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Optimized spatial and temporal pattern for coral bleaching heat stress alerts for China's coral reefs

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ABSTRACT

Most studies on coral bleaching alerts use common Degree Heating Week (DHW) thresholds; however, these may underestimate historical patterns of heat stress for coral reef ecosystems. Taking an optimized DHW threshold for coral bleaching alerts for Coral Reef Watch (CRW) and Coral Reef Temperature Anomaly Database (CoRTAD) products, we analyzed the precise spatial and temporal pattern of heat stress on China's coral reefs from 2010 to 2021 in the South China Sea (SCS) and the Beibu Gulf (BG). We compared acute heat stress using common and optimized thresholds. Results indicated that the ocean warming rate in 2010–2021 was approximately 0.43 ± 0.22 °C/10a, showing a significant increase in the northern SCS and the BG. More severe bleaching events were predicted by the optimized thresholds and the high-frequency areas were mainly in the northern SCS. The number and intensity of years with severe heat stress anomalies was in the order 2020 > 2014 > 2010 > 2015. Heat stress duration was the longest in the Xisha Islands among offshore archipelagos, and longest in 2020–2021 in Weizhou Island in BG in the relative high-latitude inshore reefs. These abnormal events were mainly caused by El Niño, but La Niña was also involved in 2020.

1. Introduction

Heat stress, induced by abnormally high sea surface temperature (SST), is among the most important factors affecting the health of coral reef ecosystems (Hoegh-Guldberg, 1999). High temperatures can force zooxanthellae out of their host scleractinian coral. This gives rise to mass coral bleaching or mortality, and potentially leads to the outbreak of coral disease (Darling and Côté, 2018; Yuan et al., 2019; Howells et al., 2020). In recent years, frequent occurrences of abnormally high SST around the world have led to large-scale coral bleaching events (Eakin et al., 2008; Frade et al., 2018; Hughes et al., 2018; Head et al., 2019; Howells et al., 2020; Cannon et al., 2021; Cheung et al., 2021). Moreover, SST in parts of the southwest Pacific is increasing at more than three times the global average, which further threatens reef health (AIMS, 2021; Zuo et al., 2021). Research on the historical patterns and driving factors of heat stress can help to identify reefs with potential resilience for protection and predict future reef health during climate change.

Compared with field surveys, remote sensing is a more effective tool for monitoring large-scale SST variations over coral reef areas. At present, coral bleaching alert indexes have been established using satellite SST data, such as HotSpot and Degree Heating Week (DHW). These indexes are included in the Coral Reef Watch (CRW) and Coral Reef Temperature Anomaly Database (CoRTAD) products and are widely used for global coral bleaching alerts (Selig, 2010; Liu et al., 2014a; Zuo et al., 2015a; Sully and van Woesik, 2020; Liu et al., 2021; van Woesik and Kratochwill, 2022). Researchers have focused on analyzing the spatial and temporal patterns of SST and heat stress in coral reef regions around the world. In terms of SST spatial variations, the warming trends of sea water were investigated in the Gilbert Islands of Kiribati in 1985–2009, the South China Sea (SCS) coral reefs in 1982–2010, and global coral reefs in 1985–2012 (Carilli et al., 2012; Zuo et al., 2015a;

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Heron et al., 2016; Khalil, 2019). Researchers mainly used the common DHW thresholds of 4°C-weeks and 8°C-weeks to investigate the heat stress pattern that induced coral bleaching and severe coral bleaching or even mortality in the Coral Triangle, Kiribati's Gilbert Islands, Caribbean Sea, and the global coral reef areas (Peñaflor et al., 2009; Carilli et al., 2012; Heron et al., 2016; Muñiz-Castillo et al., 2019).

It should be noted that because corals have regional differences in their temperature tolerance, the prediction accuracy of coral bleaching events using satellite heat stress products varies according to the region (Donner, 2011; Li et al., 2011). For example, studies found that coral bleaching or mortality often occurred when DHW values of CoRTAD or CRW were below the common thresholds in the northern Great Barrier Reef and in the SCS (Li et al., 2011; Zuo et al., 2015a; Hughes et al., 2018; Liu et al., 2021). Therefore, researchers began to improve the coral bleaching alert capabilities on the basis of in-situ coral health data. The targets included improving the computational temperature thresholds above the Maximum Monthly Mean (MMM) SST of HotSpot, optimizing the coral bleaching alert thresholds of DHW, and improving the 12-week accumulation window in the DHW calculation method (Kumagai et al., 2018; Skirving et al., 2019; McManus et al., 2020; Lachs et al., 2021; De et al., 2022; Eladawy et al., 2022; Qin et al., 2023). However, there is still a lack of research on accurately analyzing the spatial and temporal pattern of coral heat stress on the basis of the optimized thresholds.

The SCS and its coastal areas contain more than 200 coral reefs. These reefs have rich biodiversity and provide many people with food and services (Huang et al., 2015). Satellite SST analysis showed that the average warming trend of sea water in the SCS was 0.20 °C per decade in 1982–2009 (Zuo et al., 2015a). Since 2010, many coral bleaching events of varying degrees have been reported (Liu et al., 2021; Yao and Wang, 2021; Feng et al., 2022). The spatiotemporal pattern of coral reef heat stress in the SCS has been analyzed using the common DHW thresholds from 1982 to 2019 (Zuo et al., 2015a; Lu et al., 2022). However, Qin et al. (2023) found that when the DHW products of CRW and CoRTAD were used to warn of coral bleaching, the thresholds of the actual occurrence of coral bleaching events in the field were lower than the common thresholds. Therefore, the intensity of heat stress in coral reef areas in the SCS and the coastal areas may have been underestimated.

This paper used China's coral reefs in the SCS and the Beibu Gulf (BG) as the study area. We analyzed the SST trend of chronic heat stress, and the frequency, intensity, and anomaly duration of acute heat stress from 2010 to 2021. The precise spatiotemporal pattern of acute heat stress in the SCS was investigated using the optimized DHW thresholds of Qin et al. (2023) who adopted the CRW and CoRTAD heat stress products, and was then compared with DHW common thresholds. The aim of this study was to 1) obtain the difference in historical patterns of coral bleaching heat stress analyzed from common and optimized thresholds, and 2) provide more accurate data for coral reef conservation and management in the SCS and the BG.

2. Materials and methods

2.1. Study area

China's coral reefs in the SCS and the BG include the offshore SCS archipelagoes and the fringing reef areas (Fig. 1). The SCS archipelagoes include the Nansha Islands, Xisha Islands, Dongsha Islands, and Zhongsha Islands, which are mainly atolls. The Nansha Islands are the southernmost archipelago in the SCS, with more than 200 coral reefs and 251 species of scleractinian corals (Huang et al., 2021). Located in the northern and central SCS, the Zhongsha Islands are made up of more than 20 atolls and islets, most of which have long been submerged. The Xisha Islands in the northwest SCS have 36 coral reefs and 204 species of scleractinian corals (Huang et al., 2011). The Dongsha Islands are the

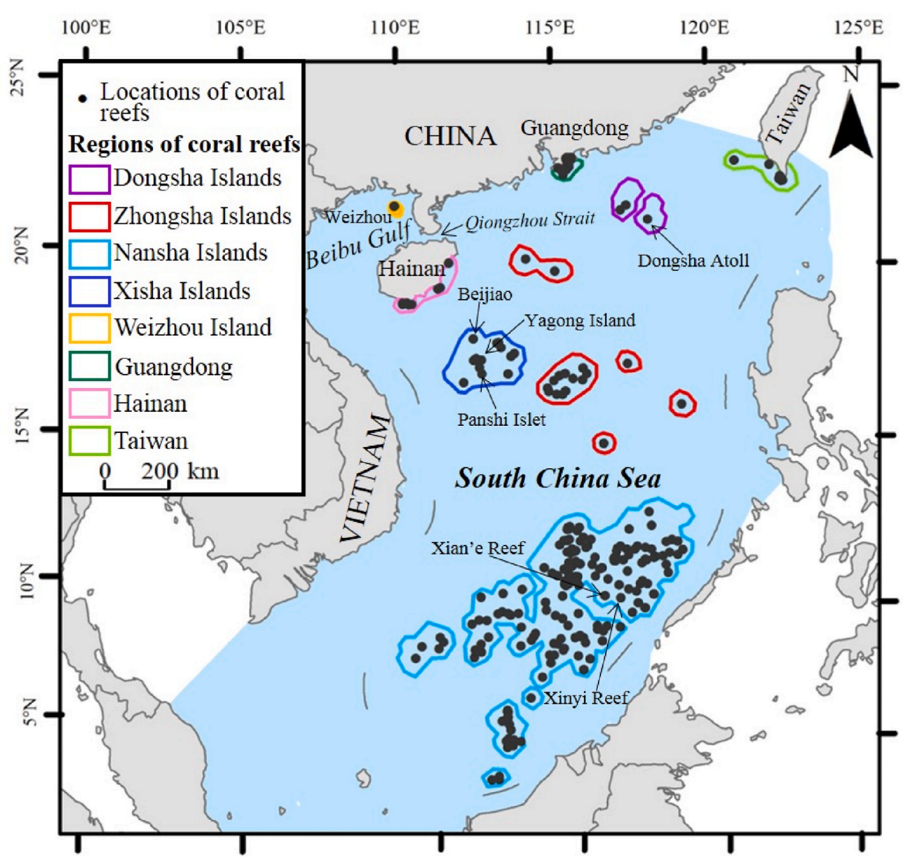

Fig. 1. Locations of coral reefs in the study area.

northernmost archipelago, and 101 species of scleractinian corals have been recorded (Dai et al., 1995).

The inshore fringing reefs of Hainan and Taiwan in the SCS are typical tropical coral reef coasts. The fringing reefs in Guangdong province in the SCS and Weizhou Island in the BG are relatively high-latitude coral reefs with low coral coverage and diversity; they have 55 and 49 species of scleractinian corals, respectively (Zou, 2001; Liang et al., 2021).

2.2. Data

2.2.1. Locations of coral reefs

Point data were used to represent the locations of coral reefs. The reef location data of the Xisha Islands, Zhongsha Islands, Dongsha Islands and Nansha Islands came from the Reef Archive of China. The location data of coral reefs in Hainan, Taiwan, Guangdong, and Weizhou Island were acquired from ReefBase (http://reefgis.reefbase.org/).

2.2.2. CRW heat stress data

The daily CRW Version 3.1 data included CoralTemp (°C), HotSpot (°C), and DHW (°C-weeks) products from 2010 to 2021, which had a 5 km spatial resolution and were obtained from the NOAA Satellite and Information Service website. The CoralTemp data are a combination of nighttime SST data from different satellites, calibrated to a depth of 0.20 m. They provide more stable coral bleaching heat stress calculations than daytime and day–night mixed SST data (Skirving et al., 2020). Studies have shown that coral bleaching occurs when the SST exceeds the summertime maximum SST by more than 1 °C (Glynn and D'Croz, 1990; Liu et al., 2014a). The CRW HotSpot is the temperature obtained by subtracting the MMM SST from CoralTemp. CRW uses SST data from 1985 to 2012 to generate the MMM SST. DHW is the cumulative heat stress experienced by the reef over a period of 3 months (12 weeks or 84 days), expressed in °C-weeks. One DHW means that the SST exceeds the MMM by 1 °C for 1 week, and two DHW_S means that the SST exceeds the MMM by 2 °C for 1 week or by 1 °C for 2 weeks, and so on. The cumulative values of HotSpot ≥1 °C within the previous 84 days is the CRW DHW index, using for coral bleaching alerts.

2.2.3. CoRTAD heat stress data

The 2010–2021 weekly CoRTAD Version 6 data were downloaded from the NOAA National Centers for Environmental Information website, including the MedfillSST (°C), thermal stress anomaly (TSA) (°C), and TSA_DHW (°C-weeks) data products with 4 km spatial resolution. CoRTAD data have been developed specifically for coral reef climate and ecosystem applications. MedfillSST uses the average day and night SST data from the 4 km AVHRR Pathfinder SST as well as the 3 × 3 window median for spatial interpolation, which are accurate when compared with field SST data from coral reef depths of at least 10 m (Selig, 2010). The TSA is equivalent to CRW HotSpot and is calculated by subtracting the maximum weekly climatological SST from the MedfillSST. The SST data from 1982 to 2017 are used to calculate the maximum weekly climatological SST in CoRTAD. TSA_DHW is the TSA Degree Heating Week and is equivalent to the CRW DHW, which is accumulated by a TSA ≥1 °C in the previous 12 weeks.

2.3. Methodology

Chronic heat stress, such as long-term SST increases, and acute heat stress, or short-term abnormal SST increases, represent two kinds of heat stress threats for coral reefs (Hoegh-Guldberg, 1999; Mumby et al., 2014). The SST trends for chronic heat stress and the frequency, intensity, and anomaly durations of acute heat stress in the study area from 2010 to 2021 were analyzed.

2.3.1. Chronic heat stress

NOAA CRW daily CoralTemp data were used to calculate the chronic heat stress from 2010 to 2021. Firstly, annual minimum SST, annual mean SST, and annual maximum SST from January to December 2010–2021 were computed for all sub-regions (Fig. 1) using the CRW CoralTemp data to investigate the recent local climate environments. The SST trend (S) during summer was calculated using a linear regression method on the basis of CRW's monthly-mean CoralTemp data, to measure the intensity of chronic heat stress (Selig, 2010; Zuo et al., 2015a). The F test was used to determine whether the SST trend was significant. P represents the significance at the level $\alpha = 0.05$. The significance of the SST trend was divided into six categories: extremely significant increase ($S > 0$, $P < 0.01$), significant increase ($S > 0$, $0.01 < P < 0.05$), no significant increase ($S > 0$, $P > 0.05$), no significant decrease ($S < 0$, $P > 0.05$), significant decrease ($S < 0$, $0.01 < P < 0.05$), and extremely significant decrease ($S < 0$, $P < 0.01$).

2.3.2. Acute heat stress

The DHW thresholds for bleaching and severe bleaching alerts were set to T1 (Threshold 1, °C-weeks) and T2 (Threshold 2, °C-weeks), respectively. They were established on the basis of the DHW heat stress levels and the in-situ coral bleaching data. Studies indicate that significant bleaching is likely be observed when T1 ≤ DHW < T2, while severe bleaching and significant mortality is likely be observed when DHW ≥ T2 (Liu et al., 2014a; Donner et al., 2017; Qin et al., 2023). In this paper, the global DHW common thresholds (Liu et al., 2014a) and optimized thresholds by Qin et al. (2023) for CRW and CoRTAD products for coral bleaching alerts were adopted to analyze patterns of acute heat stress in the SCS. The settings of the optimized DHW thresholds in Qin et al. (2023) aimed to reduce the false positive rate to successfully predict more bleaching events. Compared with the common thresholds, the optimized thresholds enhanced the prediction accuracy of the CRW and CoRTAD products, and were a closer match to actual coral health surveys (Qin et al., 2023).

First, DHW_MAX was extracted at the locations of coral reefs in each year from 2010 to 2021. Second, using the common thresholds (T1 = 4°C-weeks, T2 = 8°C-weeks) for CoRTAD and CRW, the optimized thresholds for CoRTAD (T1 = 2.36°C-weeks, T2 = 4.14°C-weeks) and the optimized thresholds for CRW (T1 = 3.32°C-weeks, T2 = 4.52°C-weeks) (Qin et al., 2023), the frequency of mild bleaching heat stress (number of years when T1 ≤ DHW_MAX < T2) and severe bleaching heat stress (number of years when DHW_MAX ≥ T2) were counted for CRW and CORTAD, respectively. Frequencies of 0–2, 3–4, and 5 were defined as the low-frequency, medium-frequency, and high-frequency of coral bleaching heat stress regions, respectively.

Third, the proportion of coral reefs affected by bleaching-level heat stress (DHW_MAX ≥ T1), mild-bleaching heat stress (T1 ≤ DHW_MAX < T2), and severe-bleaching heat stress (MAX_DHW ≥ T2) were calculated to evaluate the intensity of heat stress in each year using the common and optimized thresholds. Then screening was carried out for the years of severe heat stress anomalies using the criterion that at least 50% of coral locations experienced bleaching-level heat stress. Finally, the anomaly duration in each coral reef region was measured on the basis of all the heat stress anomaly events in a year. Because CRW had better coral bleaching alert capability than CoRTAD in the study area (Qin et al., 2023), the cumulative number of days with HotSpot ≥1 °C (Glynn and D'Croz, 1990) for CRW data were calculated to analyze the heat stress duration time in each coral reef area year by year.

3. Results

3.1. Climatological SST

The variations of climatological SST in each region of the study area in 2010–2021 are shown in Fig. 2. The highest SST occurred in 2010, 2015–2016 and 2019–2020 (Fig. 2). The annual minimum SST rose rapidly in winter in the fringing reefs of Hainan and Weizhou Island from 2019 to 2020 (Fig. 2E and F). In general, the annual mean SST of

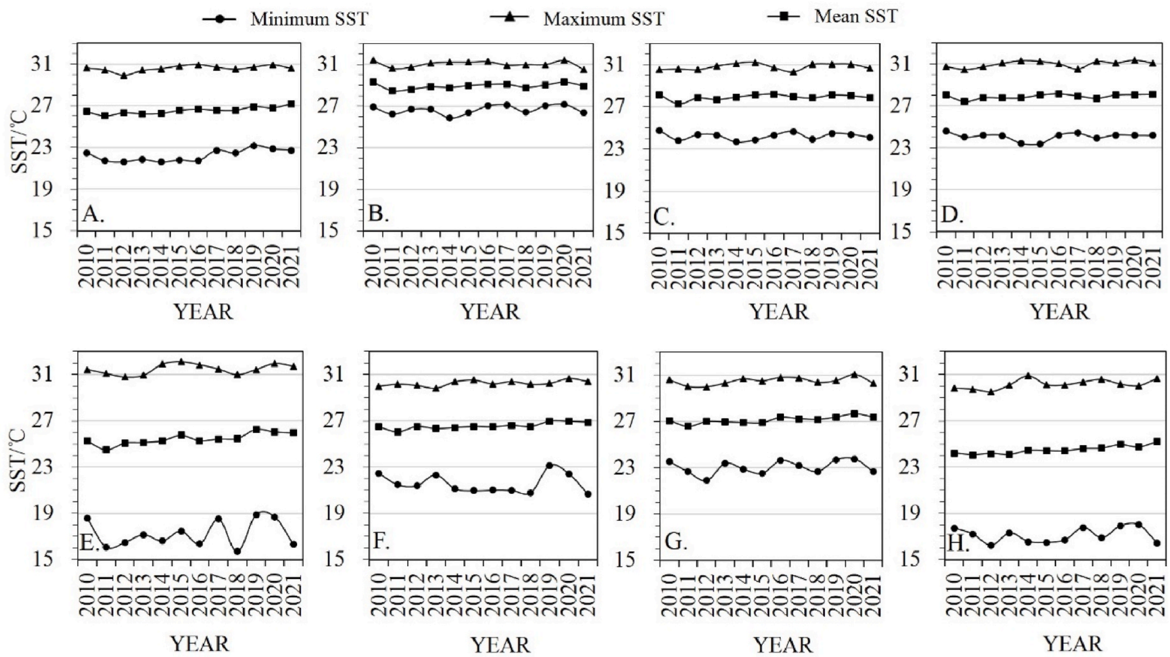

Fig. 2. Climate statistics for coral reefs in 2010–2021 using CRW SST products in the study area.
(Note: Plot-A is Dongsha Islands; Plot-B is Nansha Islands; Plot-C is Xisha Islands; Plot-D is Zhongsha Islands; Plot-E is Weizhou Island; Plot-F is the southern coast of Hainan Island; Plot-G is the southern coast of Taiwan; Plot-H is the coast of Guangdong).

each coral reef region showed an upward trend (Fig. 2).

3.2. Chronic heat stress

The warming trend of sea water from 2010 to 2021 and their significance levels are shown in Fig. 3. Fig. 3a suggests that the SST in the SCS and the BG had an overall increasing trend (S > 0) from low latitude to high latitude over the past decade, with an average increase rate of approximately 0.43 ± 0.22 °C/10a. The extremely significant SST increase regions (S > 0, $P < 0.01$) were mainly distributed in the northern Zhongsha Islands, Dongsha Atoll, eastern Hainan Island, Guangdong, and Taiwan in the SCS and Weizhou Island in the BG (Fig. 3b). The SST in southern Hainan Island and the northwestern Dongsha Islands showed a significant increasing trend (S > 0, $0.01 < P < 0.05$) (Fig. 3b). The sea warming rate in the BG, the northeastern Dongsha Islands and the northern Zhongsha Islands was as high as 0.80 ± 0.20 °C/10a, and even exceeded 1 °C/10a in Weizhou Island of BG (Fig. 3a).

3.3. Acute heat stress frequency

The heat stress frequency of mild and severe bleaching differed spatially for CRW and CoRTAD data using the optimized thresholds. The moderate–high-frequency (more than 3 years) of mild bleaching areas in the SCS for CRW were mostly located in the southwestern Nansha

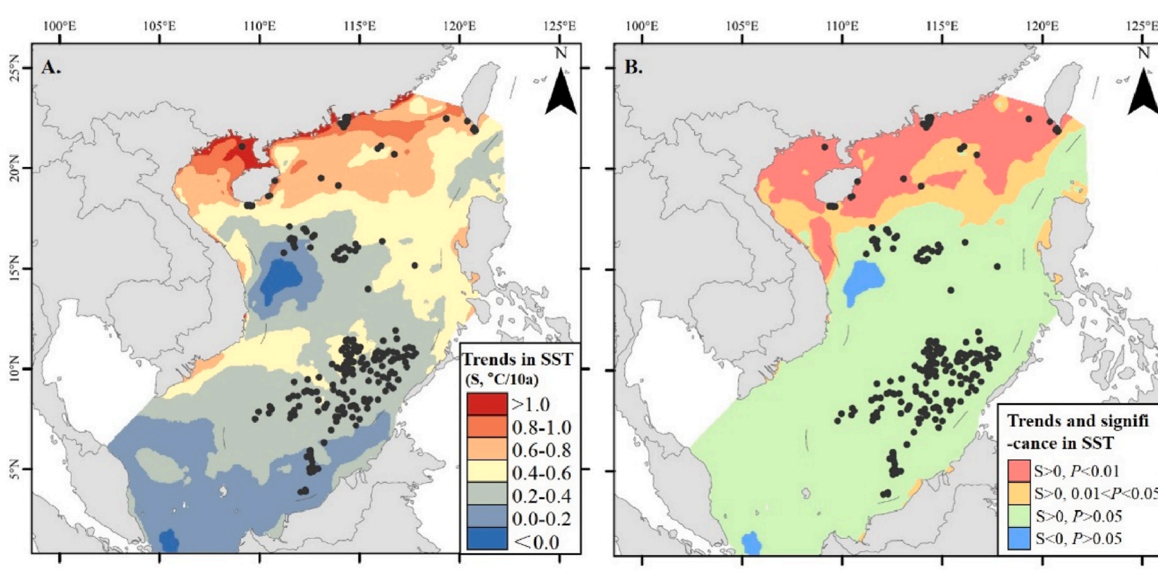

Fig. 3. SST increasing trends using CRW data in the South China Sea and the Beibu Gulf from 2010 to 2021.
(Note: S (°C/10a) in Plot-B represents the trend in SST in Plot-A, P in Plot-B represents the significance. Categories in Plot-B include extremely significant increase (S > 0, $P < 0.01$), significant increase (S > 0, 0.01 < P < 0.05), no significant increase (S > 0, P > 0.05), and no significant decrease (S < 0, P > 0.05).).

Islands and the northwestern Dongsha Islands (Fig. 4B), whereas for CoRTAD they were concentrated in the Nansha, Zhongsha, Xisha and the northwestern Dongsha Islands (Fig. 4D). The high-frequency areas of severe bleaching for CRW and CoRTAD were primarily concentrated in the Dongsha Islands, Xisha Islands, Zhongsha Islands, and the central and northern Nansha Islands (Fig. 5B and D).

Compared with the common thresholds (Fig. 4A and C; Fig. 5A and C), the high-frequency areas of mild bleaching with optimized thresholds were substantially smaller, and the high-frequency areas of severe bleaching were significantly larger for both CRW and CoRTAD (Fig. 4B and D; Fig. 5B and D). The high-frequency areas of mild bleaching were upgraded to high-frequency areas of severe bleaching in the northeastern and western SCS, including the Dongsha Islands, Zhongsha Islands, western Xisha Islands, and northwestern Nansha Islands (Fig. 4A and C; Fig. 5B and D). This showed that severe bleaching events in the northeastern and western SCS would be significantly underestimated if common thresholds were applied to alerts.

3.4. Acute heat stress intensity

The years of severe heat stress anomalies on coral reefs were extracted using the criterion that at least 50% of coral reefs experienced bleaching-level heat stress (Fig. 6). On the basis of the optimized thresholds, the years of severe anomaly heat stress in 2010–2021 extracted from the CRW were 2010, 2014, 2015, and 2020, and those extracted from the CoRTAD were 2010, 2013, 2014, 2015, 2016 and 2020 (Fig. 6).

For the CRW, the optimized bleaching-level heat stress intensity for 2020 was the highest compared with that extracted from the common thresholds, with 90.8% of the reefs affected by bleaching-level heat

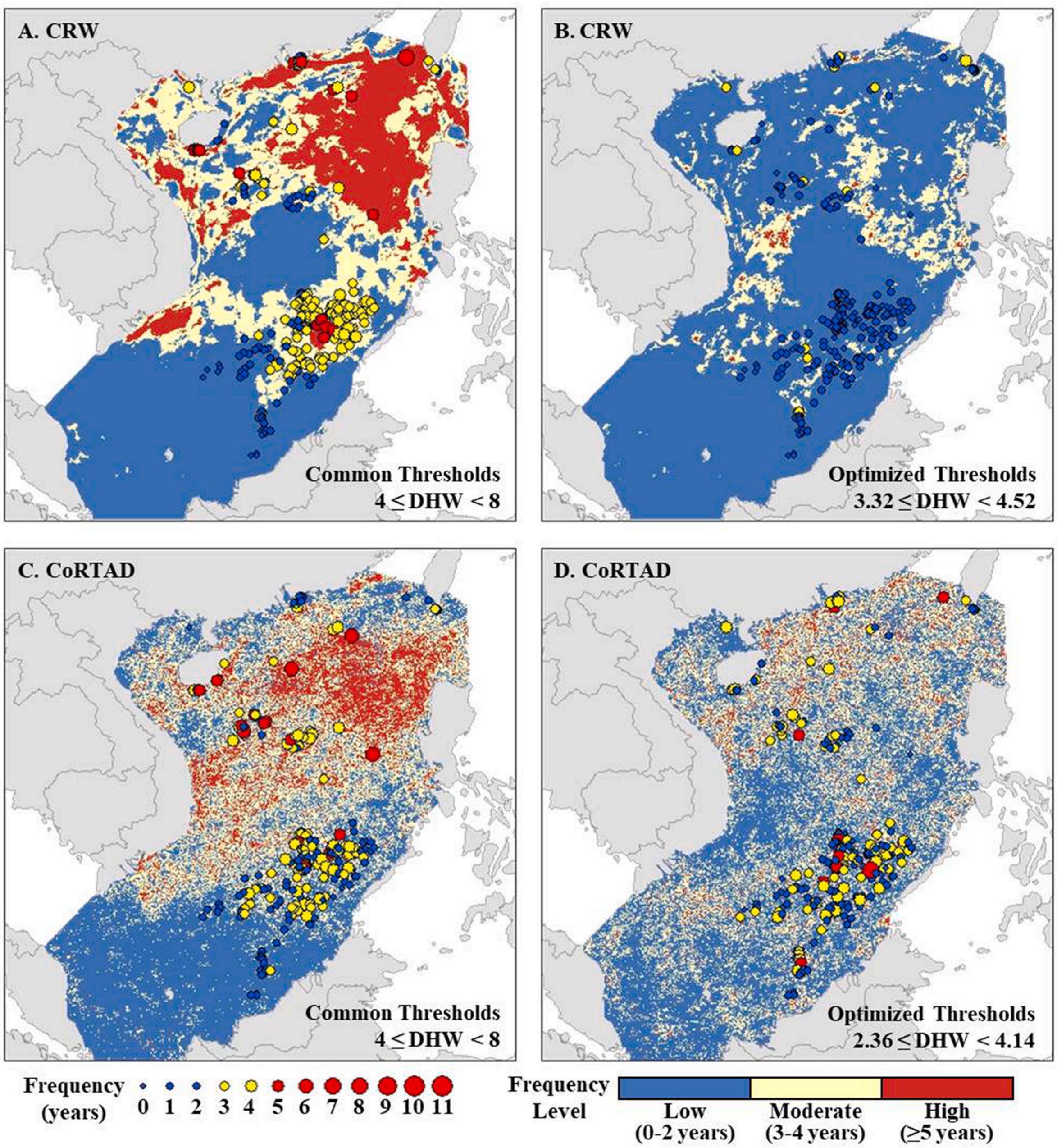

Fig. 4. Frequency distribution of mild bleaching heat stress for CRW and CoRTAD from 2010 to 2021.
(Note: Plot-A and C are mild bleaching heat stress extracted at common thresholds; plot-B and D are mild bleaching heat stress extracted at optimized thresholds; DHW unit is °C-weeks).

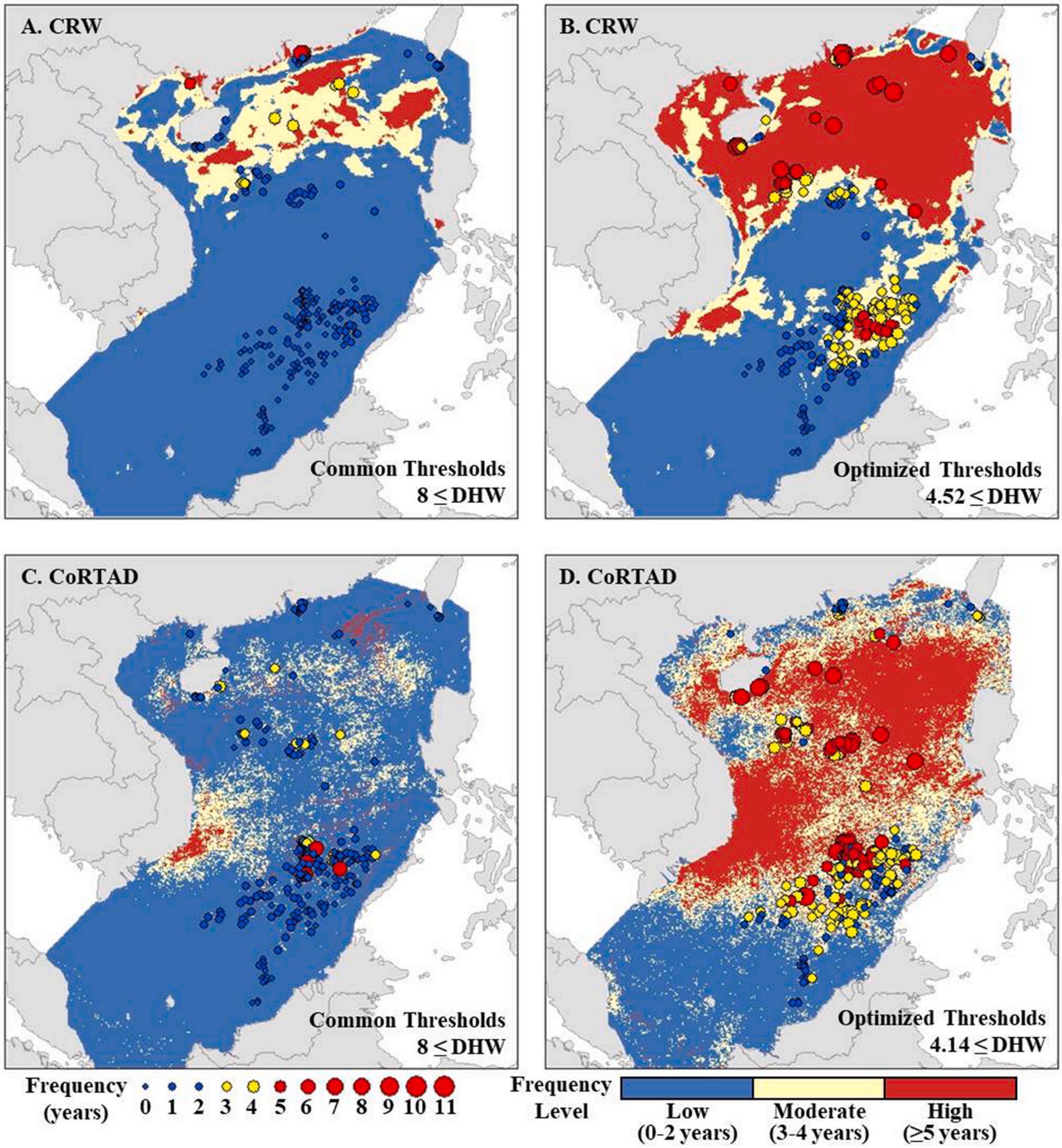

Fig. 5. Frequency distribution of severe bleaching heat stress for CRW and CoRTAD from 2010 to 2021.
(Note: Plot-A and C are severe bleaching heat stress extracted at common thresholds; plot-B and D are severe bleaching heat stress extracted at optimized thresholds).

stress in 2020, and up to 85.2% of the corals experiencing severe bleaching-level heat stress (Fig. 6A). In 2014, there was a higher bleaching-level heat stress intensity with CRW data than that in 2010, which was contrary to the results obtained using the common thresholds (Fig. 6A). For the CoRTAD, the optimized bleaching-level heat stress intensity for 2010 was still the highest compared with the common thresholds (Fig. 6B). Overall, the annual bleaching-level heat stress intensity extracted by both CRW and CoRTAD using optimized thresholds was generally higher than that using common thresholds. Moreover, the proportion of coral reefs experiencing severe-bleaching heat stress intensity was significantly increased (Fig. 6). Because the study showed that CRW can better alert to coral bleaching events in the SCS than the CoRTAD (Qin et al., 2023), this paper concluded that the years of severe anomaly heat stress and their intensity from 2010 to 2021 were in the order of 2020 > 2014 > 2010 > 2015 using the CRW products (Fig. 6).

3.5. Acute heat stress anomaly duration

Results showed that the average duration of heat stress in each coral reef area increased from 2010 to 2021, although there were large annual fluctuations (Fig. 7). In severe heat stress anomaly years, the overall average duration of heat stress in offshore archipelagos in the SCS showed a pattern of Xisha Islands > Dongsha Islands > Zhongsha Islands > Nansha Islands, with approximately 50 days, 40 days, 35 days, and 26 days, respectively (Fig. 7A). The Xisha Islands' average duration was the longest for offshore archipelagos in the severe anomaly years of 2014, 2015, and 2020, reaching approximately 90 days in 2020 (Fig. 7A). For the Dongsha Islands, the highest average duration was approximately 65 days in 2020 (Fig. 7A).

The overall average duration also had an increasing trend for inshore fringing reefs and peaked in 2020–2021 (Fig. 7B). The overall average duration in Guangdong was the shortest, with the most prolonged

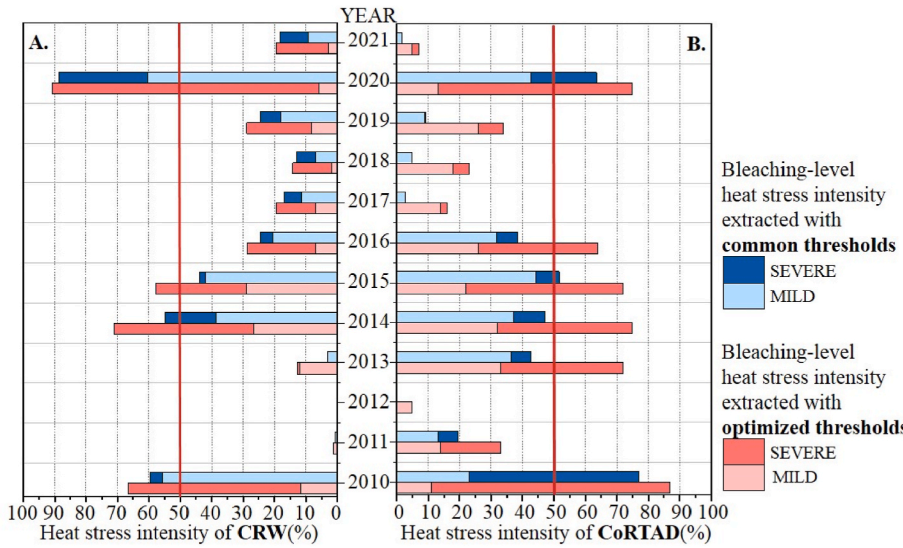

Fig. 6. Heat stress intensity of CRW and CoRTAD from 2010 to 2021.
(Note: Plot-A shows the heat stress intensity from CRW for each year's mild and severe bleaching levels; Plot-B shows the heat stress intensity from CoRTAD for each year's mild and severe bleaching levels).

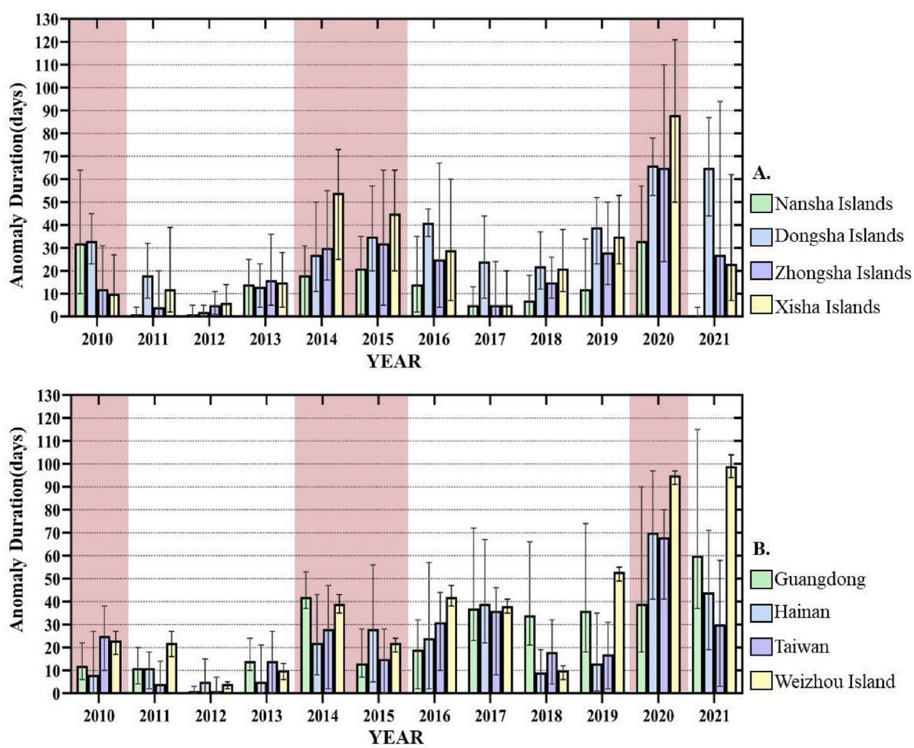

Fig. 7. Heat stress anomaly duration in coral reef areas from 2010 to 2021.
(Note: Plot-A is the maximum, minimum, and average duration for offshore reef areas; Plot-B is the same for inshore fringing reef areas. The red shaded area indicates the years with severe heat stress anomalies).

average duration at approximately 60 days in 2021 (Fig. 7B). The average duration of Hainan and Taiwan was approximately 70 days in 2020 (Fig. 7B). The average duration of Weizhou Island in the BG was the highest, reaching more than 95 days in 2020–2021 (Fig. 7B).

4. Discussion

4.1. *Repeated heat stress in the South China Sea Islands*

Results showed that heat stress anomaly events in the SCS occurred frequently from 2010 to 2021 (Figs. 4–5). The intensity of acute heat stress increased (Figs. 6–7), with the year and intensity of heat stress anomalies in the order of 2020 > 2014 > 2010 > 2015 (Fig. 6). These anomalous heat stress years correspond well with the field survey data of coral bleaching. In the summer of 2010, coral bleaching occurred in shallow waters of Dongsha Atoll in the Dongsha Islands owing to elevated seawater temperatures (Keshavmurthy et al., 2017). Severe ocean warming in the summer of 2014 also led to mass coral bleaching at Beijiao and Yagong Island in the Xisha Islands, and scattered coral bleaching was found on Yin Islet in this archipelago in early June (Li et al., 2016; Zuo et al., 2015b, 2017; Huang et al., 2021). During the global-scale coral bleaching events in 2015–2016, the coral microbiome community data collected in the SCS showed a significant decrease in coral zooxanthellae densities and an increase in potential pathogens, indicating that the corals in SCS had suffered from the heat stress anomaly (Qin et al., 2020). Coral bleaching was also found in the initial stages in Xinyi Reef and Xian'e Reef of Nansha Islands in June 2016 (Qin et al., 2019; Sun et al., 2022).

In 2020, the overall average coral bleaching rate was 23.90% in the Xisha Islands, and Beijiao in this area had the highest coral bleaching rate at 49.30% (Xiao et al., 2022). Meanwhile, crown-of-thorn starfish (COTS) outbreaks have recurred in Xisha Islands since 2018 (Wang et al., 2023). Owing to the concurrent negative effect of the COTS outbreaks and the longest average duration of heat stress anomalies in the offshore islands (Fig. 7A), coral reefs in the Xisha Islands have been severely degraded from 2010 to 2020 (Zuo et al., 2017, 2020; Chen et al., 2019). Panshi Islet in the southwest Xisha Islands only had 0.40% live coral coverage in 2020 (Tkachenko and Hoang, 2022; Xiao et al., 2022). Coral reefs in South–Central Vietnam in the SCS also collapsed during 2016–2020, experiencing a 93% decrease in live coral coverage and a sixfold decrease in coral diversity (Tkachenko et al., 2023). If repeated coral bleaching heat stress and severe natural impacts continue in the future, the ecological condition of coral reefs in the SCS will decline.

We compared the patterns using optimized thresholds and common thresholds (Qin et al., 2023). The patterns using the optimized thresholds were more closely related to the actual coral health surveys. For example, Qin et al. (2019) found in situ mild coral bleaching events on June 10, 2016 in Xinyi Reef of Nansha Islands in the SCS, where the maximum DHW of CRW (3.87 °C-weeks) and CoRTAD (3.5 °C-weeks) predicted no coral bleaching events with the common thresholds. When using the optimized thresholds, both CRW and CoRTAD predicted a mild bleaching event, which was consistent with the field survey. Sun et al. (2022) surveyed a severe coral bleaching event on 16 June 2016 at Xian'e Reef in the Nansha Islands in the SCS, whereas the maximum DHW of CRW (5.03°C-weeks) and CoRTAD (5.64°C-weeks) suggested a mild coral bleaching event with the common thresholds. However, both CRW and CoRTAD predicted a severe bleaching event with the optimized thresholds, which also concurred with the field survey. Therefore, the patterns evaluated by the optimized thresholds in this study were more accurately aligned with the actual situation compared with those of the common thresholds.

4.2. Relationship between heat stress anomalies and ENSO

Studies indicate that the SST warming induced by El Niño events in the SCS lags by 7–9 months, with the El Niño 3.4 index (Lu et al., 2022). El Niño events result in bimodal warming in the subsequent year following the El Niño development year in the SCS. The first warming is due to a decrease in cloudiness in the SCS around February in the subsequent year following El Niño development, which increases net solar radiation flux. The second warming is due to weakening summer winds, which leads to reduced latent heat loss and weakens the influence of upwelling off the coast of Vietnam, resulting in an abnormal increase in SST around August in the subsequent year following El Niño development (Liu et al., 2014b; Zuo et al., 2015a). According to the El Niño index, a weak El Niño occurred in 2009 and 2019, and a strong El Niño occurred in 2014 that lasted 20 months until June 2016 (Li et al., 2021). The years 2010, 2015 and 2020 are the subsequent years of El Niño development. The year 2014 was in the early stages of strong El Niño development (Li et al., 2021).

It should be noted that the weak El Niño-influenced 2020 had the highest intensity of heat stress, which was higher than the strong El Niño-influenced 2015 and even comparable with that in 1998 (Fig. 6). The strong El Niño in 1998 caused the first global widespread coral bleaching event. On the basis of CoRTAD products and the bleaching alert threshold of 4°C-weeks, 66% of coral reefs in the SCS were predicted to experience bleaching-level heat stress in 1998 (Zuo et al., 2015a), while 64% of coral reefs in the SCS experienced bleaching-level heat stress in 2020 in this study (Fig. 6). The high heat stress event of 2020 was mainly caused by El Niño, but La Niña was also involved in some of this heat stress. Yao and Wang (2021) suggested that rapid decay of El Niño is more conducive to strengthening the summer western North Pacific subtropical high. Thus, the La Niña event in the summer of 2020 accelerated the decay of the El Niño event, leading to an abnormal intensification and westward extension of the western North Pacific subtropical high, which weakened summer winds and caused upwelling in southern Vietnam to diminish or even disappear. Furthermore, the appearance of anomalous easterlies in the equatorial Pacific led to the formation of an anomalous anticyclone through Ekman dynamics over the northern SCS and northwestern Pacific in the summer of 2020. This anomalous anticyclone, related to the La Niña event, increased the downward latent heat flux and shortwave radiation, causing an anomalous warming of the SST in the northern SCS (Chen et al., 2022). Additionally, the current study discovered that the Dongsha Islands, Weizhou Island, and Guangdong waters in the northern SCS experienced the most prolonged heat stress anomaly duration in 2021, which was the subsequent year following a La Niña event (Fig. 7). A few studies have found that marine heat waves in the SCS may also occur in other years after a La Niña event (Tan et al., 2022). The sea warming showed a single peak from February to May in the subsequent year of the La Niña, and it was concentrated in the BG (Liu et al., 2022).

Compared with the anomalously high temperature in the SCS in 1982–2009, which was mainly caused by El Niño events (Wang et al., 2006; Zuo et al., 2015a), the pattern of SST anomaly in the SCS in 2010–2021 has become more complex with continued global warming. This is reflected by the fact that anomalous heat stress events occurred not only in the subsequent year of El Niño development but also in the development year of a strong El Niño, a La Niña year, and the subsequent year of a La Niña. Overall, the El Niño mainly caused severe heat stress anomaly events but La Niña was also involved in some of them in the study area. In addition, extremely high temperatures are also driven by various factors such as the Interdecadal Pacific Oscillation, the East Asian monsoon, and global warming (Romero-Torres et al., 2020; Xiao et al., 2022), which can be further combined to affect the occurrence pattern of SST anomalies in the SCS.

4.3. The heat stress intensity of relatively high-latitude reefs

The SST average increase rate was approximately 0.43 ± 0.22 °C/10a in the SCS from 2010 to 2021 (Fig. 3). This was higher than the worldwide SST average increase of 0.10 ± 0.02 °C/10a and higher than that of 0.20 °C/10a in 1982–2009 in the SCS (Zuo et al., 2015a). The SCS is one of the most heat-stressed regions in the context of global warming, thus it is critical for coral conservation to identify its thermal refuges. It is commonly assumed that turbid nearshore environments may act as potential coral reef refuges in high-temperature environments (Yuan et al., 2019; Sully and van Woesik, 2020), such as Weizhou Island in BG. However, the results of this study showed that Weizhou Island's regional SST average warming rate exceeded 1 °C/10a (Fig. 3; $P < 0.01$) from 2010 to 2021, which was much larger than the whole SCS's SST average increase during the same period (Fig. 3). Also, the average duration of the severe heat stress anomaly of the Weizhou Island was the highest, including more than 95 days in 2020 (Fig. 7B). This was much longer than the relatively low-latitude Nansha Island's average duration of 26 days (Fig. 7A).

Previous studies have shown that zonal wind, latent heat flux, and a strong El Niño have substantial effects on SST in the BG (Yao et al., 2022). In 2020, the BG was completely controlled by the western North Pacific subtropical high, resulting in more sunny and less cloudy weather, enhanced solar short-wave radiation, a weakened monsoon, and reduced convective activities (Yao and Wang, 2021; Zi et al., 2022). The water depth in the Gulf is shallower than 100 m (Gao et al., 2017), which might cause this area to be more sensitive to atmospheric warming because of its smaller heat capacity compared with the SCS. Previous studies have also shown that the shallow sea areas of the BG heat up faster (Liu et al., 2021). In addition, the land has a smaller heat storage capacity than ocean water, thus the temperature on land changes quickly, and the river water in summer is hotter compared with the ocean water. The BG is enclosed by the mainland on three sides. Possibly influenced by the warm waters discharged from the Red River and the westerly flow of the Qiongzhou Strait, the largest warming in summer in the BG was observed in the region along the west coast and west mouth of the Qiongzhou Strait (Liu et al., 2021), which is consistent with this study (Fig. 5).

During the summer of 2020, Weizhou Island and Hainan Island experienced the most severe anomalous SST in recent years, with a widespread coral bleaching event in the field survey (Lyu et al., 2022). Although the satellite SST precision of the inshore coral reefs may be influenced by the land, the SST anomalies have generally extended from tropical reefs to Hainan Island and relatively high-latitude reefs in recent years, consistent with the results of this study (Fig. 7B). Therefore, in the conditions of continued global warming and the increasing frequency of extremely high heat stress, the frequency and severity of coral bleaching in relatively high-latitude reefs will increase in the future, even beyond their resilience. It is predicted that they may not serve as thermal refuges for coral reefs in the SCS in the future.

5. Conclusion

Taking China's offshore and inshore coral reefs in the SCS and the BG as the study area, the accurate spatiotemporal patterns of chronic heat stress and acute heat stress from 2010 to 2021 were analyzed. Acute heat stress was evaluated and compared using the DHW common and optimized thresholds for coral bleaching alerts for CRW and CoRTAD products. The main conclusions are as follows.

(1) The SST average warming rate for chronic heat stress in the SCS was approximately 0.43 ± 0.22 °C/10a from 2010 to 2021, presenting a significant increase in the northern SCS and the BG.
(2) The moderate–high-frequency (more than 3 years) of mild bleaching areas in the SCS were mostly located in the Nansha Islands, Xisha Islands and the Dongsha Islands. The high-frequency areas of severe bleaching level events were mainly focused in the central and northern SCS. Compared with the common thresholds, more severe bleaching events can be better predicted by the optimized thresholds.
(3) The heat stress intensity increased from 2010 to 2021, with the intensity in the years of severe anomaly heat stress in the order 2020 > 2014 > 2010 > 2015. These severe anomaly heat stress events were mainly caused by El Niño events, but La Niña events were also involved in 2020.
(4) The overall anomaly duration on offshore archipelagos in the SCS showed a pattern of Xisha Islands > Dongsha Islands > Zhongsha Islands > Nansha Islands. Coral reefs in the Xisha Islands have significantly deteriorated owing to the concurrent negative effects of repeated heat stress anomalies and COTS outbreaks. The inshore fringing reef of Weizhou Island in the BG in the relative high latitudes had the longest average heat stress duration time of more than 95 days in 2020–2021. High-latitude reefs areas are predicted not to be suitable thermal refuges for SCS reefs in the future.

This study emphasizes the importance of optimizing the spatial and temporal patterns of heat stress on coral reefs and provides a more accurate spatial and temporal mapping approach for the conservation and management of coral reef ecosystems in the SCS. We deem that both offshore and inshore coral reefs in the SCS and BG need attention and protection.

Author statement

Xiuling Zuo: Conceptualization, Methodology, Investigation, Writing - Original Draft, Reviewing and Editing, Funding acquisition. **Binni Qin**: Methodology, Validation, Investigation, Writing - Original Draft. **Juncan Teng**: Writing- Editing. **Xiaopeng Duan**: Figures, Writing- Editing. **Kefu Yu**: Conceptualization, Writing- Reviewing, Supervision. **Fenzhen Su**: Conceptualization, Methodology, Writing- Reviewing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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