningaloo Reef Bundegi and Tantabiddi sites in 2011 (Hughes et al., 2018). However, a marine heatwave was reported in both eastern and western Ningaloo Reef in the year 2013 where DHWs peaked at 12, more or less similar to that reported in this study (DHW = 12 Figure 2b based on CoralTemp). Still, bleaching occurrence was not reported due to the higher thermal tolerance by surviving small colonies and the severe reduction of coral cover (in particular bleaching susceptible taxa) in the previous bleaching event (Babcock et al., 2021; Depczynski et al., 2013). Several other mechanisms could also explain the lack of bleaching observed. At Ningaloo Reef, oceanographic processes not captured by SST products (e.g., upwelling that serves as a cooling mechanism at depth) could explain the lack of bleaching observed despite the bleaching predicted by satellite-derived SST. In addition, the coral cover at Bundegi Reef remained stable until 2011, then dropped significantly to 17% in 2011, and further declined to 1% in 2013 (Babock et al., 2021), yet there were no reports of bleaching. At the same time, conflicting reports suggest that the exposure to high temperatures can increase coral resilience and help alleviate bleaching occurrences (Ainsworth et al., 2016; Donner, 2011; Fox et al., 2021; Schoepf et al., 2015; Sully et al., 2019). This illustrates the complexity of bleaching mechanisms, and temperature may not be the only variable involved. Therefore, the first step in understanding coral bleaching and implementing management measures is to improve temperature predictions.

4.4. Limitations

In spite of the importance of our findings for coral reef conservation efforts, our study has a few notable limitations. First, corals are highly dynamic, and their life histories and biological components differ, which may result in varying Sr/Ca signals in cores from the same reef. For instance, the calibration of Sr/Ca to SST data in Browse Island showed a different Sr/Ca range in each site (Figure S1 in Supporting Information S1). In addition, the temporal coverage of coral proxy data differed among various sites, which limits the scope of the analyses. Other reef locations with longer monthly Sr/Ca proxy time series could be assessed for their suitability in recording longer historical DHM. Many long coral records are derived from coral oxygen isotopes. Thus, it may also be possible to calculate DHM from monthly oxygen isotope proxy records at locations where SST is dominating the signal. Second, GCM simulations can vary between the different models. Therefore, using a single GCM model may result in inaccurate general inferences about GCMs. In addition, GCM-based prediction of future thermal stress should be downscaled to the reef scale in order to provide meaningful hindcasts. Moreover, tests of the predictive ability of the observed bleaching were based on a few observation data points where data was previously collected. It is possible that some historical bleaching events may not have been recorded in some reefs due to difficulties in accessing them. Also, no bleaching records were available for Browse Island; consequently, data from the Kimberley region were used. Spatial mismatch between bleaching data and spatial SST data aggregated across larger spatial scales may reduce the accuracy of temperature data. Lastly, where possible calibration of coral cores should be done with in situ data. In this case, sufficient in situ data points were not available. Consequently, we used satellite data for the calibration. As a result, comparisons between satellite and coral core data may be problematic due to circularity.

5. Conclusions

Differences between SST data sets continue to exist at a level relevant to understanding the mechanisms of coral responses to thermal stress and identifying coral bleaching risks. These differences reflect inconsistent definitions (e.g., whether the time of day of SST observation is adjusted for), and differing SST source data and retrieval algorithms. The question arises of which choices in creating SST time-series are most appropriate for the specific application of quantifying thermal stress on corals. The study has quantified the degree of consistency in two commonly used thermal stress indicators (based on weekly and monthly time scales) between common data sources and products, finding differences in sensitivity and specificity when applied to predicting historical coral bleaching events. Differences in data sources are sufficient to lead to inconsistencies in bleaching prediction and studies on thermal histories. Coral bleaching events continue to increase in prevalence and reliably identifying potential climate refugia is necessary. The thermal environment and variability are the key to such refugia, as it remains important to advance the exploitation of SST capability from various sources to reduce uncertainty in application to coral reefs. A data fusion solution is recommended to synthesize different data sets to generate a harmonized product for biophysical coral reef applications.

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Data Availability Statement

The R markdown code used for this study can be accessed in GitHub repository (vanessa-neohf et al., 2023).

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