

Assessment of Thermal Stress on South China Sea Coral Reefs in Response to Climate Change and Differentiated Conservation Strategies

Changtong Jiang

jiangchangtong@mail.bnu.edu.cn

Beijing Normal University

Cong Jiang

Leibniz-Institute of Freshwater Ecology and Inland Fisheries in the Forschungsverbund Berlin eV:
Leibniz-Institut für Gewässerökologie und Binnenfischerei

Xin Yin

Beijing Normal University

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1 **Assessment of Thermal Stress on South China Sea Coral Reefs in**
2 **Response to Climate Change and Differentiated Conservation**
3 **Strategies**

4 Changtong Jiang^{1,2}, Cong Jiang³, Xin Yin^{1,2*}

5 ¹ School of National Safety and Emergency Management, Beijing Normal University,
6 China

7 ² Joint International Research Laboratory of Catastrophe Simulation and Systemic Risk
8 Governance, Beijing Normal University at Zhuhai, Zhuhai 519087, China

9 ³ Department of Ecohydrology and Biogeochemistry, Leibniz-Institute of Freshwater
10 Ecology and Inland Fisheries (IGB), Berlin, Germany

11 * Corresponding author: Xin Yin (xin.yin@bnu.edu.cn)

12 **Abstract**

13 In recent decades, rising sea surface temperatures driven by global climate change have
14 increased the frequency and intensity of coral bleaching events, posing severe threats
15 to coral reef ecosystems worldwide. As an important tropical marine ecosystem in the
16 western Pacific, the coral reefs of the South China Sea Islands are highly sensitive to
17 climate change and have become a key region for assessing future thermal stress and
18 conservation priorities. This study employs satellite-observed CoRTAD and CMIP6
19 climate model CanESM5 SST data (1982–2100), calibrated with historical OISST
20 observations, to calculate thermal stress scenarios for South China Sea coral reefs. It
21 identifies priority conservation zones under diverse climate projections. Under SSP126,
22 SSP245, SSP370, and SSP585 scenarios, approximately 40.7%, 26.6%, 32.8%, and
23 39.8% of coral reefs respectively exhibit high ecological conservation priority. Priority
24 area identification comprehensively considered future bleaching duration, temperature
25 trends, and ecological resilience. Differentiated management recommendations were
26 proposed for reefs experiencing varying levels of thermal stress. These findings
27 establish a scientific foundation for future marine protected area siting, climate-resilient
28 ecological governance, and regional collaboration.

Keywords: Coral reef; South China Sea; thermal stress; climate change; CMIP6; conservation priority

1 Introduction

Coral reefs constitute not only a vital component of marine ecosystems but also the foundation for marine resource development, management, and the safeguarding of maritime rights and interests. Temperature serves as a limiting factor for reef-building coral growth, with an optimal range of 22–28°C. Temperatures exceeding or falling below this range trigger coral bleaching due to the expulsion of symbiotic algae from their tissues(Zhu et al., 2004). However since the mid-20th century, increased global greenhouse gas emissions have disrupted marine thermal equilibrium, leading to rising sea surface temperatures (SST) (IPCC, 2013).The subsequent thermal stress from elevated sea temperatures has caused widespread coral bleaching and mortality (Hoegh-Guldberg, 1999; Sheppard et al., 2017; Van Hooidonk et al., 2013). This includes bleaching events observed on Subi Reef and Mischief Reef in the Spratly Islands in 2007(Li et al., 2011; Zuo et al., 2015). Coral reefs in the South China Sea constitute 5% of global coral reef resources, distributed across the Dongsha, Xisha, Zhongsha, and Nansha Islands(Zuo et al., 2020). Furthermore, satellite observations indicate a summer sea surface temperature (SST) increase trend of 0.2°C per decade in the South China Sea, with particularly pronounced warming in the northern and southeastern regions(Zuo et al., 2015). Consequently, research into the impacts of climate change on South China Sea coral reefs is of paramount importance.

In the establishment of coral reef conservation areas, maintaining ecological resilience is central(Mumby et al., 2014), necessitating consideration of the dual impacts of both persistent stress from long-term sea temperature increases (i.e., chronic thermal stress) and intense shocks from short-term rapid warming events (such as El Niño) (i.e., acute thermal stress)(Zuo et al., 2020). Chronic thermal stress gradually diminishes coral growth, repair, and reproductive capacity, disrupting entire ecosystem structures. Acute thermal stress, however, represents the intense impact of short-term, severe warming events (such as El Niño), potentially triggering coral bleaching or even mortality within weeks, posing a more immediate lethal threat. Under chronic thermal

stress, corals may gradually adapt. However, when confronted with the high-intensity, short-duration impacts of acute thermal stress, their recovery capacity and adaptability face extreme challenges. Assessing these two stresses respectively reflects adaptive risk and catastrophic risk. Regions experiencing high chronic but low acute stress imply long-term change with lower short-term risk, making them suitable for climate-adaptive conservation areas.

This study comprehensively utilised CoRTAD satellite observations from 1982 to 2100 alongside CMIP6 CanESM5 climate model outputs to systematically evaluate the spatial distribution and temporal evolution of coral reef thermal stress under multiple Shared Socioeconomic Pathways (SSP126, SSP245, SSP370, SSP585) throughout history and into the future. Based on these findings, this paper further identifies coral reef areas with high conservation priority for the future and proposes zoned management and conservation strategies tailored to different levels of thermal stress. This provides scientific evidence and decision support for climate-adaptive conservation and restoration practices of coral reef ecosystems in the South China Sea region (Tkachenko & Soong, 2017).

2 Data and Methods

2.1 Data

This study divides the period 1982–2100 into two phases: (1) 1982–2014 as the historical period; (2) 2015–2100 as the future period, encompassing four Shared Socioeconomic Pathway scenarios (SSP126, SSP245, SSP370, SSP585). Three types of SST data were employed, with specific sources and resolutions detailed in Table 1.

Table 1. SST data and characteristics employed in the study. CoRTAD: Coral Reef Temperature Anomaly Database; CanESM5: Canadian Earth System Model version 5; OISST: Optimum Interpolation Sea Surface Temperature.

Temporal Range	Purpose	Data Name	Spatio-temporal resolution
1982–2014	Chronic & Acute Heat Stress	CoRTAD	4 km, weekly
2015–2100	Chronic & Acute Heat Stress	CanESM5	1°, monthly
1982–2100	Corrected CanESM5 model data	OISST	1°, monthly

2.2 Methodology

Chronic thermal stress under the SSP scenarios for 1982–2014 and 2015–2100 was assessed based on the rate of sea surface temperature increase (°C/decade) in the South China Sea during June–August.

For acute thermal stress, this study employs the DHWs index to construct indicators of cumulative ecological recovery time and annual bleaching duration, thereby assessing the resilience of coral reef ecosystems following short-term thermal shock events.

For the period 1982–2014, the cumulative recovery time of coral reef ecological functions (measuring the number of years required for coral ecosystems to recover from thermal stress) served as the acute thermal stress indicator, calculated as follows:

$$t_{c,cum} = \sum t_c \quad (1)$$

Where t_c denotes the coral reef ecological function recovery time, calculated as follows:

$$t_c = \frac{c}{1+ae^{-bx}} + d \quad (2)$$

Where t_c denotes the recovery time for coral reef ecological function corresponding to

the maximum annual thermal cycle x . Parameters are defined as: $a = 94.63$, $b = 0.44$, $c = 20$, $d = -0.21$ which is calculated using $d = -c/(1+a)$.

For the period 2015 – 2100, the acute thermal stress intensity under different SSP scenarios for 2015 – 2100 is determined by calculating the annual coral bleaching duration. The annual bleaching duration is conservatively defined as the starting year of bleaching events occurring in 10 consecutive years, which is considered unsustainable for coral reefs (Sheppard et al., 2017). The bleaching threshold was selected based on the global coral reef annual bleaching time. If the annual bleaching time for reefs in the South China Sea islands occurred earlier than the global coral reef annual bleaching time, it was considered high acute thermal stress; if later, it was deemed low acute thermal stress. In this study, global coral reefs were similarly modelled using CanESM5, with a bleaching threshold of 6 DHWs. The calculated annual global coral reef bleaching thresholds for each SSP scenario are presented in Table 2.

Table 2. Average annual bleaching duration for global coral reefs under different SSP scenarios (unit: years)

SSP Scenario	SSP126	SSP245	SSP370	SSP585
Global average annual bleaching duration	2043	2052	2047	2044

From 1982 to 2014, the monthly mean temperature (MMM) for each coral reef pixel was extracted from CoRTAD data. Where weekly SST exceeded the MMM by 1°C or more, the excess amount was statistically recorded as the cumulative heat stress value (DHWs). For the period 2015–2100, as CMIP6 data are of monthly resolution, precise calculation of thermal weeks is unfeasible. Therefore, cumulative thermal months (DHMs) were first calculated for June – August periods where SST exceeded the MMM, then multiplied by 4.34 to convert cumulative thermal months into equivalent cumulative thermal weeks.

Through this methodology, annual cumulative thermal week time series were

constructed for each coral reef pixel in the South China Sea region under various SSP scenarios from 2015 to 2100. To express the intensity of acute thermal stress experienced by corals, two key metrics were further extracted from the DHWs sequence: firstly, the cumulative ecological function time. Second, annual bleaching duration: assessing the starting year of each decade during which corals will persistently experience severe thermal stress ($DHW \geq 6$) under different future scenarios (2015–2100), reflecting critical future thermal stress years.

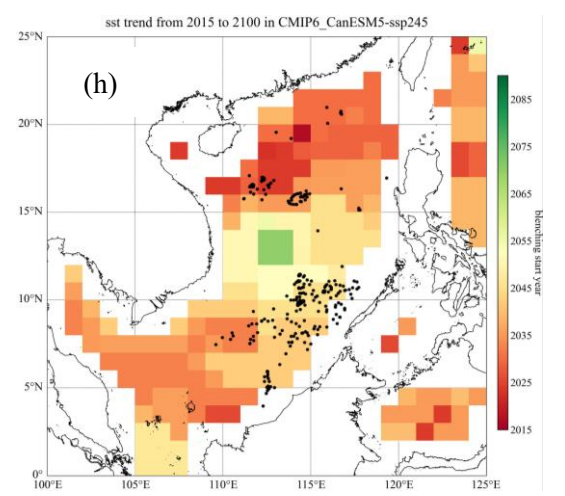
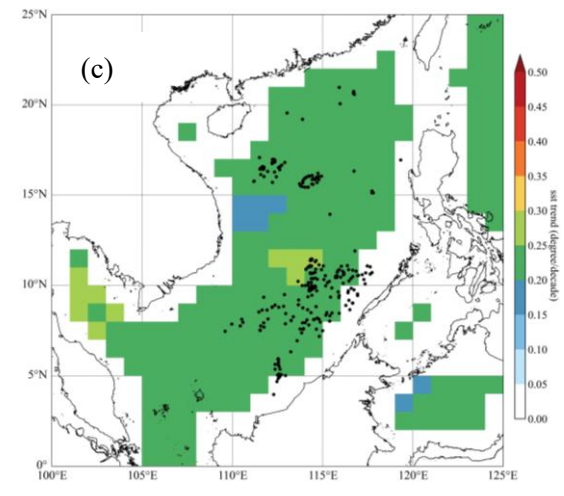
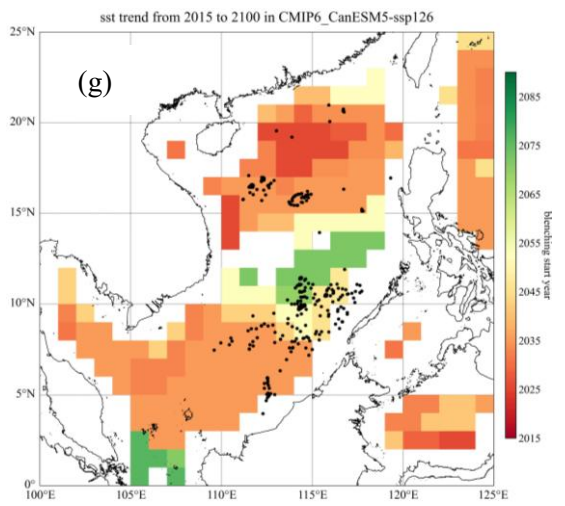
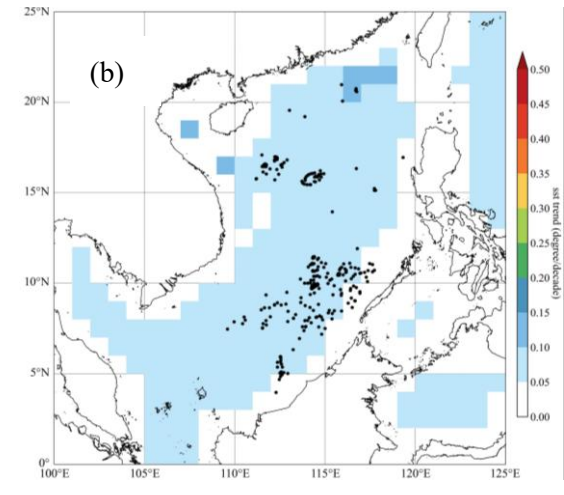
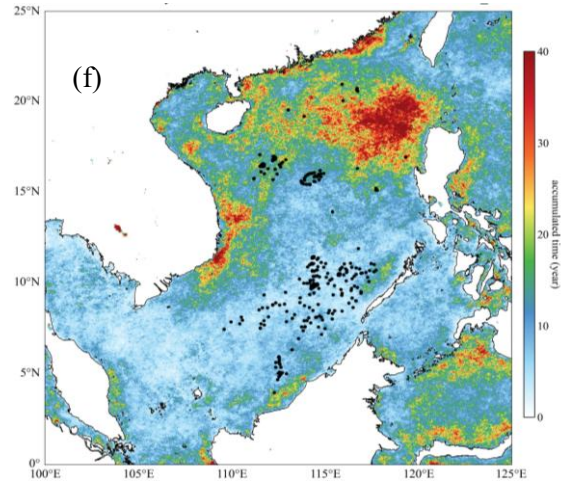
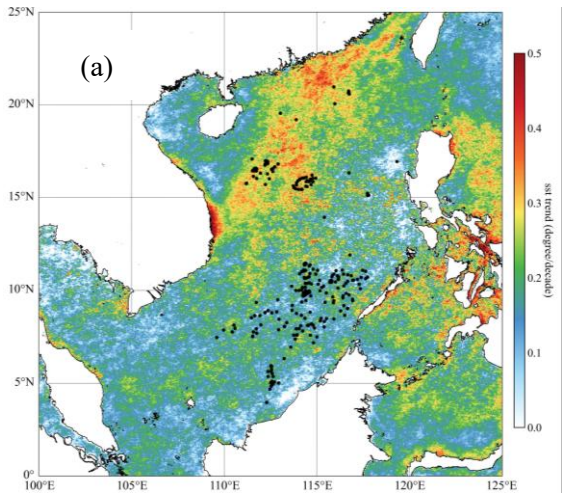
In planning marine protected areas for coral reefs, priority should be given to reef regions experiencing both the most severe and mildest thermal stress. To enable effective hierarchical management, this study employs a quantile approach, dividing the thermal stress distribution into upper and lower 33% percentiles to identify "high" and "low" stress levels for chronic and acute thermal stress respectively. Future acute thermal stress is assessed against the global average annual bleaching duration. Reefs experiencing bleaching later than the global average are classified as "low stress", while those bleaching earlier are designated "high stress". Based on prior research (Li et al., 2011), nine thermal stress states requiring management attention exist within the study area, as illustrated in Fig. 1



Fig. 1 Thermal stress scenarios: Nine thermal stress scenarios were defined within the study area, comprising combinations of high and low levels of chronic and acute thermal stress based on observed and projected values; Management strategy rationale for each scenario is provided; Conservation targets (dark green vertical lines) and their coverage within Marine Protected Areas (MPAs) (green bars) are displayed for each thermal stress scenario. Conservation targets specify the percentage of total coral reef area requiring management (100%, 50%, or 30%) and the required management type (Prohibited Development Zone – solid green bars; multiple-use zones – dashed green bars). Horizontal bars indicate the percentage coverage of each thermal stress scenario by the two MPA types: green bars denote no-take zones, while light green bars denote multiple-use zones (Li et al., 2011) .

3 Results

3.1 South China Sea Thermal Stress



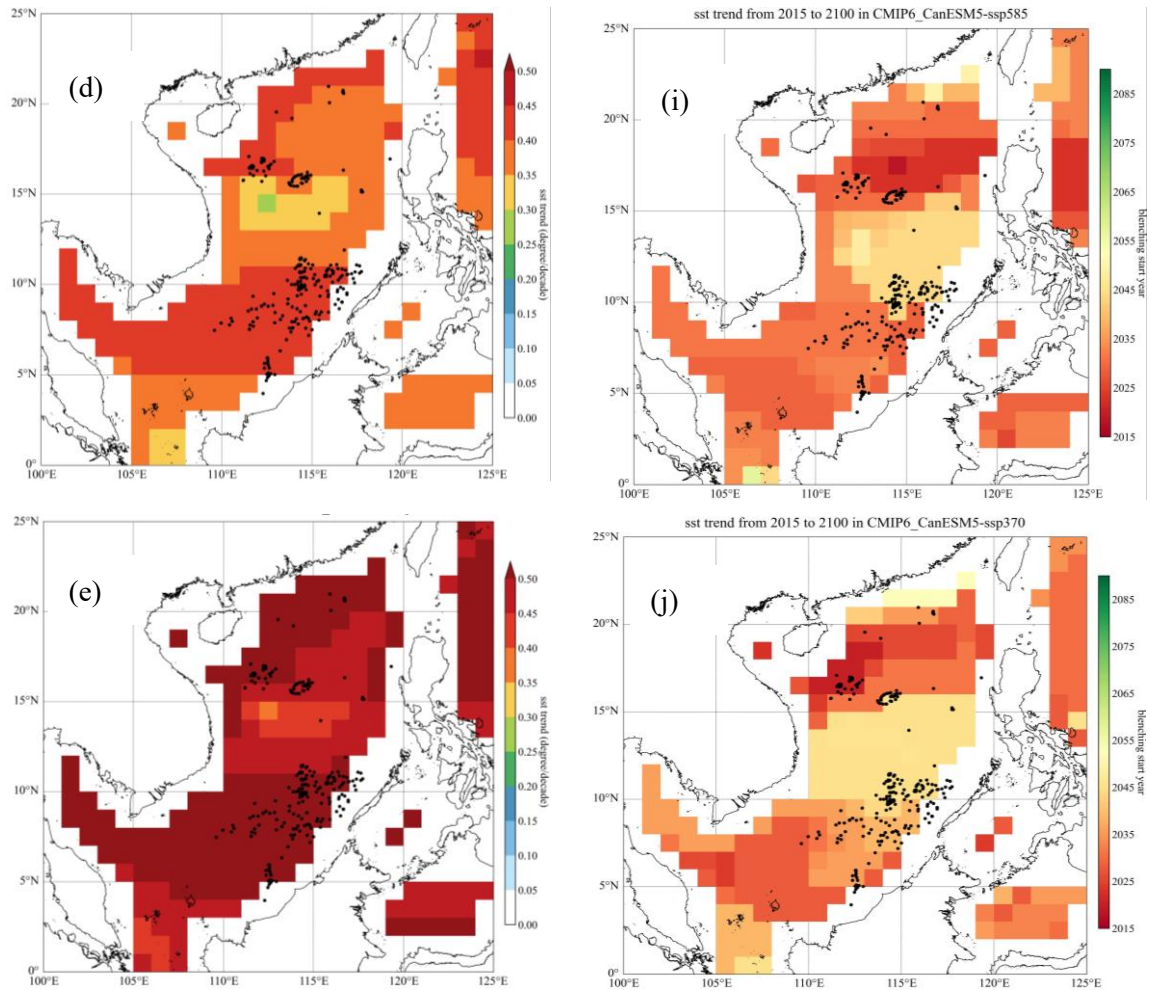


Fig. 2 (a-e) Summer sea surface temperature warming rates ($^{\circ}\text{C}/\text{decade}$) for the South China Sea islands: (a) Results based on CoRTAD satellite observations for 1982–2014; (b-e) CanESM5 model simulations for 2015–2100 under SSP126, SSP245, SSP370 and SSP585 scenarios. (f-j): Annual bleaching duration for the South China Sea Islands; (f) Estimated cumulative recovery time for coral ecological function based on CoRTAD data for 1982–2014 (unit: years); (g-j) Annual bleaching duration simulated by the CanESM5 model for 2015–2100 under different scenarios (unit: year).

As shown in Fig. 2(a), CoRTAD observational data from 1982 to 2014 indicate that the Dongsha Islands, Xisha Islands, Zhongsha Islands, and the seas north of these archipelagos exhibit relatively high summer SST warming rates, reaching $0.3\text{--}0.4^{\circ}\text{C}$ per decade. Among these, the Dongsha Islands and the seas north of them are particularly affected by chronic thermal stress, which is presumed to be related to their latitudinal position, ocean current pathways, and the superposition of ENSO events. SST warming rates in the South China Sea archipelago waters are slightly lower, below 0.3°C per decade. Fig. 2(b-e) indicate significant variations in summer SST

warming rates across South China Sea islands under different SSP scenarios. The spatial pattern of chronic thermal stress undergoes systematic changes with intensified emission scenarios: under SSP126, SST warming rates range from 0.05–0.1 °C/decade across most areas, except for Dongsha Atoll and Nanwei Reef/Beihai Reef in the Dongsha Islands, which exhibit rates of 0.15–0.2 °C/decade (Fig. 2(b)). Under SSP245, the northwestern part of the Spratly Islands exhibited SST warming rates of 0.25–0.3 °C/decade, while other areas generally showed rates of 0.2–0.25 °C/decade (Fig. 2(c)). Under the SSP370 scenario, most areas of the Xisha and Nansha Islands exhibit SST increase rates exceeding 0.4 °C per decade (Fig. 2(d)). Under the SSP585 scenario, summer SST increase rates across the Dongsha, Xisha, and Nansha Islands generally exceed 0.5 °C per decade, while most islands and reefs in the Zhongsha Islands exhibit SST increase rates of 0.4–0.5 °C per decade (Fig. 2(e)). It is evident that although the Spratly Islands currently experience the least chronic stress, under high-emission scenarios they will become one of the most significantly chronically thermally stressed regions in the future.

Fig. 2(f) reveals significant spatial variation in the intensity of acute thermal stress experienced by the South China Sea islands between 1982 and 2014. The ecological recovery time for Nanwei Shoal, Beiwei Shoal, and Dongsha Atoll in the Dongsha Islands, as well as Shenhu Shoal and Yitong Shoal in the Zhongsha Islands, may exceed 20 years. This exhibits a temporal pattern characterized by earlier recovery in the north and later in the south. Concurrently, Dongsha Atoll exhibited cumulative recovery times exceeding 20 years between 1982 and 2014, indicating exposure to frequent and intense thermal events. This aligns with field observations of extensive coral bleaching in 1998 and 2007. The Spratly Islands recorded the shortest cumulative recovery times for coral reef ecological functions, predominantly ranging from 0 to 10 years. Fig. 2(g) illustrates the annual bleaching timing for each reef's pixel location under the SSP126 scenario. Among these, Shenhu Shoal and Yitong Shoal in the Zhongsha Islands experienced earlier bleaching events, followed by the Dongsha Islands and northern Paracel Islands, then southern reefs of the Paracel and Spratly Islands, with the latest bleaching occurring in northern Spratly Islands. Fig 2(h) presents the SSP245 scenario.

212 The earliest bleaching occurred in the northeast Xisha Islands, followed by the western
213 Xisha Islands, Dongsha Islands, and Shenhui and Yitong Shoals in the Zhongsha Islands.
214 This was followed by other reefs in the Zhongsha Islands and some western reefs in the
215 Nansha Islands, with the latest bleaching occurring in the central and eastern Nansha
216 Islands. Fig 2(i) displays the annual bleaching timing under the SSP370 scenario. It is
217 evident that the annual bleaching onset dates for most reefs in the Xisha Islands occur
218 earlier than in the preceding scenarios. Under the SSP585 scenario, the annual
219 bleaching onset dates advance for most coral reefs in the South China Sea, particularly
220 for reefs in the southern Spratly Islands (Fig. 2(j)).

221 Coupled analysis of acute and chronic thermal stress indicates that their spatial
222 distribution and temporal evolution are not entirely synchronized. Some areas, despite
223 enduring prolonged high chronic thermal stress, exhibit relatively weak acute thermal
224 stress, potentially indicating strong adaptive or buffering capacity. Conversely, certain
225 regions currently experiencing lighter thermal stress show a sharp increase in acute
226 threats under future scenarios. Therefore, scenario models based on dual indicators are
227 required to establish more targeted conservation response pathways for coral reefs of
228 different risk types.

231 3.2 Priority Coral Reef Conservation Areas

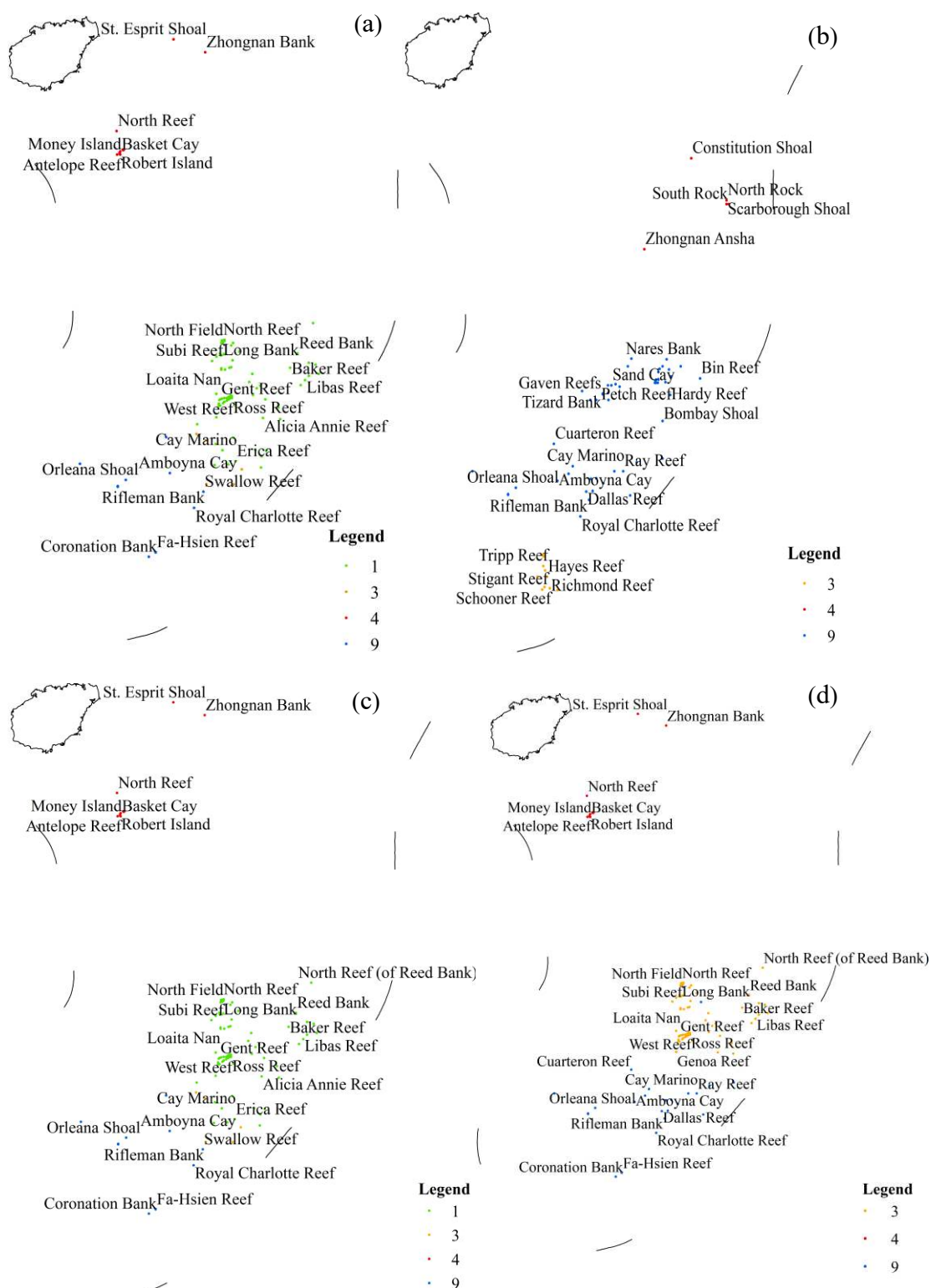


Fig. 3 Thermal stress scenarios for selected coral reefs in the South China Sea under different SSP pathways: (a) SSP126, (b) SSP245, (c) SSP370, (d) SSP585.

Under each SSP scenario, the coral reefs falling into the nine priority protection

thermal stress scenarios, along with their quantities and proportions, are shown in Fig. 3 and 4. Under the SSP126 scenario, 77 (46.1%) coral reefs in the Spratly Islands fall under Scenario 1. Nearly 47% of the Spratly Islands' coral reefs fall under thermal stress Scenario 1 under SSP126, indicating the region's potential to maintain ecological stability in the future. It is recommended that these areas be designated as "Strictly Protected Areas" (100% prohibition on exploitation). Five (3.0%) fell under Scenario 3, and ten (6.0%) under Scenario 9; Two (6.3%) reefs in the Zhongsha Islands and ten (20.0%) in the Xisha Islands fall under Scenario 4 (Fig. 4a), indicating long-term chronic stress risks warranting designation as "30% No-Take Zones".

Under SSP245, 11 (6.6%) and 52 (31.1%) reefs in the Spratly Islands fell into Scenario 3 and Scenario 9 respectively; 5 (15.2%) in the Paracel Islands fell into Scenario 4 (Fig. 4b). Under the SSP370 scenario, 46 (27.5%) and 28 (17.0%) coral reefs in the Spratly Islands fall into Scenarios 3 and 9 respectively; 10 (20.0%) in the Paracel Islands fall into Scenario 4 (Fig. 4c), indicating relatively stable yet difficult-to-mitigate pressures. It is evident that under the SSP245 scenario, the proportions of thermal stress scenarios 3 and 9 increased significantly, with protection types shifting towards "50% prohibited use" and "30% multi-purpose protection".

Under the SSP585 scenario, 66 (39.5%) and 24 (14.4%) coral reefs in the Nansha Islands fall into thermal stress scenarios 3 and 9 respectively, indicating elevated thermal risk. Ten (20.0%) reefs in the Xisha Islands and two (6.1%) in the Zhongsha Islands remain within scenario 4 (Fig. 4d).

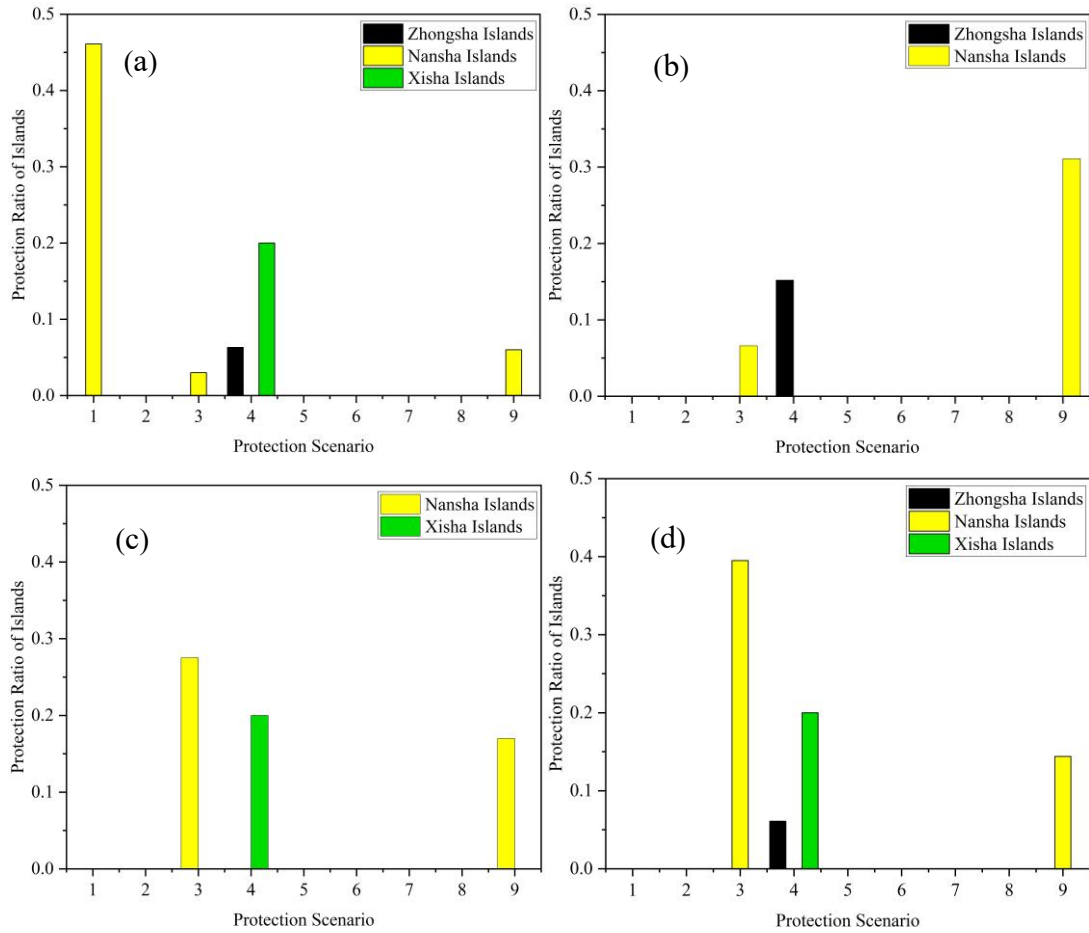


Fig. 4 Proportional distribution of thermal stress scenarios for South China Sea coral reefs under different SSP pathways: (a) SSP126; (b) SSP245; (c) SSP370; (d) SSP585.

4 Conclusions

This study systematically analysed satellite observations from 1982 to 2014 alongside CanESM5 model simulations for 2015–2100 under various SSP scenarios. It comprehensively assessed chronic and acute thermal stress faced by coral reefs in the South China Sea islands against a warming climate background, revealing the following thermal stress characteristics: During the 1982–2014 period, summer sea surface temperatures (SST) in the Dongsha, Xisha, and Zhongsha Islands increased at rates of 0.2–0.4°C per decade. Under future high-emission scenarios (SSP370/SSP585), SST warming rates exceeding 0.4°C per decade are projected for the majority of reefs, intensifying chronic thermal stress. Acute thermal stress analysis indicates that between

1982 and 2014, Dongsha required 15–20 years for ecological recovery due to high-frequency thermal anomalies (DHWs index), whereas Nansha required only 0–10 years. Projections suggest that parts of Dongsha, Xisha, and Zhongsha may experience consecutive bleaching events around 2035, with Nansha lagging slightly but still facing significant threats.

South China Sea islands and reefs primarily face four thermal stress scenarios: Scenario 1 (low thermal stress, 100% no-use zones, e.g. 47% of the Spratly Islands under SSP126); Scenarios 3/4 (medium-high thermal stress, 30–50% no-use zones); Scenario 9 (multiple stressors, designated as 30% multi-purpose protected areas).

This study integrates remote sensing data, climate models, and ecological management standards to establish a dynamic "observation–assessment–classification–management" technical framework. This supports tiered conservation of global tropical coral reefs, providing scientific foundations for marine ecological restoration and the "Blue Territory" strategy. This study excludes the potential impacts of ocean acidification, though existing research indicates acidification significantly impairs coral calcification capacity, spatial competitiveness, and related ecological structuring functions. Long-term, it may exacerbate coral degradation and threaten ecosystem stability. Future research should incorporate ocean acidification factors into analytical frameworks to comprehensively assess the integrated impacts of climate change on coral reefs.

Author contributions Xin Yin was responsible for the study design, data collection, and data analysis. The manuscript was primarily drafted by Xin Yin, Changtong Jiang. All authors participated in the revision of the manuscript, provided important intellectual input, and approved the final version for publication.

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Data availability The sea surface temperature (SST) data used in this study were

derived from three datasets. The Coral Reef Temperature Anomaly Database (CoRTAD) was obtained from the National Centers for Environmental Information (NCEI) of the National Oceanic and Atmospheric Administration (NOAA). Future SST projections during 2015–2100 under four Shared Socioeconomic Pathway (SSP) scenarios (SSP126, SSP245, SSP370, and SSP585) were obtained from the Canadian Earth System Model version 5 (CanESM5). These projections were used to assess future chronic and acute heat stress. The Optimum Interpolation Sea Surface Temperature (OISST) dataset from NOAA was used for bias correction of the CanESM5 outputs.

Declarations Competing interests The authors have no relevant financial or non-financial interests to disclose

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